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Active distribution network fault location methodology: A minimum fault reactance and Fibonacci search approach

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ABSTRACT

Active Distribution Networks (ADN) are defined as distribution networks with presence of Distributed Energy Resources (DER). In this paper, a Fault Location (FL) analytical methodology for active distribution networks is presented. The proposed technique combines the minimum fault reactance concept and a Fibonacci search method to estimate the fault location. Synchronized current phasors provided by Intelligent Electronic Devices (IED) located at the DER units are considered. A ladder-based technique is proposed and used to estimate the current contribution of each DER to the fault point. Proposed analytical methodology is applicable for all DER types without need to know its individual parameters and model. Validation is made using the IEEE 34-nodes test feeder. Test feeder is modeled using ATP/EMTP software and modified with the addition of several DER. Test results show the robustness of the methodology, indicating its potential for real-life applications.

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Introduction

Recent studies have exposed that widespread adoption of Distributed Energy Resources (DER) in power distribution networks can play a key role in generating clean and reliable energy with substantial environmental benefits [1]. DER comprises several Distributed Generation (DG) and energy storage technologies. The integration of DER and their simultaneous operation with controllable loads and storage equipment are new challenges that distribution utilities must address. Supervision, monitoring and management of electrical networks with auto-regeneration (self-healing) features become more complex under this new scenario [2]. Fault location (FL) is a most important task for fast maintenance and restoration of the electricity supply. However, despite recent distribution systems automation technology deployment and society's higher power quality expectations, still distribution networks FL is inefficient, requiring a great amount of time and money [3]. Recently several analytical methodologies based on different mathematical formulations for distribution systems FL have been proposed [4–8]. One of the most accepted techniques are the impedance-based approaches [4]. Some of these proposed methods for distribution systems have presented excellent results [5–8], which can be easily implemented on power distribution networks with low capitol cost [3]. However, as a drawback, some features, such as potential presence of DER, have not yet been addressed. More recently, analytical methodologies that consider the DG impact on FL have been presented [9–17]. In [9,10,16,17], DG impact is considered through a synchronous machine approximate model. Reported results are encouraging, however, formulation derivation is made considering distribution networks in presence of only synchronous machine based DG. Therefore, all other DG technologies are not considered. Additionally, in [9,10], proposed methods consider operating scenarios with only one DG unit connected in the system.

In [11–15] different methodologies to consider DG impact on distribution networks FL are formulated using synchronized current and voltage phasors provided by digital fault recorders and GPS. These approaches assume that measurement devices located at distributed power sources are available. However, validation is made considering only one single synchronous machine based DG unit connected. One interesting approach is proposed in [15]. This work presents a method that uses remote measurements at each DG unit and is formulated considering multiple DG units connection. Nevertheless, also, validation considering only one DG technology type is presented.

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In this work, an analytical methodology based on the minimum fault reactance concept combined with the Fibonacci search method [18] to estimate the FL in distribution networks in presence of multiple DER types is presented. The approach removes potential correlation between search step and accuracy of the fault reactance method. Still, the DER impact is considered using synchronized current phasors provided by Intelligent Electronic Devices (IEDs) located in each DER unit terminal. Additionally, a ladder-based technique is proposed and used to estimate the fault current contribution from each DER type. Still, in contrast from other works [11–15,19], where synchronized voltage and current phasors at terminals of each DGs are required, the proposed method only requires the synchronized current phasors measured at each DER terminal. Aiming to show the main contributions of the proposed methodology, consider Table 1. On such table, main aspects considered by FL state-of-the-art methods and proposed methodology are highlighted.

The remainder of this paper is organized as follows. Section 'Proposed fault location equations' presents the proposed fault location equations. Section 'Fibonacci based search approach applied to fault location' presents the Fibonacci search method. Section 'Fault location analytical methodology for distribution networks with DER' presents the proposed analytical methodology. Section 'Case study' presents a case study, as well as test results and discussion. Finally, the conclusions of this work are presented on section 'Conclusions'.

Proposed fault location equations

The proposed analytical methodology is based on the minimum fault reactance concept [24]. The core idea of this approach is that, for each analyzed line section, a random value for the fault distance estimate is supposed. Considering this and using circuit analysis derived equations, which are presented in the following, one can estimate the fault reactance. The assumed fault distance value is then systematic varied, from local bus to the line length section. For each assumed fault distance, a fault reactance is estimated. This procedure is repeated on all system lines. Considering that most line faults have resistive nature, the chosen fault location is the one that generates the smaller fault reactance estimate [6]. Fault reactance is estimated using voltages and currents measured at substation, and DER measured currents.

