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Protection of microgrids using voltage-based power differential and sensitivity analysis

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ABSTRACT

Microgrids are emerging as an alternative mode of operation for distribution systems integrated with Distributed Energy Resources (DERs). With appropriate management and control of the DERs, a section of a distribution system can operate isolated from the main grid thereby enhancing the reliability and security of supply to consumers. However, the integration of DERs has raised many technical challenges including protection. The traditional distribution system protection cannot provide reliable protection to the microgrid in the isolated mode due to the limited short-circuit capacities of the converter-interfaced DERs. This paper proposes the application of a new voltage-based relay type for the protection of microgrids. The relay algorithm achieves its protection function through active power differential and sensitivity calculations based on voltage measurements within a specified protection zone. In the paper, the new relay type is modelled in Digsilent PowerFactory software and installed at the nodes of a microgrid test system. The performance of the relay type is investigated under variety of faults. The relay is shown to operate correctly and effectively to detect and identify faults in both radial and meshed microgrids integrated with inverter-interfaced DER technologies.

1. Introduction

Policies being enacted by governments worldwide towards reducing greenhouse effects have influenced a shift towards clean energy sources [1]. This has seen an increasing number of distributed energy resources (DERs) based on renewable sources being integrated into the power grid. The DERs are relatively small and numerous compared to the traditional generating sources, and are dispersed according to resource availability. This is leading to fundamental changes to the topology and characteristics of the electric power system, especially at the distribution level [2,3]. With the penetration of DERs, microgrids are emerging as an alternative mode of operation for distribution systems where a section of a distribution system can operate isolated from the main grid [4]. With appropriate management and control, the DERs in the isolated system can supply the connected loads thereby creating an autonomous distribution system, or microgrid. This mode of operation allows the microgrid to provide reliable and secure energy supply to the local consumers in the event of grid faults [4]. Excess local generation can also be exported back to the grid and support quick recovery of the grid following fault. Microgrids also provide a flexible architecture for the supply of reliable and secure energy to rural communities that are remote from the national grid [5].

However, the integration of DERs has raised many technical challenges including protection. It has been shown [6] that system protection at the distribution level is compromised when a significant amount of DER units are integrated into the power system, leading to possible loss of coordination of the traditional protection that may significantly impact the reliability of the distribution system. The protection problem is exacerbated when the distribution system operates in the microgrid mode. The traditional distribution protection cannot provide reliable protection to the microgrid due to the limited short-circuit capacities of the converter-interfaced DERs in the microgrids [4]. The growing penetration of DERs, therefore, makes microgrid protection an important research topic on the future of power systems.

Notwithstanding the on-going research and published work on microgrid protection, a dedicated and effective microgrid protection system has not been achieved [4]. This has seen protection systems traditionally found on the transmission and sub-transmission systems, such as directional overcurrent relays (DOCR), distance and differential relays being proposed for use on the microgrid.

Zarei et al. [7] have proposed a comprehensive protection strategy that uses different protection relay types for the different elements of the microgrid. These include DOCR, directional negative sequence current and differential protection. The various protection elements are

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employed in a coordinated manner. However, Hooshyar et al. [4] have presented a comprehensive analysis of the performance of traditional protection systems when applied to the microgrid and found that the difference between the fault characteristics of microgrids and transmission systems impact the performance of DOCR, distance and differential relays. An additional drawback of differential relays is the considerably higher cost. The work reported in [8,9] propose new types of directional elements that are not affected by the fault behavior of the DER units and help improve performance of the DOCR.

Due to the difference in sensitivity requirements, some researchers [10,11] have proposed dual-strategy protection schemes for the microgrid, with one strategy for grid-connected mode and the other for islanded mode. In addition to sensitivity requirements, the protection strategies are also influenced by the topology of the microgrid, whether radial or looped [10,12,13].

Communication networks are expected to play a critical role in microgrid protection systems [11]. Communication facilitates the application of protection systems such as distance and differential relaying. The DOCR relays, when applied to the microgrid, may need to adapt their tripping currents due to the varying nature of the DER outputs. Researchers in [14] have proposed a communication assisted dual setting DOCR protection scheme for micro-grids with grid connected and islanded capability. Optimal settings are calculated and proper coordination is maintained with the aid of communication. The work reported in [15] overcomes the overcurrent selectivity problems by using selectivity mechanisms that are supported by agent-based distributed communication. In [9], an adaptive directional overcurrent relaying technique based on the positive-sequence (PSQ) and negative-sequence (NSQ) superimposed currents is proposed.

