International Conference on Renewable Energies and Power Quality (ICREPQ'13)
Bilbao (Spain), 20th to 22th March, 2013
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.11, March 2013

Microgrid Protection: Technical challenges and existing techniques

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Abstract. The design of protection systems associated with medium and low voltage networks has traditionally been based on the assumption of unidirectional power flows, making the use of time coordinated overcurrent relays an efficient and reliable way of protecting against network faults. The changes that these systems have undergone over the recent decades regarding distributed generation, along with the fact that many of these sources can be connected to form independent microgrids, have challenged this perspective.

A number of alternative solutions have recently appeared in technical literature. Therefore, this paper aims to provide a comprehensive overview of the existing proposals for protection design in microgrids. Apart from describing the most relevant options presented to date and classifying them in specific groups, a comparative analysis is performed in which the most important benefits and drawbacks of each approach are presented. Finally, some conclusions and practical recommendations are derived from the analyzed references.

Key words

Microgrid protection, inverter-interfaced microgrids, islanded microgrid.

1. Introduction

During the last decade, the concept of microgrid has emerged as a remarkable way of integrating sustainable energy sources in the electric network. Its main benefits lie in that it supplies power locally, reduces grid investment due to lower network capacity requirements, reduces operation costs and losses, shaves the peak load and increases reliability [1]. However, along with these benefits, microgrids have also raised a number of challenges, amongst them the issue of protection [2].

This way, there are two main issues the microgrid has to address with regard to its protection [3]:

- Firstly, the determination of the time when it should be islanded from the main grid, e.g. in response to abnormal conditions that the utility may experience;
- And secondly, the provision of properly coordinated and reliable protection system so that it can reliably trip in the event of a fault within it.

The aim of this paper is to provide a brief analysis with respect to the work published in technical literature to date which deals with issues of microgrid protection. An attempt has been made to group these proposals in terms of their specific protection approach. Due to space restriction and format requirements of this publication, the scope of the paper has been limited to the cases where the following two conditions apply:

- Protection proposals for microgrids with inverter-interfaced microsources, including those dealing with protection coordination issues associated with the change of operation mode, from grid-connected to islanded;
- Protection methods that specifically consider the concept of microgrid.

2. Technical challenges in microgrid protection

The microgrid concept has to face a number of challenges in several fields, not only from the protection point of view, but also from the control and dispatch perspective [4]. Nevertheless, due to their specific characteristics and operation, microgrid protection systems have to deal with new technical challenges [4, 5]:

- Generation systems in both medium voltage (MV) and low voltage (LV) systems, making power flow bidirectional;
- Two operational modes: grid connected and islanded/stand-alone;
- Topological changes in LV network due to connection/disconnection of generators, storage systems and loads;
- Intermittence in the generation of several microsources connected in the microgrid;
- Increasing penetration of rotating machines, which may cause fault currents that exceed equipment ratings.
- Insufficient level of short-circuit current in the islanding operation mode, due to power-electronics interfaced distributed generation (DG);

– Reduction in the permissible tripping times when faults occur in MV and LV systems, in order to maintain the stability of the microgrid;
– Nuisance tripping of protection due to faults on adjacent feeders.

As mentioned above, the fact is that many microsources are generally connected to the microgrid by means of a power electronic inverter, either because their output is not compatible with the grid voltage (photovoltaic panels, microturbines, etc.) or because of the flexibility provided by power electronics in the energy extraction management (wind turbines, etc.) [6]. Due to the low thermal inertia of semiconductor switches, inverters are actively current limited and, because of their small fault current contribution, they lead unavoidably to different problems that have to be considered by the protection system [6, 7]:

– Characteristics of the inverters under fault conditions may not be consistent with the existing protection devices;
– Throughout the whole microgrid, there may be different inverters with different characteristics;
– Even in the case of individual inverter, its basic characteristics may differ depending on its design or application;
– There may be difficulties in characterizing inverter behavior for short-circuit studies, since it depends on the control strategy;
– Significantly reduced fault current level when changed from grid-connected to islanded mode of operation.

The last point particularly is one of the key issues which have been under research for the past years. The characteristics of most protective devices used in microgrids are usually similar to those used in distribution networks [7] and the protection of traditional distribution networks are based on large fault currents. However, under islanded-operation, the utility grid cannot contribute to the fault and, therefore, its magnitude is limited to what the microsources can provide. Consequently, traditional overcurrent protection schemes may be no longer applicable due to the current limitations of most inverters.

