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J. Electrical Systems 10-1 (2014): 1-10

Regular paper

Review and Analysis of Existing Protection Strategies for Micro-grids

JES
Journal of Electrical Systems

Micro-grids are becoming increasingly attractive to consumers and in the near future, a great number of them will be installed in consumer's sites. One of the major difficulties associated with the implementation of micro-grids is to explore a suitable protection strategy which is able to protect them in both modes of operation, that is, the grid connected mode and the autonomous mode. To remedy the difficulty, various strategies have been recently proposed in the literatures. The objective of this paper is to provide a comprehensive review of the existing protection strategies deployed for addressing micro-grid protection issues in both grid-connected and islanded mode of operation. In addition to description of available protection strategies to date and classifying them into certain groups, a comparative analysis is accomplished in which the benefits and drawbacks of each strategy are evaluated. Finally, after the evaluation of various protection strategies, some conclusions and recommendations are put forward for the micro-grid protection in the future.

Keywords: Micro-grid protection; Grid-connected mode of operation; Autonomous mode of operation; Distributed generation units.

1. Introduction

The electrical networks are experiencing radical changes in parallel with the growing concerns on efficiency and stability. Distributed Generation (DG) is expected to replace the bulk of the centralized power generation since it permits generation close to consumption points and, thus, reduces transmission losses [1-2]. This is important, given that the current transmission lines are operating close to their thermal limits and construction of new lines is a great challenge. Furthermore, these DG units may be based on Renewable Energy (RE) resources such as wind turbines and solar systems. In such cases, the utilization of these cleaner energy resources reduces greenhouse gas emissions that alleviate some of the environmental concerns associated with power generation.

Existing distribution systems were not designed for significant penetration of DG as they were traditionally designed with the assumption of a passive network. When RE based DG systems are connected to these networks, the characteristics of the system change and key technical challenges arise which were previously unknown [3]. Moreover, DG systems also make contributions to the fault currents around the network. Hence, in case of a fault, the fault current in a network becomes a combination of the fault current contributions from all DGs in the network as well as the grid contribution. The fault currents no longer flow in one direction and relays are required to have bidirectional operation [4]. Under normal operation, at a given instant, several DGs may connect to/disconnect from the grid and their

Manuscript received April 6, 2013; revised November 05, 2013; accepted December 13, 2013.
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respective operating currents and fault currents need to be taken into account in order to avoid unnecessary trippings such as nuisance tripping.

The micro-grid concept has been introduced, in an effort to tackle these problems. A micro-grid is a collection of loads and micro-generators along with some local storage and behaves just like a model-citizen from grid side thanks to intelligent control [5]. Although a micro-grid is itself composed of many generators and loads, it appears as a net load or a net generator to the broader grid with well-behaved characteristics [6]. The configuration of a typical micro-grid is depicted in Figure 1.

Micro-grids have the ability of operating in both grid-connected and islanded mode of operation [7-10]. The philosophy of the micro-grid's operation is that under normal circumstances the micro-grid operates in the grid-connected mode but when the utility damages or has a power failure, it immediately disconnects from the utility by the Static Switch (SS) at the Point of Common Coupling (PCC) and then operates in the islanded mode [11].

Even though micro-grids have provided numerous benefits for the costumers, there are some technical challenges which require to be met for the engineers. Micro-grid protection and its entity is one of them. The protection of the traditional distribution networks is designed in accordance with the large short- circuit currents and the unidirectional power flow, whereas such protection strategy cannot be regarded in order to protect active distribution networks such as micro-grids. It is owing to the fact that when a short-circuit takes place in the micro-grid with widespread proliferation of inverter- based DG sources, operating in islanded mode of operation, the DGs are not able to contribute sufficient currents to the total short-circuit current. It is because of the fact that inverters have a low thermal overload capability, restricting their maximum output current to about 2-3 times the rated current [8-9]. Hence, in order to protect micro-grids in both grid-connected and islanded mode of operation, innovative protection schemes should be utilized [12].

The goal of this paper is to present a brief analysis of the various protection schemes based on the published papers in attempting to provide an appropriate protection strategy which is able to protect micro-grids in both grid-connected and islanded mode of operation.

