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Towards active distribution networks fault location: Contributions considering DER analytical models and local measurements

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ABSTRACT

This paper presents an analytical methodology to estimate the fault location in active distribution networks. State-of-the-art solutions for active distribution networks fault location consider wide-area measurements, which include synchronized measurements obtained by Phasor Measurement Units (PMU). For distribution networks though, the capital cost of such solutions is prohibitive. Most recently, solutions have been proposed without considering synchronized measurements. However, they have some limitations, such as not considering multiple inverter-interfaced Distributed Energy Resources (DER). The solution presented is composed of a load flow based approach, which uses only locally available measurements. A ladder iterative technique is proposed to estimate the system state variables during the fault period. DERs models, which consider various modes of operation and fault conditions are used. An impedance formulation which considers distribution networks inherent characteristics is presented. The proposed methodology is validated on the IEEE 34-nodes test feeder. The ease of implementation of design, formulation of parameters and encouraging test results indicate potential for real-life applications.

1. Introduction

Recent years have shown a steady and constant penetration of Distributed Energy Resources (DER) into Power Distribution Networks (PDN) [1]. DERs comprise Distributed Generation (DG) technologies, such as diesel engines, micro-turbines, photovoltaic, small wind turbines and energy storage technologies, such as fuel cells and flywheels [2]. Most of these technologies require a power electronic based interface for PDN interconnection and synchronization. In this work, such devices are named inverter-interfaced DER. The integration of DERs on PDNs however, presents new challenges to protection engineers. To start, operation characteristics of typical radial PDNs change. The presence of bidirectional power flows essentially changes how PDNs are operated and protected [1,3]. Recently, some strategies to improve supervision and management of PDNs were proposed and developed [4]. One of the new paradigms proposed for smarter PDN supervision and management are self-healing capabilities. PDNs with self-healing capabilities are capable of autonomous fault location and load restoration [5,6]. As such, determination of FL is the most important aspect for self-healing capabilities.

Fault location on PDNs is not a new research theme. Several methodologies based on local or wide-area measurements have been proposed [7]. Among them, there are methods based on travelling waves, machine learning and apparent impedance. Travelling-wave methods proposed [8,9] present some of the most interesting results. These methods analyze the fault-generated electromagnetic wave to infer a fault location. These approaches though, present some important requirements, as high sampling rate disturbance recording equipment. Artificial intelligence based methods, such as machine learning methods, assume that every possible class and the distribution of possible samples for each of these classes are appropriately characterized by training data. Thus, having databases with good-quality information is essential in order to perform the learning process. However, such databases might be difficult to generate on real-life applications [6]. Impedance-based approaches [10,39] are easy to implement in real-life applications, present good precision, and have a high cost-benefit ratio. However, limitations of such techniques are related with the multiple estimation problem, which can be reduced by learning-based strategies

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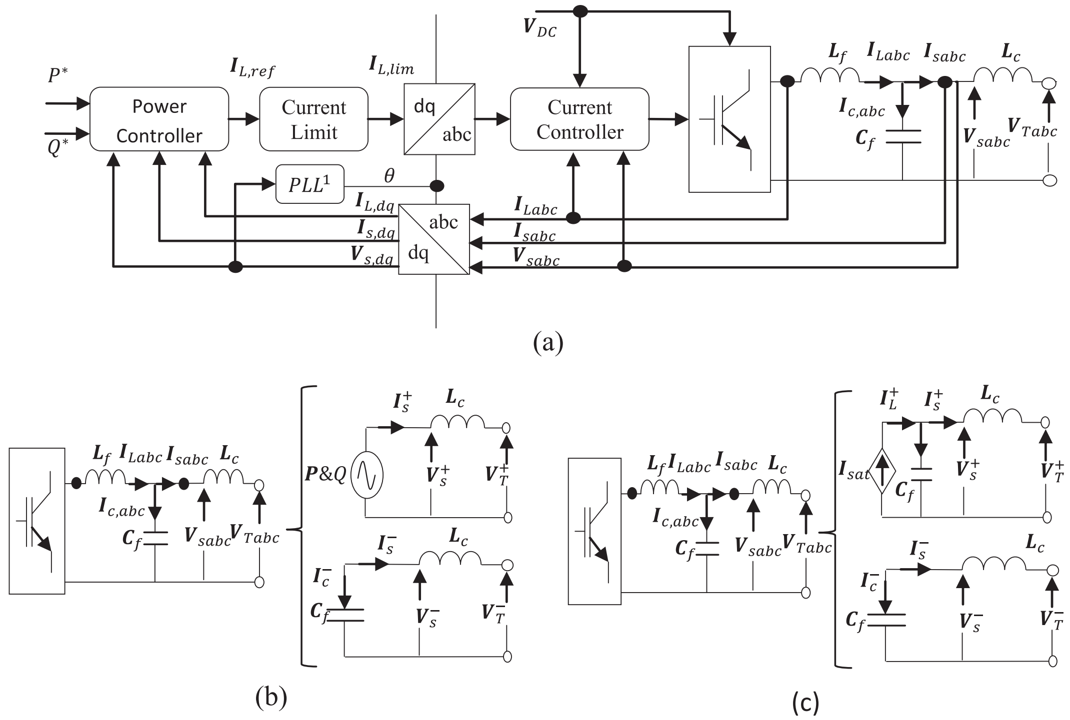