3. Existing techniques for microgrid protection

One of the main benefits of DG is the possibility of improving the reliability and continuity of energy supply by making possible that a part of the network operates autonomously, in an islanded or stand-alone mode, during a power outage of the main grid [8, 9]. For this purpose, an increasing number of countries (e.g. Germany) are updating their regulations in order to ensure that DG sources supply adequate short circuit current. Also, in order to improve reliability and stability of the system, fault-ride-through capability requirements for DG connected in high voltage (HV) and MV networks have been introduced. For the LV level similar guidelines are being considered nowadays.

The main scope of this section is to provide an overview of different solutions proposed to date to address the most common issues related to microgrid protection, especially overcurrent protection, either in grid-connected or in islanded mode of operation.

A. Adaptive protection systems

These proposals are mainly based on the use of adaptive relays, which can have their settings, characteristics or logic functions changed on-line, in a timely manner, by means of externally generated signals or control action [10].

R.M. Tumilty et al. [11] propose to use the difference in voltage drop response that would appear in shorcircuits and overloads, with regard to its magnitude, so as to clearly differentiate these two events and, therefore, adjust the time-current characteristic of the protection accordingly, without the need of communication. Some years later, A. Oudalov and A. Fidigatti [12] present a system that is aimed at maintaining settings of each relay updated with regard to the current state of the microgrid. This is achieved in two main steps: off-line analysis and on-line operation.

Similarly, N. Schaefer et al. [4, 9] describe a scheme and the algorithm of an adaptive protection relay, which comprises a real-time block and a non-real time block, both implemented in software and hardware. At the same time, Y. Han et al. [13] propose that, comparing the system's impedance and the microgrid's impedance, overcurrent instantaneous protections can be automatically adjusted to the new situation.

Then, K. Dang et al. [14] propose to use a way of comparison between the zero-sequence current and a threshold. Also, T.S. Ustun et al. [15] present an adaptive protection system based on an extensive communication system that monitors the microgrid by means of a Central Protection Unit (CPU). Finally, M. Khederzadeh [16] provides an algorithm to coordinate different relays in a specific microgrid.

As a result of the different proposals, it can be concluded that the main problems with regard to a possible implementation of an adaptive protection system may be:

– The need for prior knowledge of all possible microgrid configurations;
– The requirement of running extensive power flows or short circuit calculations when a topology change is detected;
– The need for communication infrastructure may be high;
– The necessity to update or upgrade many protection devices (fuses, etc.) that are currently used in the existing power system.

B. Voltage based methodologies

The following proposals mainly use voltage measurements in order to provide an adequate protection system in microgrids.

The main work in this field was conducted by a research group at the University of Bath, mainly formed by H. Al-Nasseri and M.A. Redfern. After different stages of development, the authors propose to monitor the microsource output voltages, converting the measured signals from the abc operating frame to DC quantities in the dq frame in two steps. In order to differentiate between in-zone and out-of-zone faults, a communication link is used between the relays. Besides, this technique is completed by developing a decision-making procedure for the comparison of the average voltage values in each relay [17]. Simultaneously, the authors also propose to utilize the total harmonic distortion (THD) to improve the protection system in microgrids with inverter-interfaced microsources, for ground faults [18]. After identifying the type of fault by monitoring the variation of the fundamental frequency (50 Hz), the voltage THD of different feeder relays is analyzed in order to determine the faulted zone.

In order to avoid the difficulty of the previous methods associated with detecting the oscillation waveform of the voltage variation, instead of using the voltage magnitude, C. Hou and X. Hu [19] propose to use only its positive sequence. Besides, they conclude that, due to the different processes that have to be implemented, the total detection time might eventually be affected. In the same year, T. Loix et al. [20] claim that a distinction among the three fault types can be made only considering the direct and inverse voltage components, without using the homopolar information. Additionally, the authors propose a microgrid protection strategy based on voltage and current measurements of the fault.

Finally, X-p. Wang et al. [21] propose a very similar approach by determining the fault occurrence and the fault zone, based on a busbar voltage measurement and its subsequent transformation from abc coordinates to dq coordinates. The authors also provide hardware and software implementation of the method.

All in all, the main problems that may be faced when dealing with voltage-based methodologies are:

- Minor differences in voltage drop among the relays located at both ends of short lines lead to protection operation failures, due to reduction of the voltage gradient;
- Relatively high calculation complexity when it comes to Park's transformation application;
- Problems in detection of high impedance faults;
- Problems with practical application of some of these methodologies, as well as with communication infrastructure, when high number of DG units are present;
- Methods may be strongly dependent on the network architecture and on the definition of "protection zone" for the relay associated with each generator.

C. *Differential protection*

The approaches outlined below base their performance on some kind of comparison between measurements in different parts of the microgrid.