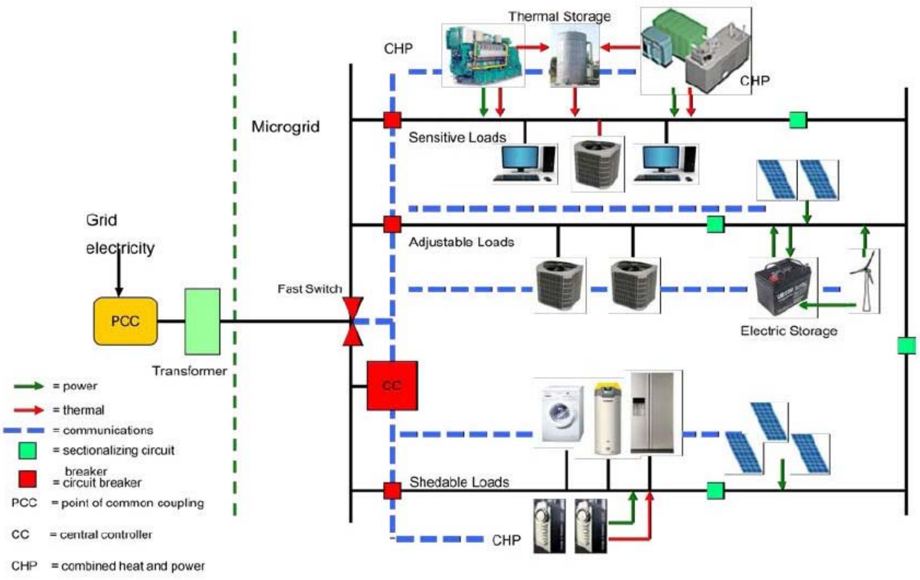

Figure 1. The configuration of a typical micro-grid

2. Existing protection strategies

The protection of Micro-grid should respond to both utility grid and micro-grid fault incidents. If a fault takes place on the utility grid, the desired response is to isolate the micro-grid from the rest of network. This leads to islanding operation of micro-grid. If a fault occurs within the micro-grid, the protection system should isolate the smallest possible faulted area of micro-grid to clear the fault. In recent years, various strategies have been put forward to present a reliable protection scheme for micro-grids that are summarized in Figure 2. The strategies will be illustrated precisely in the following subsections.

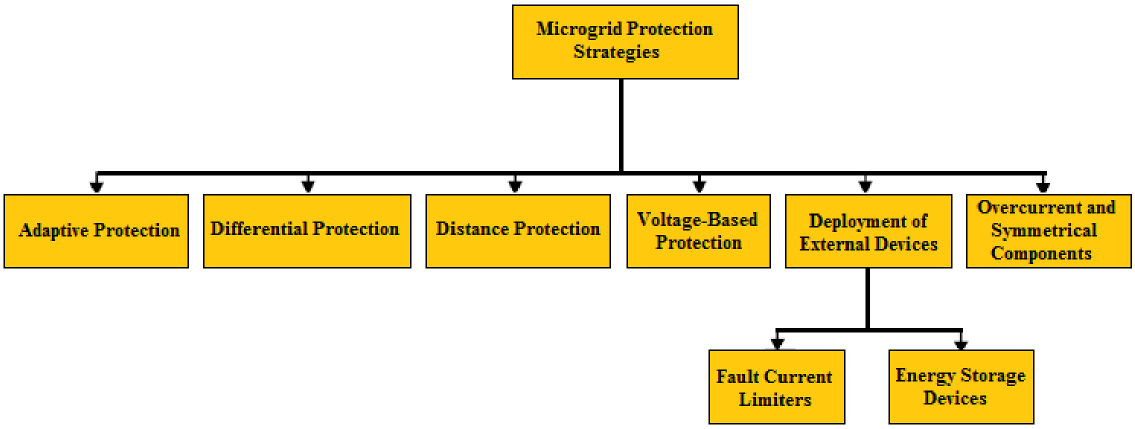

Figure 2. Different micro-grid protection strategies

2.1. Adaptive protection: proposed strategies and their challenges

Adaptive protection scheme solves the problem both in grid connected as well as islanded mode. In adaptive protection system there is automatic readjustment of relay settings when micro-grid changes from grid connected mode to islanded mode and from islanded mode to grid connected mode. Adaptive protection is an online system that modifies preferred protective response to change in system conditions or requirements in timely manner by means of external generated signals or control actions. Technical requirements and suggestions for practical implementation of an adaptive protection system make use of numerical directional over current relays. Numerical directional over current relays should have possibility of using tripping characteristics (several settings groups) that can be parameterized locally or locally. For effective protection make use of communication system and standard communication protocol such that individual relays can communicate and exchange information with a central computer or between different individual relays.

