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Fault location in active distribution networks using non-synchronized measurements

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ABSTRACT

Fault location is a necessity to realize the self-healing concept of modern distribution networks. This paper presents a novel fault location method for distribution networks with distributed generation (DG) using measurements recorded at the main substation and at the DG terminals. The proposed method is based on an iterative load flow algorithm, which considers the synchronization angle as an unknown variable to be estimated. Therefore, it obviates the need of synchronized measurements. A new fault location equation is also proposed which is valid for all different fault types, hence the fault type information is not required. The developed method can be simply implemented by minor modifications in any distribution load flow algorithm and it is applicable to different distribution network configurations. The accuracy of the method is verified by simulation studies on a practical 98-node test feeder with several DG units.

1. Introduction

According to failure statistics, approximately 80% of all customer interruptions are due to faults on distribution networks [1]. It is therefore required to manage distribution faults in an efficient and effective manner to maintain the quality of service by minimizing the outage time. Distribution outage management is closely related to operators ability to find the fault location. In branched distribution networks dispersing over vast rural and urban areas, fault location can be a great help in minimizing the inspection and service restoration times. Accordingly, significant research efforts have been devoted to the subject. The proposed approaches can be classified into outage area location methods [2,3], and fault location methods. The first class uses data such as customer calls or fault indicating signals to find the most likely interrupted area, while the second class finds the location of the fault, which caused the resulting outage [4].

Based on the required inputs and their computational process, distribution fault location methods can be categorized into: impedance-based methods [5,6], algorithms based on sparse measurements [7–11], traveling waves-based methods [12–14], learning-based methods [15,16], and integrated methods [17–19]. Although some of these methods have presented excellent results, most of them are designed for radial networks with a unidirectional power flow. However, the future distribution networks are expected to accommodate a variety of distributed generation (DG) sources, which change the radial nature of distribution systems to multi-source networks with bidirectional power flows. Hence, there is a need for a new class of fault location methods for such systems.

Recently, some fault location methods are proposed for distribution networks with DG. In [20] authors present a learning-based scheme with very short online execution time. However, learning-based methods mostly require several actual or simulated fault cases for training and retraining following to any change in network topology. The methods described in [21–24] are modified impedance-based algorithms. These methods solve a set of equations for all line sections, one by one, to find all possible fault locations. In [25,26], authors propose algorithms based on sparse measurements. These algorithms apply the fault at all network nodes, one by one, and calculate the change in three-phase voltages at nodes having measurements. Finally, by comparing the measured and calculated values for all nodes, they identify the node with the minimum difference as the fault location. The genetic algorithm-based technique proposed in [27], optimizes the process of the methods of [25,26] to decrease their computational time. In [28], an integrated method finds all possible fault locations using an impedance-based algorithm and then uses the measured DG terminal voltages to identify the best solution. The authors of [29] propose a method based on a time-domain

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numerical analysis using a data window moving from pre-fault to post-fault in time domain. Although this algorithm considers the dynamic behavior of generators during fault transients, it is only applicable to synchronous machine-based DGs.

The above mentioned fault location methods mostly rely on synchronized measurements provided by meters installed at the main substation and at the DG terminals. It is possible to synchronize the measurements using the global positioning system (GPS) or computer networks [30]. However, unavailability of the synchronized measurements, even in some recent smart metering projects [31], limits the application of these methods. Therefore, there is a need for a new method that can employ the non-synchronized measurements to find the accurate location of faults in distribution networks with DG.

To obviate the need of synchronized measurements, this paper presents a new impedance-based fault location method, which considers the synchronization angle as an unknown variable to be estimated. Compared to the previously proposed fault location methods, the main contributions are as follows:

- The proposed method can solve the fault location problem in distribution networks with or without DGs using synchronized and/or non-synchronized measurements;
- A new fault location equation is proposed which is valid for all different fault types. Therefore, in contrast to the previously proposed impedance-based methods [5,6,21–23], the proposed method does not require fault type information;
- Compared to the methods proposed in [21,29], which are designed for synchronous DGs, the presented method is applicable to all DG types without requiring their models and parameters.
- The proposed method is fully load flow-based and it can be simply implemented by minor modifications in any distribution load flow algorithm.

In the rest of the paper, Section 2 presents the details of the proposed fault location method. Section 3 gives the simulation results for different fault scenarios and finally, Section 4 concludes the paper.