H. Nikkhajoei and R.H. Lasseter [22] propose a combined methodology for microgrid protection based on differential protection and analysis of symmetrical components. Based on a network zoning approach, the relay dividing each zone uses differential protection to detect single line-to-ground (SLG) faults that occur in its down-stream zone.

The same year, H.H. Zeineldin et al. [23] address two main challenges of future microgrids: voltage/frequency control and protection. Each line is equipped with two current transformers (at opposite ends of the line), and once a previously specified threshold is exceeded, the differential relays are designed to operate in 50 ms. The protection is additionally coordinated with the islanding detection algorithm.

Then, S. Conti et al. [24] present a protection scheme for multi-phase faults in micro-grids with inverter-interfaced generators, considering both amplitude and direction of the measured currents.

E. Sortomme et al. [25] propose a protection scheme based on relays with a communication overlay, considering both radial and meshed microgrid architectures, and also addressing the problem of high impedance faults. Inspired by the previous methodology, A. Prasai et al. [26] provide a PLC communication-based methodology aimed at meshed microgrids, whose protection is substantially different to radial-configured ones. Apart from analyzing the differential protection in all the elements involved in the microgrid, the authors propose three different levels of protection: primary, secondary and tertiary/backup protection.

M. Dewadasa et al. [27] propose a new differential approach to improve protection in meshed inverter-interfaced microgrids, as well as those with radial configuration. Not only do they focus on feeder protection, but they also offer solutions to protect other subgroups (buses, DG sources, etc.).

Finally, a new approach to a differential protection for microgrids is presented by S.R. Samantaray et al. [28]. The authors propose a differential energy based protection scheme, which is argued to be less sensitive to synchronization errors than the conventional approach based on differential current.

These methodologies also have some implementation problems or difficulties which can be summarized as follows:

- Need for communication infrastructure that may fail at some point, leaving the microgrid unprotected. For this reason, some authors provide different levels of backup protection;
- Need for synchronized measurements;
- Problems due to transients when connecting and disconnecting DG sources;
- Problems due to unbalanced systems or loads;
- Relatively high cost.

D. *Distance protection*

The techniques in this field use admittance or impedance measurements in order to detect the fault and trip adequately.

The main methodology in this group is the one developed by M. Dewadasa et al. [29, 30]. The authors propose a new admittance relay with inverse time tripping characteristics (Inverse Time Admittance, ITA), capable of detecting faults in both grid-connected and islanded operation modes. Apart from adding inverse time characteristics to each zone of protection, it also has the ability to isolate the faults occurring at either side of the protected circuit, since it can also operate for reverse faults. However, the reach settings should be different for forward and reverse faults.

Nevertheless, there are a number of shortcomings when it comes to an accurate performance of the ITA relay, which are listed below:

– Limited fault resistance that can be reliably detected;
– Errors in the measured admittance because of the fault resistance;
– Increasing tripping time because of the down-stream source infeed;
– Loss of accuracy due to problems in fundamental extraction, caused by harmonics, current transients and decaying DC magnitude and time constant.

E. *Overcurrent protection and symmetrical components*

These proposals try to enhance the performance of traditional overcurrent protections, sometimes resorting to measurement and calculations with symmetrical components.

H. Nikkhajoei and R.H. Lasseter [22] present a possible solution for fault detection in islanded microgrids based on the measurements of current symmetrical components. To be precise, the authors propose to use zero-sequence current detection in the event of an up-stream SLG fault (coordinated with unbalanced loads) and negative sequence current for line-to-line (LL) faults.

Two years later, B. Li et al. [31] briefly describe a novel pilot instantaneous overcurrent protection scheme, based on two routines, which can perform instantaneous protection for local line and remote bus-bar, regardless of the DGs location. In the same year, R.J. Best et al. [5] propose a communication assisted protection selectivity strategy with three structural levels, to be applied with voltage-restrained directional overcurrent protection.

Continuing their previous work for coordination of protection devices in conventional distribution networks, Zamani et al. [32] propose a strategy for protection in LV microgrids based on microprocessor-based overcurrent relays and directional elements. Adequate for both modes of operation (grid-connected and islanded), it does not require communications and it is independent of the fault current magnitude.

One year later, M.R. Miveh et al. [33] also consider the use of symmetrical components for all types of faults (asymmetrical and symmetrical) in microgrids, along with a communication channel with a narrow bandwidth (only to exchange the status information, not electrical measurements).

It needs to be noted that the main problem in these kinds of protection systems is usually related to the necessity of an extensive deployment of communication system. In such cases, in the event of communication system failure, the whole overcurrent protection and coordination may be jeopardized.