In reference [13], Tumilty, Brucoli, Burt and Green suggested an adaptive protection strategy without the need of communication system. In the strategy, they employed a voltage based fault detection method to discriminate the voltage drop in short-circuit incidents and over-load events. Then, Oudalov and Fidigatti in [14] presented another protection scheme that was aimed at adjusting the setting of the relays according to micro-grid's current state based on offline analysis and online operation. One year later, Han, Hu, and Zhang in [15] deployed the voltage and current fault components at the installation of protection to determine the system impedance. Afterwards, current instantaneous protection could adjust the settings automatically by comparing with the utility grid and micro-grid impedances.

In reference [16], Dang, He, Bi, and Feng made use of Energy Storage (ES) and isolation transformers to recognize micro-grid's mode of operation. Then, the fault could be identified by means of comparing between the zero sequence current and a threshold value. Afterwards, Ustun, Ozansoy and Zayegh in [1] proposed additional adaptive protection scheme that made use of extensive communication for monitoring and updating settings of relays in accordance with different micro-grid's operation mode. In the proposed scheme, micro-grid was equipped with a Central Protection Unit (CPU) which communicated with the relays to update their operating currents and with DGs to store their status as ON/OFF.

Finally, M. Khederzadeh in [17] put forward a methodology to coordinate the over-current relays within a certain micro-grid. In the methodology, the settings of the relays were adapted to the status of micro-grid according to their different operating modes.

The main problems associated with the implementation of the above-mentioned adaptive protection strategies are as follows:

- The need for updating or upgrading the protection devices which are currently utilized in the power networks.
- The necessity to know all possible configurations of micro-grid before implementing these schemes.
- Establishment of a communication infrastructure can be costly.
- Short-circuit calculations will be complicated for a micro-grid with different operating modes.

2.2. Differential protection: proposed strategies and their challenges

Differential protection, as its name implies, compares the currents entering and leaving the protected zone and operates when the differential between these currents exceeds a pre-determined magnitude. Figure 3 indicates the structure of the differential protection.

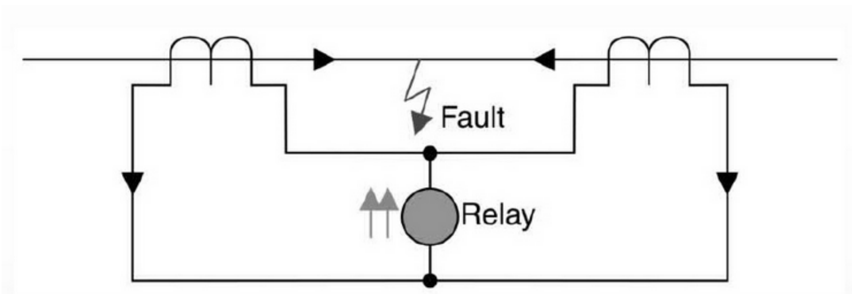

Figure 3. The structure of the differential protection

The following proposals mainly used differential protection to provide an adequate protection system in micro-grids:

Nikkhajoei and Lasseter in [18] presented a combined technique to protect micro-grids by differential protection and symmetrical components calculations. They detected Single

Line-to-Ground (SLG) and Line-to-Line (LL) Faults within the micro-grid using zero sequence and negative sequence currents, respectively. In Reference [19], Zeineldin and his research group discussed the future of micro-grids and regarded two major challenges including voltage/frequency control and protection. In the developed strategy, they made use of differential relays in both ends of each line. These relays designed to operate in 50 ms were able to protect micro-grid in both grid-connected and autonomous operation modes. Afterwards, Conti, Raffa and Vagliasindi in [20] described three protection strategies to detect phase-to-ground faults in isolated neutral micro-grids. Additionally, three more protection schemes were presented for three-phase faults in micro-grids with synchronous based generators.

