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Optimal placement of voltage measurements for wide area fault location observability considering the uncertainty of network parameters

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A B S T R A C T

This paper proposes an optimization method based on genetic algorithm (GA) to determine the number and location of phasor measurement units (PMUs) in order to wide area fault location based on voltage measurement. In the practical condition, due to the uncertainty of network parameters including measurement errors and inaccuracy of line parameter values, the estimation of the fault location may be not accurate. Therefore, the proposed method has been developed to determine the number and location of PMUs in order to achieve an acceptable accuracy with required reliability. Since the number and location of PMU depends on the fault location method, a new fault location method has been developed with minimum required number of PMUs. The new method can determine the fault location by measuring from one side of the fault point instead of two sides. Therefore, the number of required PMUs is minimized at comparison to previously presented methods. The weighted least-square (WLS) method is used to solve the fault location problem by minimizing the measurement errors. To consider unsynchronized condition of measurements, the formulation has been modified using only the magnitudes of voltage measurements. Finally, the method has been applied on New England 39-bus test system, and the results show the efficiency of the proposed PMU placement and fault location methods in the network with the uncertainty of parameters.

1. Introduction

Accurate and prompt estimation of fault location is very important and critical for transmission line to identify faulted line and system restoration which can help to reduce outage time, and improve the system reliability [1].

Many studies have been conducted in the past for improving the fault location estimation. The single-end impedance-based fault location algorithms have been developed for locating faults in power systems. These methods utilize only local voltage and current measurements from one terminal [2]. The fault resistance may reduce the fault location accuracy and even may cause to produce wrong results in these methods [3]. In Ref. [4], a technique was proposed for reducing and compensating the impact of fault resistance. To enhance fault location estimation, double-end, and multi-end algorithms were developed [5–9]. A fault location technique for multi-terminal lines was proposed that estimates the fault location by redundant network equation, and least square method [10]. A fault location scheme based on neural network was explored in Ref. [11]. Ref. [12] presented a scheme for multi-terminal line fault location with taking benefits of synchronized voltages for all terminals. Further, a fault location method for a two terminal transmission line was presented in Ref. [13] using an iterative method with considering measurement errors.

Wide area scheme for fault location of transmission line based on travelling wave has attracted increasing attention recently [14,15]. Although these methods have high accuracy, the high sampling rate devices are required. A fault location method based on bus-impedance matrix was proposed in Ref. [16], which uses voltage measurements from one and two buses of the network. In Ref. [17], a fault location index relating voltage measurements was defined to determine fault area and then fault point.

Despite the effectiveness of these methods, they cannot determine the fault location accurately and uniquely in the case of uncertainty in the network parameters. To develop prompt and accurate fault location, the studies have been devoted to propose wide-area fault location in power system with considering uncertainty of parameters [18–20]. In Ref. [18], the formulation has been extracted for fault location estimation with considering uncertainty on the line parameters and voltage measurements. In this method, fault location estimation accuracy has improved by detecting and removing of bad measurement data. In Ref. [19], the fault location was determined, by checking least square error and possible fault distance for all transmission lines. This method

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requires high running time, as well as large numbers of PMUs for large-scale power network. A non-iterative fault location algorithm was suggested to locate faults on un-transposed transmission network [20]. In Ref. [21], a fault location method on double-circuit transmission-line was proposed. In this paper, to remove bad measurements, the equations of any two measurement units are solved simultaneously. In Ref. [22], a method based on linear WLS was proposed to fault location estimation. In this paper two auxiliary variables are determined to transform nonlinear fault location equations to a linear WLS problem.

An optimal meter placement algorithm was proposed in Ref. [23] for fault location observability. In this paper all combinations of meter placements were investigated using direct search. In Ref. [24] the optimal PMU placement algorithm which had been presented in Ref. [23], was developed. This method uses an algorithm based on integer linear programming. Refs. [23] and [24] uses the fault location method of Ref. [16] without considering uncertainty of network parameters.

In this paper, a method based on GA is proposed to obtain optimal placement of PMUs for fault location observability. In the real network, due to the uncertainty of network parameters the estimation of fault location may be not accurate. Therefore, in the proposed algorithm, the number and locations of PMUs are determined in order to obtain acceptable accuracy with required reliability. Also to reduce the number of measurements, the fault location equations are developed based on fault location and fault resistance. So, the method can determine the fault location by measuring from one side of the fault point instead of two sides. WLS method is used to minimize the error of fault location. For unsynchronized measurements the formulation is adapted to consider only the magnitudes of voltage measurements.

One of the important aspects for evaluation of a fault location method is the number of required measurements. Therefore, a method is needed for determining optimal number and location of measurements considering fault observability with acceptable range of accuracy and reliability. In fact, this is the gap that this paper tries to fill.

This paper is organized as follows. Section 2 presents the proposed method fulfilled by formulating of fault location, and estimating the fault distance and fault resistance. Section 3 presents the method for optimizing PMU locations for fault location observability considering a constraint. Section 4 demonstrates the simulation results. Finally, conclusion is given in Section 5.

2. Fault location method based on one side voltage measurement

In the previous studies [17–20], the fault location formulations are based on two parameters; fault location and fault current. In these methods, at least two PMUs on two sides of the fault point are needed to determine the fault location. Therefore, PMUs should be installed in all of the terminal buses to make the network observable. However, in the proposed method, the formulations are based on fault location and fault resistance. The new method is capable of determining the fault location by measuring from one side of the fault point. So, the number of required PMUs can be reduced considerably. The new method for fault location using synchronized and unsynchronized voltage measurements is presented in this section.