F. *Use of external devices for protection improvement*

In situations when fault current levels are drastically different between the grid-connected and the islanded operation (typically with inverter-interfaced DG), the design of an adequate protection system, which performs properly in both situations, can be a real challenge. In this regard, there is a possibility of applying a different approach which actively modifies the fault current level when the microgrid changes from grid-connected to islanded operation and vice versa, by means of certain externally installed devices. These devices can either increase or decrease the fault level. The main options are as follows:

– To reduce the aggregated contribution of many DG sources, which can alter the fault current level enough to exceed the design limit of various equipment components, as well as to guarantee an adequate coordination despite the feeding effect of DG to fault current, fault current limiters (FCL) can be used [4]. This effect is particularly evident with synchronous machine based DG.
– To equalize the fault current level in both grid-connected and islanded operation, due to the reduced fault contribution by inverter-interfaced DG sources. This can be achieved in two different ways:
  1) by incorporating energy storage devices (flywheels, batteries, etc.) into the microgrid in order to increase the fault current to a desired level, allowing overcurrent protection to operate in a traditional way [34, 35].
  2) by installing certain devices between the main grid and the microgrid, to alleviate the contribution of fault current from the utility grid [36, 37].

The main problems associated with the use of these types of devices embedded in the microgrid are as follows:

– Storage devices require large investment and need to match the main grid's short circuit level so as to guarantee that faults are cleared in a timely manner.
– The application of schemes based on a FCL technology is only possible up to certain amount of DGs connected. For very high levels of DGs, it can be difficult to determine the impedance value of the FCL, due to the mutual influence of the DGs.
– Sources with high short circuit capability (flywheels, etc.) require significant investments and their safe operation depends on the correct maintenance of the unit.
– The methods based on an additional current source are highly dependent on the technology of islanding detection and the correct operation of the current source.

G. *Other techniques*

Apart from the methodologies described in the previous sections, there are also other approaches that are less frequently proposed. These have been divided into three groups.

The first group is related to high frequency treatment or transient information. The proposals in this field are mainly based on Wavelet Transform, using different wavelet functions applied to high frequency measurements or travelling waves [38, 39].

The second group includes methodologies based on Artificial Intelligence. Within this group, most of the proposals use the Particle Swarm Optimization (PSO), mainly for coordination improvement purposes [40]. There are also some authors that recommend the use of Artificial Neural Networks (ANN), but without having conducted any kind of study for microgrid protection [41]. Some authors also mention a research line conducted in a Canadian University, using a Data Mining technique [42].

The third group includes the proposals that are based on a purely mathematical approach. Within this field, there is a wide variety of approaches such as: using Dijkstra's algorithm (a graph search algorithm) in order to obtain the relay hierarchy of the network [43]; a different concept called brittleness entropy of a complex system to detect faults [44]; a state observer technique as a fault detector, by dividing the microgrid into different zones [45]; using the transient fault information (time and polarity features) included in the initial current travelling waves, and applying a modified mathematical morphology technology [46]; using Time-Coloured Petri Nets for fault diagnosis in microgrids [47].

4. Conclusions

Based on the analysis of the wide range of technical publications presented in the previous sections, the main conclusions and recommendations regarding the protection of microgrids can be summarized as follows:

- There are still relatively small number of references that address and describe the proposed solution to the microgrid protection problem properly, let alone giving enough information to fully understand the approach. In many cases, the information given in these references is short or incomplete, barely including verification simulations or tests, most of them to be more of an idea than a thoroughly studied solution.
- Although the authors that are most related to protection manufacturing companies seem to favor adaptive protection systems, a general trend in this direction has not been observed.
- It seems to be clear that there is an increasing need or even necessity to upgrade many protection devices (fuses, etc.) currently used in power systems, mainly in LV systems, in order to provide new capabilities for the application of new unconventional protection systems in microgrids.
- Regardless of the protection methodology, it seems likely that some kind of communication is going to be necessary, either centrally operated or distributed.
- In order to deal satisfactorily with the protection problems associated with a bidirectional power flow, the need for a directional feature is clear. This would imply different settings for each fault direction and, even in some cases, it may be necessary to use different methodologies for each fault direction.
- Many references divide the microgid into a number of smaller zones and subsequently apply the proposed methodology separately to each one of them: divide and conquer type approach.
- Compared to other areas of power system protection, the number of references using artificial intelligence techniques in order to improve the microgrid protection is not very high.
- There are some specific problems that are hardly analyzed in cited references, such as high impedance faults and protection of meshed networks.
- Similarly to other research areas in power system protection, it is likely that, in order to get an optimal protection system for microgrids, a combined action of different protection techniques will be necessary.

Acknowledgement

The work presented in this paper has been supported, partially, by the Basque Government (Ref. IT532-10) and by the University of the Basque Country UPV/EHU (UFI 11/28).

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