One year later, Sortomme, Venkata and Joydeep in [21] offered a novel protection scheme based on some of the principles of synchronized phasor measurements and microprocessor relays to recognize all kinds of faults including High Impedance Faults (HIFs). By installing the relays on the end of each line of micro-grid, a robust protection could be provided. In reference [22], Parsai, Du, Paquette, Back, Harley and Divan introduced a Power Line Carrier (PLC) communication-based methodology with multiple levels of protection to provide the most effective form of network protection for meshed micro-grids. Lastly, a novel methodology based on differential protection was put forward by Dewadasa, Ghosh and Ledwich [23] in 2011. This Methodology in which all the protection challenges such as bidirectional power flow and reduction of fault current level in islanded operation mode were taken into account, was able to protect micro-grids in both grid-connected and islanded modes of operation. One of the salient features of this method was that the authors not only concentrated on feeder protection but they also proposed some solutions to protect buses and DG sources within the micro-grid.

One of the most significant benefits of implementing the differential protection approaches is that they are not sensitive to bidirectional power flow and reduction of fault current level in islanded micro-grids. However, some challenges associated with them can be summarized as follows:

- As the communication system may fail, providing a secondary protection scheme is necessary.
- Establishing a communication infrastructure is relatively expensive.
- Unbalanced systems or loads may result in some difficulties in the above-mentioned protection schemes.
- Transients during connection and disconnection of DGs may bring on some problems.

2.3. Distance protection: proposed strategies and their challenges

Since the impedance of a line is proportional to its length, for distance measurement it is appropriate to use a relay capable of measuring the impedance of a line up to a predetermined point (the reach point). Such a relay is described as a distance relay and is designed to operate only for faults occurring between the relay location and the selected reach point.

The main stratetegy in this group was developed by Manjula Dewadasa [24-25]. It was based on an admittance relay with inverse time tripping characteristics. The relay had the ability to distinguish and isolate the faults in both grid-connected and autonomous micro-grids.

Some challenges associated with the application of these types of relays are as follows:

- Harmonics and transient behavior of current may result in some problems in the accuracy of extracting fundamentals.
- Fault resistance may make some errors in the measured admittance.
- The measurement of the admittance for short lines in distribution networks is challenging.

2.4. Voltage-based protection: proposed strategies and their challenges

Voltage-based protection techniques substantially make use of voltage measurements to protect micro-grids against different kinds of faults.

The main approach in this field was the one proposed by Al-Nasseri and Redfern [26] in 2006. The scheme, in which output voltages of DG sources were monitored and then transformed into dc quantities using the d-q reference frame, had the ability to protect micro-grids against in-zone and out-of-zone faults. Moreover, a communication link was deployed in the scheme to discriminate in-zone and out-of-zone faults. Since the distances within a micro-grid are usually short, the communications could make use of pilot wires, optical fibers or the Ethernet.

Subsequently, Loix, Wijnhoven and Deconinck [11] proposed a novel protection strategy in 2009. This strategy which was based on the effect of different fault types on Park components of the voltage was capable of protecting micro-grids against three phase, two phase and one phase-to-earth faults. The protection methodology did not rely on communication system for its operation, but it could be optimized through communication links between different detection modules. The salient feature of this scheme compared to the one in [26] was that the proposed strategy was not only designed for a certain micro-grid and could be used to protect different micro-grids with various configurations.

Finally, Wang, Li and Yu [27] introduced additional protection strategy based on busbar voltage analysis and the fault direction to protect micro-grids in both grid-connected and autonomous operation modes. Furthermore, the authors designed the relay protection hardware and software using Industrial Personal Computers (IPCs).

The main challenges in regard to possible implementation of voltage-based protection strategies are:

- Any voltage drop within the micro-grid may lead to mis-operation of protection devices.
- HIFs cannot be identified using above-mentioned methodologies.
- Most of these techniques are designed and tested for specific micro-grids. In fact, they are strongly dependent on the micro-grid configuration and on the definition of protection zone. So, they may not be convenient for micro-grids with different structures.
- Less sensitivity in the grid-connected mode of operation.

2.5. Protection strategies with the deployment of external devices and their challenges

As mentioned earlier in the introduction, the micro-grid protection challenge is pertaining to the dramatic difference between the fault current level in the grid-connected mode and autonomous mode [28]. Thus, the implementation of an adequate protection scheme which is able to operate suitably in both grid-connected and autonomous modes can be an effective solution.

These protection schemes are substantially based on modifying the short-circuit level when the operation mode of micro-grid changes from grid-connected to autonomous, or vice versa. These devices can be categorized into two groups as follows:

2.5. 1. Fault Current Limiters (FCLs)

FCLs which can be used to reduce the aggregated contribution of many distributed generation units are able to change the short circuit current level enough to exceed the design limit of different equipment components.