2. Fault location method

Following the occurrence of a fault and the protection system operation, the fault locator uses the measurements recorded at the head of the distribution feeder and at the feeder DG terminals to find the fault location. Smart meters, digital relays or fault recorders can provide the required measurements [30]. The proposed method considers the synchronization angle as an unknown variable to be estimated. Therefore, the measurements do not need to be synchronized. However, each meter should still be able to provide the during-fault voltage and current magnitudes, recorded for the same fault event, as well as their angular difference. A simple communication infrastructure such as the one described in [31] can provide the required measurements for the fault locator. System data such as network topological information, line section impedances, and load data are also required, which can be extracted from the distribution system database. Having the required measurements and system data, the fault locator solves the fault location equation for all network line sections to find the fault location.

2.1. Fault location equation

Consider a faulted line section of a radial distribution system, as shown in Fig. 1, where $[V_S] = [V_a, V_b, V_c]^T$ and $[I_S] = [I_a, I_b, I_c]^T$ are the vectors of the sending end voltages and currents, $[I_R] = [I_{ra}, I_{rb}, I_{rc}]^T$ is the vector of downstream currents and $[I_F] = [I_{fa}, I_{fb}, I_{fc}]^T$ is the vector of fault currents. The fault location voltage can be expressed as follows:

$$[V_F] = [V_S] - d\,[Z]\,[I_S] \tag{1}$$

where d is distance to the fault and $[Z]$ is the line impedance matrix:

$$[Z] = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{bmatrix}$$

Having the fault location voltage and its upstream and downstream currents, the three-phase current and apparent power flowing to the fault can be calculated using the following equations.

$$[I_F] = [I_S] - [I_R] \tag{2}$$

$$S_F = P_F + jQ_F = [V_F]^T [I_F]^* \tag{3}$$

By assuming a pure resistive fault, the fault distance can be calculated by splitting the imaginary part of Eq. (3) and equalizing it to zero.

$$d = \frac{\sum_{k=a,b,c}\left(V_k^i I_{fk}^r - V_k^r I_{fk}^i\right)}{\sum_{k=a,b,c}\sum_{j=a,b,c}\left(I_{fk}^i\left(I_j^i z_{k,j}^i - I_j^r z_{k,j}^r\right) + I_{fk}^r\left(I_j^i z_{k,j}^r + I_j^r z_{k,j}^i\right)\right)} \tag{4}$$

where r and i represent, respectively, the variables real and imaginary parts.

This equation is applicable for all different shunt fault types. Therefore, the proposed method does not require any information regarding the fault type.

Due to the voltage drop caused by the fault, the during-fault downstream current in Eq. (2) is different from its pre-fault value and it is also an unknown variable. Therefore, for each line section, having the voltage and current phasors at the sending end ($[V_S]$, $[I_S]$), the following iterative procedure is carried out to solve the fault location equations, at which $[I_R]$ and d are unknown values:

(1) Assume the fault at the beginning of the line ($d = 0$);
(2) Calculate the fault location voltage using Eq. (1);
(3) Use the voltage obtained in step 2 to calculate $[I_R]$ by performing load flow for downstream network;
(4) Calculate the fault current ($[I_F]$) using Eq. (2);
(5) Substitute $[I_F]$ into Eq. (4) to obtain the fault distance;
(6) Repeat the above steps until the estimated fault distance converges to a certain value.

Fig. 2 shows the flowchart of the proposed fault location method. The fault locator starts from the first line section. For this line, the sending end voltage and current ($[V_S]$, $[I_S]$) are equal to the voltage and current measured at the head of the distribution feeder. Fault distance is initially assumed to be zero and using Eq. (1), the fault location voltage ($[V_F]$) is calculated. Then, the calculated $[V_F]$ is taken as reference and as described in Section 2.2, a load flow is performed for the downstream network to obtain its current ($[I_R]$). In the next step, having $[V_S]$, $[I_S]$, $[I_R]$ and $[Z]$, the proposed method solves Eq. (4) to find d. If the calculated distance is less than the line section length, fault locator repeats the above procedure until d converges to a certain value. Otherwise, the fault is not in that section and the above steps should be repeated for another line section with the calculated voltage and current phasors at its sending end. The details of the proposed load flow-based algorithms for estimation of the downstream current and calculation of each line section sending end voltage and current are described in the next two subsections.