The methods that do not require physical communications are reported in the literature [12,16]. The authors in [12] proposed a method for microgrids with looped configuration that employs simple overcurrent relays with inverse time-current characteristics. The relays have the same pick-up and time multiplier settings. Following a fault in the microgrid the inverter control at each DER acts to contribute current to the fault that is proportional to the microgrid impedance measured at that location. Selectivity is achieved by the DER closest to the fault contributing a relatively larger current. In [16] inverter control is manipulated to limit the fault current to acceptable limits but also injects a percentage of fifth harmonic to the fault current. The Fast Fourier Transform (FFT) is used to extract the harmonic currents and facilitate identification of the fault. Droop control based on the current-fault resistance characteristic is also employed to make the inverter closer to the fault inject larger current to the fault and achieve selectivity by inverse-time current principle.

The authors in [17,18] have presented an argument for the decoupling of protection strategies from inverter control and shift towards voltage-based protection strategies. Using voltage-based protection, the fault current contribution from the DERs may not be required to achieve effective protection. Various voltage-based protection methods are reported in the literature. Voltage Total Harmonic Distortion (THD) has been identified as a feature that can be used for fault detection. Protection schemes presented in [7,19] use the THD content of the voltage for the identification and location of fault in networks with inverter interfaced DERs. The THD arises due to the inverter controller limiting the current to 1.2–2 times the nominal current. The limiter saturates under fault conditions resulting in the generation of distorted voltages and currents. Researchers in [20,21] use Park's (abc-dq) transformations on the measured system voltages to detect faults through disturbances they cause to the d-q values.

This paper proposes an algorithm that achieves its protection function through active power differential and sensitivity calculations based on synchronized voltage phasor measurements within a specified protection zone. Some sensitivity-based fault detection indices (FD-Indices) were identified that are generated when a fault occurs within a protection zone. The proposed relay type has the potential to overcome the challenges of protecting the microgrid in various ways:

a. The performance of the relay algorithm is independent of the DER technology, whether inverter interfaced or directly coupled to the grid,
b. The algorithm implements a form of distributed protection, meaning that information exchange is limited between relays or intelligent electronic devices (IEDs) located at neighbouring nodes, not network wide,
c. The algorithm is independent of the topology of the network,
d. The possible configuration of the microgrid does not need to be predefined before implementation of the protection. The algorithm is reconfigurable depending on the number of feeders terminating at a node, and
e. The algorithm is instantaneous in operation which allows fast voltage recovery to facilitate fault ride through capability of the DERs and improved microgrid stability.

The rest of this paper is organized as follows: Application of the new relay type is introduced in Section 2. The microgrid adopted for the study is described in Section 3, after which the algorithm of the new relay type and its application to the microgrid is discussed in Section 4. The modelling of the new relay type in Digsilent *Powerfactory* is described in Section 5. The performance of the relay when applied to the microgrid is demonstrated and discussed in Section 6. Conclusions are drawn in Section 7.

2. Phasor measurement technology

The use of Wide Area Measurement Systems (WAMS) is expanding in the electric power industry for improved monitoring, supervision, control and protection of power networks [22,23]. These services are facilitated by the deployment of Phasor Measurement Units (PMUs) that measure the magnitude, phase angle and frequency of the voltage and current signals. Real-time visualization of the power network can then be obtained for fast detection of disturbances.

Reliable communication systems need to be concurrently deployed in order for the various components of the WAMS to interact. Communication technologies and networks have been developed that provide bandwidth sufficient to offer the services required for the monitoring, control, operation and protection of power networks including microgrids [24]. Various physical communication links, including fibre-optic communication, have been proposed in the literature and tested for suitability to microgrid application [25,26]. Fibre-optic communication, in particular, is reliable and provides high-speed protection. The protection system proposed in this paper assumes the availability of high-speed physical communication links along the feeders to minimize communication latency and improve performance of the protection algorithm.

2.1. Proposed protection algorithm application

The protection algorithm proposed in this paper uses PMU data transferred over a suitable communication channel. Basically, the proposed protection algorithm detects fault through active power differential and sensitivity calculations over a defined protection zone. The protection zone, referred to as the Busbar Area Protection (BAP) zone, comprises a busbar and all feeders terminating at that node [3]. The algorithm requires, as inputs, the synchronized measurements of the fundamental voltage magnitude and phase at the 'home' node k (where the relay is located) and at the nodes at the remote ends of the feeders, as illustrated in Fig. 1 for a BAP zone comprising busbar 2 and its three feeders. The algorithm can detect a fault anywhere within the BAP zone; that is, on Line12, Line23, Line24, or on the busbar itself. However, peer-to-peer communication is required, as explained in Section 4.5, for identification of the actual faulted feeder within this zone.