The main protection approach in this field was the one developed by Ustan, Ozansoy and Zayegh [1] in 2011. The proposed strategy made use of a Central Protection Unit (CPU) along with a communication system to monitor the status of micro-grid and update trip value of relays based on the changes in the system.

The major difficulty of applying FCL-based protection techniques is that the determination of the FCL impedance value is difficult for the micro-grids with widespread proliferation of DGs, because of the mutual influence of DGs. In addition, the transient response of the FCL is one concern that should be considered.

2.5. 2. Energy storage devices

Since the short circuit current level in the micro-grid is restricted to roughly 2-3 times the rated current due to the existence of inverter-based DGs, energy storage devices such as flywheels and batteries can be used to provide additional short-circuit level to the network [1, 29].

The challenges with respect to the use of the strategies based on additional current source are as follows:

- Storage devices require significant investments.
- These strategies depend on the islanding detection's technology and the convenient operation of storage devices.

2.6. Protection strategies based on overcurrent and symmetrical components and their challenges

These protection strategies which are mainly based on the analysis of current symmetrical components, attempt to improve the performance of traditional over-current protection and provide a robust protection system for micro-grids.

The main proposal in this field was developed by Nikkhajoei and Lasseter [18] in 2006. They proposed a new protection technique based on the measurements of the zero sequence current and negative sequence current to distinguish single line-to-ground and line-to-line faults, respectively. Two years later, Best, Morrow, and Crossley [30] developed a three-stage communication assisted selectivity scheme. In the method, stage-one recognized the fault event in accordance with the local measurements; stage-two deployed inter-breaker communications; and stage-three adapted the settings of the relays via a supervisory controller. Subsequently, Zamani, Sidhu and Yazdani [31] proposed a new protection scheme with the deployment of micro-processor based relays to protect low-voltage micro-grids against different kinds of faults in both grid-connected and autonomous modes of operation. The salient characteristic of the proposed scheme was that all relays within the micro-grid were coordinated according to a definite-time grading method; So It had no need of communication links between the relays.

The main problem of the majority of above-mentioned protection strategies is pertaining to the necessity of communication systems. In such schemes, the protection coordination may be endangered in case of communication system failure.

3. Micro-grid protection: analysis of existing strategies and its future

Realization of future micro-grids requires that all technical issues are solved. Micro-grid protection and its entity is one of them. Based on evaluation of various protection strategies in the previous section, some conclusions and recommendations for the micro-grid protection in the future are as follows:

- In spite of many efforts which have been performed in the field of micro-grid protection, there are still a few number of references. Moreover, the information given about the micro-grid structure and the proposed strategies is short or incomplete. In other words, most of them to be more of an idea than a practical proposal.
- The majority of the presented strategies in the area of micro-grid protection are strongly dependent on the network architecture. In fact, the strategies have not the ability to protect different micro-grids with different configurations.
- A reliable protection strategy must be able to distinguish high impedance faults, which may have current magnitudes similar to those of normal loads and, therefore, not cause any noticeable voltage drop. However, only a few number of the references have considered such kind of fault.
- Most of the proposed strategies are designed only for the micro-grids with radial feeders and are not capable of protecting micro-grids containing looped feeders.
- Regardless of the protection strategy, it sounds likely that some kind of communication system is going to be necessary, either centrally operated or distributed.
- In order to possess an optimal protection system for micro-grids, a combined action of different protection strategies will be necessary.

4. Conclusion

Micro-grids have been designed to meet the reliability and power quality needs of customers. However, the emergence of micro-grids has been accompanied with significant challenges. Protection of micro-grids and its entity is one of them. One of the major challenges relevant to micro-grid protection is to find a convenient protection strategy that is effective in the grid-connected as well as islanded mode of operation. In recent decades, numerous approaches have been put forward to present an adequate protection scheme for micro-grids. A robust protection scheme should be able to protect the micro-grid against different types of faults and assure its safe and secure operation in both grid-connected and autonomous mode. The goal of the current study was to present a comprehensive review of the existing proposals for tackling the micro-grid protection issues. Moreover, an attempt was made to categorize these proposals in specific groups and finally some conclusions and practical recommendations are derived from the analyzed references.

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