Fig. 1. Control system of an inverter connected to the grid and its equivalent sequence circuits [26]. (a) Control system of an inverter connected to the grid. (b) Equivalent sequence circuit of the inverter during normal operation. (c) Equivalent sequence circuit of the inverter during operation under limiting current. [1]PLL: Three phase synchronous reference frame phase locked loop.

[11,12].

More recently, some works that consider DGs connection on PDNs have been proposed [13–19]. These methods are formulated using a wide-area measurement approach, considering synchronized current and voltage phasors observations, provided by digital fault recorders and GPS, or other measurement solutions, such as μPMU [20]. Common aspects of these methods are the consideration of several DERs types. Effects of DG penetration level as well as the impact from other factors such as fault resistance and load variation are validated in these studies. These methods though, depend strongly on wide-area measurements, and require a significant investment on communication infrastructure and sensor equipment. Other approaches have been proposed without considering synchronized measurements [21–25]. Nevertheless, the proposed method in [22] still requires measurements in each DER, and the approaches proposed in [21,23–25] are only applicable to synchronous machine based DERs.

Currently, the great majority of PDN have few available remote measurements and incipient communication infrastructure. It is most important to have methods for PDNs FL which do not rely on the availability of measurements spread throughout the network. Still, methods based on local observations have great potential for widespread use by industry, since they do not have the inherent cost associated with wide area measurement technology. With these considerations, this paper presents a PDN FL analytical methodology which considers only locally available observations. The analytical methodology considers potential inverter-interfaced DER interconnection in problem statement. Mathematical models for inverter-interfaced DERs are used for current estimation during the fault period. A ladder iterative technique is proposed for DERs during the fault period for determine the system state. Different inverter operation modes and DERs location are considered, without the need of wide-area measurements. An impedance-based fault location formulation technique is presented and used for up-to-the fault distance estimation. This work is intended as a contribution to PDNs FL methods based on local observations. This work does not propose a complete solution of the problem, but present some important contributions. In the development of this work, some considerations are made:

- The fault resistance does not change over time;
- The inherent impedance based multiple fault location estimation problem is not addressed;
- Measurements are considered free of gross errors;
- System topology before fault inception is known;
- Pre-fault system loading condition is known;
- Only inverter-interfaced DERs are considered.

The contributions of this work towards the state of the art are:

- Local observations based fault location solution which considers multiple inverter-interfaced DERs;
- A unified nonlinear impedance-based fault system model;
- During the fault period inverter-interfaced DERs current contribution is estimated through a ladder iterative technique.

The remaining of this paper is organized as follows. Section 2 presents modelling aspects of inverter-interfaced DERs. Section 3 presents the impedance-based FL model. Section 4 presents the proposed PDNs FL analytical methodology, including the ladder iterative technique applied to estimate the system state. Section 5 presents a case study and Section 6 results analysis. Conclusions of this work are presented in Section 7.

2. Inverter-interfaced distributed energy resource modelling

Different DER technologies have been developed throughout the years [2]. These technologies can be classified as follows: Inverter-Interfaced DER and Non-Inverter-Interfaced DER.

2.1. Inverter-interfaced DER during fault conditions

Inverter-Interfaced DERs use power electronic based interface to connect the primary energy source with the PDN. This power electronic