In the following, the minimum fault reactance concept equations are presented. Consider the distribution network illustrated in Fig. 1, and that there is a fault between nodes k and k + 1.

Still, consider that the faulted line section is unknown. Thus, initially, the first substation downstream line section is considered. On this analyzed line section, a distance m is initially supposed as the fault distance. Consider Fig. 2.

As illustrated in Fig. 2 different fault types can be obtained from the combination of switches $sw1$, $sw2$, $sw3$ and $sw4$. Thus, from Fig. 2 it can be obtained a generalized expression for the voltage in the fault point $[\boldsymbol{V}_F]$ given by (1) [19]:

$$[\boldsymbol{V}_F] = \left([\boldsymbol{I}] + 0.5 \cdot m^2 \cdot [\boldsymbol{Z}_{k,k+1}] \cdot [\boldsymbol{Y}_k]\right) \cdot [\boldsymbol{V}_k^f] - m \cdot [\boldsymbol{Z}_{k,k+1}] \cdot [\boldsymbol{I}_k^f] \tag{1}$$

where $[\boldsymbol{Z}_{k,k+1}]$ is the line series impedance matrix (in ohms), $[\boldsymbol{Y}_k]$ is the line shunt admittance matrix (in ohms), $[\boldsymbol{V}_k]$ is the terminal k voltages vector (in volts), $[\boldsymbol{I}_k]$ is the terminal k currents vector (in amps), $[\boldsymbol{I}]$ is the third-order identity matrix and m is the fault distance.

The fault current is estimated considering the contribution from the substation and the downstream circuit, according to (2). It should be noted that the current contribution from the downstream circuit can change its value with the presence of DER.

$$[\boldsymbol{I}_F] = [\boldsymbol{I}_U^f] + [\boldsymbol{I}_D^f] \tag{2}$$

where $[\boldsymbol{I}_U]$ is the current upstream to the fault point given by (3) and $[\boldsymbol{I}_D]$ is the current downstream to the fault point. On this work, this downstream to the fault point contribution current is estimated using a ladder-based load flow, as is presented in the section 'Fault location analytical methodology for distribution networks with DER'. Still, one can derive (3):

$$\begin{aligned}[\boldsymbol{I}_U^f] = &-\left[m \cdot [\boldsymbol{Y}_{abc}] + 0.25 \cdot m^3 \cdot [\boldsymbol{Y}_{abc}] \cdot [\boldsymbol{Z}_{k,k+1}] \cdot [\boldsymbol{Y}_{abc}]\right] \cdot [\boldsymbol{V}_k^f] \\ &+ \left[[\boldsymbol{I}] + 0.5 \cdot m^2 \cdot [\boldsymbol{Z}_{k,k+1}] \cdot [\boldsymbol{Y}_{abc}]\right] \cdot [\boldsymbol{I}_k^f]\end{aligned} \tag{3}$$

Using (1) and (2) a generalized expression to estimate the fault reactance x_F can be proposed for each fault type as follows:

$$x_F = \Im\left\{\frac{S_i \cdot V_{F_i} - S_j \cdot V_{F_j}}{S_i \cdot I_{F_i}}\right\} \tag{4}$$

Table 1
Summary of the main aspects of the analyzed fault location methods.

Analyzed aspect	Methods									
	[9]	[12]	[10]	[17]	[16]	[14]	[11]	[13]	[15]	Proposed methodology
Signal processing										
Pre-fault	√	√	√	√	√	√	√	√	–	√
Fault	√	√	√	√	√	√	√	√	√	√
DG modelling										
Electric model	√	–	√	√	√	√	–	–	–	–
Synchronized voltage phasors	–	√	–	–	–	√	√	√	√	–
Synchronized current phasors	–	√	–	–	–	√	√	√	√	√
Several DG connected	X	X	X	√	√	√	X	X	√	√
Different DG methodologies	X	X	X	X	X	√	√	√	√	√
Validation considering different DG technologies	X	X	X	X	X	X	X	X	X	√
Power distribution system features										
Symmetrical components	√	√	–	–	–	–	–	–	–	–
Phase components	–	–	√	√	√	√	√	√	√	√
Unbalance system	X	X	X	√	√	√	√	√	√	
Capacity effect	X	X	X	X	X	X	X	X	√	√
Lateral	√	√	X	√	√	√	√	√	√	√
Load variation effect	X	X	√	X	√	√	X	√	√	√
Faults features										
All fault types	X	√	X	X	X	X	√	X	√	√
Fault resistance	X	√	√	√	√	√	√	√	√	√

X does not consider, **-** not necessary and √ it is consider by approach.

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