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A closed-form solution for transmission line fault location using local measurements at a remote substation

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ABSTRACT

This paper presents a novel approach for fault location of overhead transmission lines by voltage and current measurements in a remote substation. The method is applicable when not all of the transmission lines in an area are equipped with fault-locators, although there may be a critical substation (CS) in the area equipped with a digital fault recorder (DFR). In the proposed method, the circuit equations of the network are used to find the transfer function between the fault location and each voltage and current measurement in the CS. Next, two auxiliary variables are defined to transform the nonlinear fault location estimation problem into a linear least squares problem. A closed-form solution is then obtained for fault location. The proposed formulation obviates the need to use unsynchronized or synchronized measurements from any other substation. Moreover, the proposed formulation does not necessitate fault type classification or fault resistance estimation. Furthermore, the distributed parameter model of the transmission line is considered in order for the method to be applicable to long transmission lines. Electromagnetic transient simulations for a 15-bus test system confirm accurate fault location estimation on remote transmission lines for different critical substations considered in the network.

1. Introduction

High-voltage transmission lines are frequently subject to faults. Therefore, a transmission line is equipped with protective relays which isolate the line after a fault. The protective relays, however, cannot guarantee to locate the fault along the line, accurately. Fault-locators are therefore installed in substations for accurate fault location estimation [1]. This helps maintenance crew identify the faulted component and repair the damages caused by the fault.

A number of fault-location algorithms have been developed in the past decades. Impedance-based fault location can be categorized into single-end [2–4] and double-end [5–7] methods. Single-end methods are most favorable, since they use local voltage and current measurements at one terminal of the line. They, however, may lead to large errors due to the "reactance effect". Double-end methods utilize unsynchronized or synchronized measurements from both line terminals. These methods are more accurate than single-end methods, although they are more complicated due to the use of measurements from the remote end of the line.

Conventional single-end and double-end fault-location methods require specific measurements from one (or both) terminal(s) of the faulted line. These measurements, however, may not be always available. Digital fault recorders (DFRs) are usually installed in critical substations (CS) and therefore conventional fault location may not be applicable in all cases [8]. Hence, there is a need to devise a scheme to locate faults on transmission lines by the DFR data available at a remote CS.

Thus far, unconventional fault-location techniques have been devised for fault location of remote transmission lines based on wide-area measurements [9–13]. In [9,10] faults are located based on matching the DFR data to phasors simulated through a software system simulator. The authors in [11] use a travelling-wave-based method for fault location based on the time of arrival of travelling waves at different substations. All of the above methods require measurements from multiple substations. Refs. [12,13] present a novel fault-location approach which uses voltage measurement from a single substation. The network topology and data are utilized so that the fault location on a remote transmission line can be estimated after fault type classification. It must be noted that the fault-locators concern fault location of their corresponding line. Moreover, although a distance relay in its second and third zones covers remote lines for back-up protection, the effect of infeed and outfeed currents in highly meshed networks makes distance relays ineffective for accurate fault location on remote transmission lines

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[1] (chap. 1), [14] (chap. 13). This paper aims at improving the work in [12,13] by using voltage and current measurements at a single substation for fault location of remote transmission lines. A novel transformation is introduced to translate the nonlinear fault location estimation problem into a linear estimation problem, which can be solved in closed form. The proposed method obviates the need to classify the fault type as well as to estimate the fault resistance. The method makes the most of available voltage and current measurements at a CS, which leads to the robust estimation of fault location. Furthermore, the proposed formulation takes the distributed capacitance of long transmission lines into account so that fault location on long lines can be performed accurately.

The rest of this paper is organized as follows. In Section 2, a nonlinear formulation for fault location estimation is developed based on the bus voltage as well as fault currents measured at the CS. Section 3 presents a novel transformation to formulate the problem as a linear least squares problem, which can be solved in closed form. Section 4 is devoted to evaluation studies, followed by the conclusion in Section 5.

2. Nonlinear formulation for fault location estimation

The problem addressed in this paper is fault location by using only voltage and current measurements from a single substation called critical substation (CS). The problem is modeled as an estimation problem in which the fault location along the faulted line (x) is the unknown of interest. Accordingly, the voltage of the CS and the currents through the lines connected to the CS should firstly be expressed as a function of x. It is assumed that the faulted line is a priori known based on the operation of protective relays.

2.1. Substation bus voltage as a function of fault location

Fig. 1 shows a sample transmission network in which a fault on line 8–10 has occurred. If the fault point is denoted by f, the equivalent positive-sequence circuit model of the faulted line can be constructed as shown in Fig. 2. The fault point and the fault current are represented by fictitious bus f and current source I_f, respectively. The superposition principle can be applied to this circuit model, which results in the following equation [15]:

$$V_b^1 = V_b^0 - Z_{bf}^1 I_f, \tag{1}$$

where V_b^1 and V_b^0 are the positive-sequence post- and pre-fault voltage phasors measured at the CS bus b, respectively. Z_{bf}^1 is the positive-sequence $b-f$ element of the post-fault bus-impedance matrix, which is given by [12]