2.1. Estimation of fault location utilizing synchronized voltage measurements

A model of transmission network with N bus is depicted in Fig. 1. The total equivalent impedance of line between bus n and m is $z_{nm}^{(s)}$ with s = 0, 1 or 2, indicating zero, positive and negative sequence, respectively. Consider a fault occurs at point f on transmission line $n - m$, and in x per unit distance from bus n. Since in during fault condition, fault current is injected from point f to the network; f is assumed as $(N + 1)^{th}$ bus. Z_0 is bus-impedance matrix of the pre-fault network. In during fault, bus-impedance matrix Z is a $(N + 1) \times (N + 1)$ matrix, and can be reconstructed corresponding to the elements of Z_0 as follow:

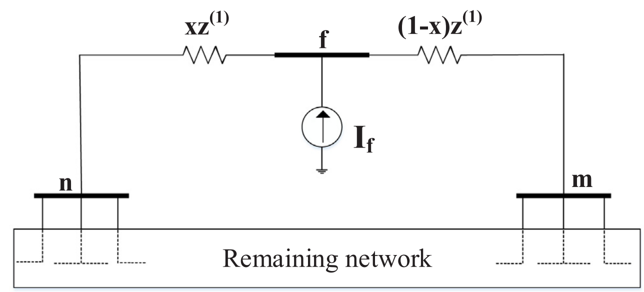

Fig. 1. Positive-sequence network during fault.

$$Z_{kf}^{(s)} = B_k^{(s)} + C_k^{(s)}x \tag{1}$$

$$Z_{ff}^{(s)} = A_0^{(s)} + A_1^{(s)}x + A_2^{(s)}x^2 \tag{2}$$

where $B_k^{(s)}$, $C_k^{(s)}$, $A_0^{(s)}$, $A_1^{(s)}$ and $A_2^{(s)}$ are constants, which are derived by the line parameters, as provided in Appendix A.

The difference between pre and post fault positive sequence voltage measurements at bus k can be written as below:

$$\Delta V_k^{(1)} = Z_{kf}^{(1)} I_f^{(1)} \tag{3}$$

where $\Delta V_k^{(1)}$ is positive-sequence voltage change at bus k, I_f is positive-sequence fault current injected at the fault point, and Z_{kf} is the element of k^{th} row and f^{th} column of Z. Since the positive sequence exists for all types of faults, only positive sequence voltage measurement is used for proposed fault location algorithm.

Considering a LLL fault occurring on the line n–m, with fault resistance R_f and fault location x, we can express injecting fault current flowing through R_f as below:

$$I_f^{(1)} = \frac{V_f^{(1)0}}{R_f + Z_{ff}^{(1)}} \tag{4}$$

where $V_f^{(1)0}$ is pre-fault positive voltage at fault point, and Z_{ff} is diagonal element of Z. Eq. (5) can be obtained substituting (1), and (2) into (3) and (4).

$$\Delta V_k^{(1)} = \frac{(B_k^{(1)} + C_k^{(1)}x)V_f^{(1)0}}{R_f + A_0^{(1)} + A_1^{(1)}x + A_2^{(1)}x^2} \tag{5}$$

For other types of faults, $I_f^{(1)}$ and $\Delta V_k^{(1)}$ formula mentioned in Appendix B. Eq. (5) contains two unknown parameters R_f and x. By considering (5) for all available PMUs, the fault location matrix can be obtained by

$$\begin{bmatrix} |\Delta V_{G_1}^{(1)}| \\ \angle\Delta V_{G_1}^{(1)} \\ \vdots \\ |\Delta V_{G_L}^{(1)}| \\ \angle\Delta V_{G_L}^{(1)} \end{bmatrix} = \begin{bmatrix} \left|\frac{(B_{G_1}^{(1)} + C_{G_1}^{(1)}x)V_f^{(1)0}}{R_f + A_0^{(1)} + A_1^{(1)}x + A_2^{(1)}x^2}\right| \\ \angle\frac{(B_{G_1}^{(1)} + C_{G_1}^{(1)}x)V_f^{(1)0}}{R_f + A_0^{(1)} + A_1^{(1)}x + A_2^{(1)}x^2} \\ \vdots \\ \left|\frac{(B_{G_L}^{(1)} + C_{G_L}^{(1)}x)V_f^{(1)0}}{R_f + A_0^{(1)} + A_1^{(1)}x + A_2^{(1)}x^2}\right| \\ \angle\frac{(B_{G_L}^{(1)} + C_{G_L}^{(1)}x)V_f^{(1)0}}{R_f + A_0^{(1)} + A_1^{(1)}x + A_2^{(1)}x^2} \end{bmatrix} \tag{6}$$

If L is supposed the number of available PMUs in the network, the number of nonlinear equations for all PMUs will be 2L. Eq. (6) can be written as below:

$$M = F(X) + e \tag{7}$$

M is the measurement vector that contains the magnitude and angle of $\Delta V_{G_i}^{(1)}$ which is defined as $M = [|\Delta V_{G_1}^{(1)}| \cdot \angle\Delta V_{G_1}^{(1)} \dots |\Delta V_{G_L}^{(1)}| \cdot \angle\Delta V_{G_L}^{(1)}]$. F is the function vector containing the unknown variables that is equal the right hand side of (6), and e is the error vector related with the measurement