$$Z_{bf}^1 = \frac{\dfrac{Z_{bi}^0}{\sinh(\gamma_{ij} l_{ij} x)} + \dfrac{Z_{bj}^0}{\sinh(\gamma_{ij} l_{ij}[1-x])}}{\left\{ \dfrac{1}{\sinh(\gamma_{ij} l_{ij} x)} + \dfrac{1}{\sinh(\gamma_{ij} l_{ij}[1-x])} + \tanh\left(\dfrac{\gamma_{ij} l_{ij}}{2} x\right) + \tanh\left(\dfrac{\gamma_{ij} l_{ij}}{2}[1-x]\right) \right\}}, \tag{2}$$

where γ_{ij} and l_{ij} are the propagation constant and the length of the faulted line, respectively. γ_{ij} is defined as follows:

$$\gamma_{ij} = \sqrt{z_{ij} y_{ij}}, \tag{3}$$

where z_{ij} and y_{ij} are the per unit length impedance and admittance of line i–j, respectively. Z_{bi}^0 and Z_{bj}^0 are b–i and b–j entries of the pre-fault bus-impedance matrix of the network, respectively.

Eq. (1) can be re-written for the voltage measurement at bus b as

$$\Delta V_b = Z_{bf}^1(x) I_f, \tag{4}$$

where $\Delta V_b = V_b^0 - V_b^1$. For example, for the fault occurred along line 8–10 in Fig. 1, fictitious bus f at the fault point as well as fault current I_f are shown in Fig. 2. It should be noted that some parts of the network in Fig. 1 are not shown in Fig. 2 for the sake of clarity. Fault location is performed by using the measurements at bus 5. Therefore, for this system, b = 5, i = 8 and j = 10. In addition, bus impedance matrices $[Z^0]$ and $[Z^1]$, whose elements can be seen in Eqs. (1), (2) and (4), correspond to the networks shown in Figs. 1 and 2, respectively.

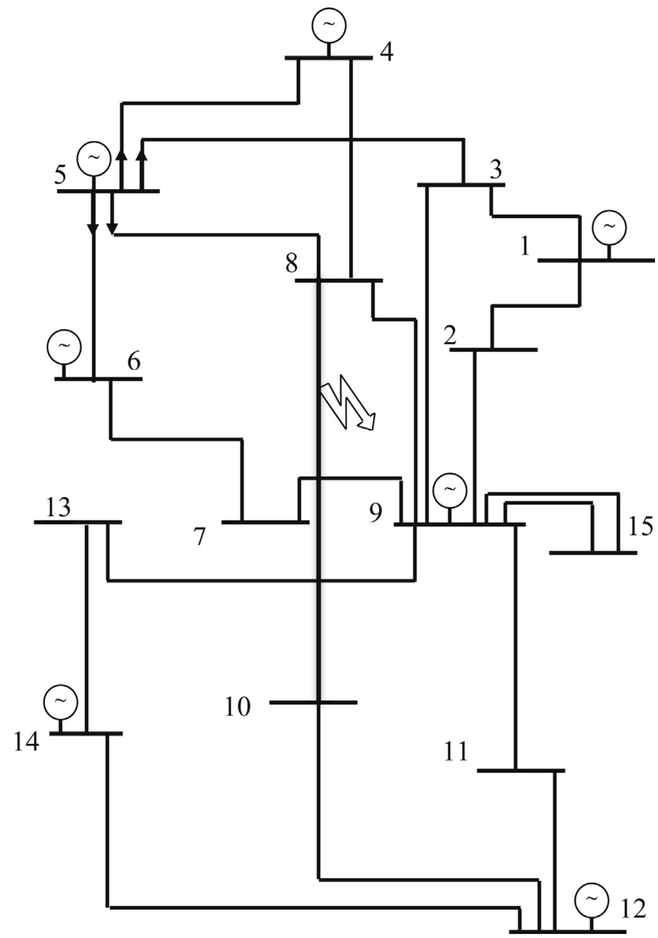

Fig. 1. Single-line diagram of a sample faulted network.

Eq. (4) demonstrates a nonlinear relation between the voltage measurement at bus b, i.e. ΔV_b, and fault location, i.e. x. In fact the formulation includes another unknown (I_f), which will be handled as will be shown later in this paper.

2.2. Substation line current as a function of fault location

The procedure for expressing a positive-sequence current measurement as a function of unknown fault distance (x) is similar. Based on the distributed parameter model of the faulted network, the positive-sequence current of any line b–d connected to the CS can be obtained by applying KVL to the circuit shown in Fig. 3 as

$$I_{bd}^1 = \frac{V_b^1}{Z_{c_{bd}}} \tanh\left(\frac{\gamma_{bd} l_{bd}}{2}\right) + \frac{V_b^1 - V_d^1}{Z_{c_{bd}} \sinh(\gamma_{bd} l_{bd})}, \tag{5}$$

where $Z_{c_{bd}}$ is the surge impedance of line b–d. Referring to Eq. (1), we can extend V_b^1 and V_d^1 in Eq. (5) to obtain

$$I_{bd}^1 = I_{bd}^0 - A_{bd} Z_{bf}^1 I_f - B_{bd} Z_{df}^1 I_f, \tag{6}$$

where A_{bd} and B_{bd} are constants defined as

$$A_{bd} = \frac{1}{Z_{c_{bd}}} \left(\tanh\left(\frac{\gamma_{bd} l_{bd}}{2}\right) + \frac{1}{\sinh(\gamma_{bd} l_{bd})} \right), \tag{7}$$