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Planning, Operation, and Protection of Microgrids: An Overview

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Abstract

The significance of microgrids is growing rapidly. Microgrids have a huge potential in boosting the sustainable growth. A microgrid can operate in grid-connected or islanded mode. In islanded mode, microgrids can provide electricity to the rural areas with lower cost and minimum power losses. In grid-connected mode, microgrids can help in supporting the main grid in many ways with voltage control, frequency control, and can provide more flexibility, control, and reliability. However, successful operation of a microgrid requires proper planning and there are major challenges regarding the operation, control, and protection of microgrids that need to be tackled for successful deployment of microgrids. Depending on the mode of operation (grid connected mode or islanded mode), necessary control strategies and protection schemes are required. Several methods have been proposed in the literature for the successful operation of a microgrid. This paper presents an overview of the major challenges and their possible solutions for planning, operation, and control of islanded operation of a microgrid.

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Keywords: Islanded microgrids; microgrids protection; planning and operation.

1. Introduction

Power generation from fossil fuels is associated with several environmental concerns and poor energy efficiency. Use of renewable energy resources as distributed generation (DG) can be a potential solution to these problems. As the penetration of these DGs in the distribution network increases, they create a microgrid. A microgrid is a low voltage, the small-scale power grid (on distribution side) with DG, storage devices and controllable loads [1].

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Microgrids can operate independently called the islanded (autonomous) mode of operation or in conjunction with the main grid called the grid connected mode of operation [2]. Fig. 1 shows the typical structure of a microgrid in which there is distributed energy resources (DERs), distribution network and loads. A microgrid can be connected or disconnected from the main grid at the point of common coupling (PCC). The limited capacity of microgrids has resulted in the evolution of multi-microgrids. Multi-microgrids are an interconnection of several microgrids which can operate with or without the main grid support.

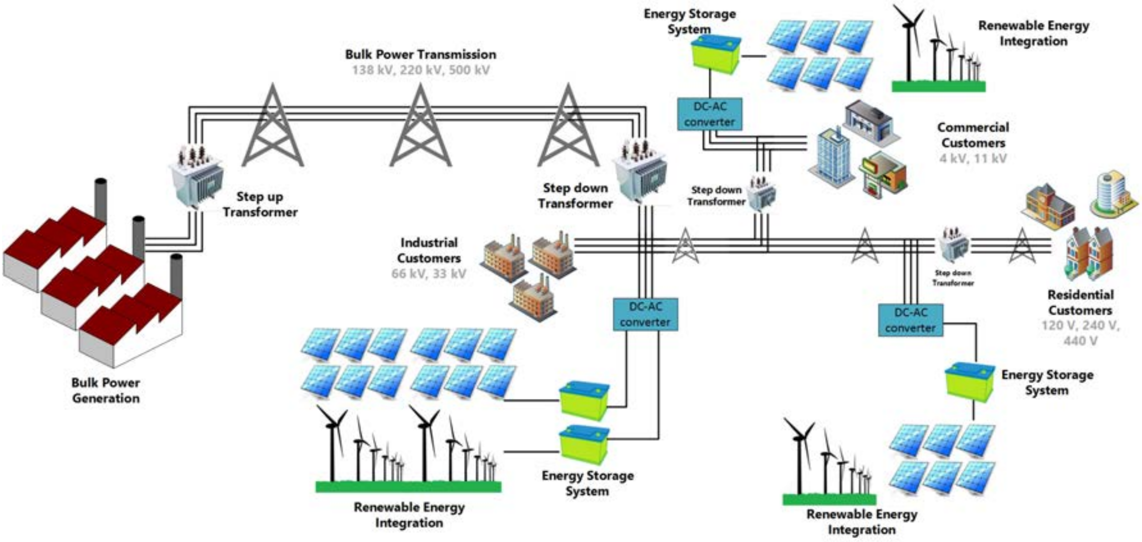

Fig. 1. Microgrid schematic.

Microgrids offer several advantages and benefits including increased reliability, improved energy efficiency and resiliency, cost reduction, reduction in transmission losses, CO_2 emission reduction, and other environmental benefits. However, they also introduce several major challenges regarding the operation, control, and protection of microgrid. Furthermore, each mode of operation (grid connected or islanded) requires unique control and protection schemes. In literature, several methods have been proposed for the successful operation of microgrids. According to the IEEE standard 1547, DGs are allowed to be connected to a distribution network but are required to be disconnected in case of a fault. This approach can be applied to very small grid-connected microgrids. However, if the DG penetration is very high, disconnection of all DGs can have adverse effects on the main grid. The major issues and potential solutions in microgrid protection and control include:

- Bidirectional power flows: The power flow in a conventional distribution system is unidirectional, i.e. from the substation to the loads. Integration of DGs on the distribution side of the grid can cause reverse power flows. As a result, the conventional protection coordination schemes are no longer valid [3];
- Short circuit capacity: In the case of inverter based DGs, the fault current is limited (maximum 2 p.u.). Hence, the conventional overcurrent relay cannot sense the fault [3];
- Stability issues: Local oscillations may arise as a result of the interaction of the control system of micro-generators. Hence, small signal stability analysis and transient stability analysis are required to ensure proper operation in a microgrid [4];
- Low inertia: In a conventional power system, the bulk power is generated at power plants and hence they have high inertia. Microgrids, on the other hand, have dispersed generation and sizes of the DGs are very small. Consequently, they have a low inertia characteristic, especially for inverter based DGs. Low inertia can result in severe frequency deviations in islanded mode operation. Hence, special control mechanism is required [4];

- Intermittent Output: Microgrids with renewable energy resources (photovoltaic, or wind) as distributed generation are intermittent in their power output. Hence, coordination between DGs and storage devices is essential.

This paper presents an overview of these methods and highlights the three major constituents (planning, operation and control, and protection) that are needed for successful implementation of a microgrid. The rest of the paper is organized as follows: Microgrid planning is presented in Section 2. Overview of operation and control strategies is presented in Section 3. Section 4 provides an outline of various protection schemes proposed for microgrids. Conclusions are drawn in Section 5.

2. Planning

Several benefits of microgrids have been mentioned in the introduction. However, these advantages should be compared with the cost of investment to justify the installation of DGs. A complete cost-benefit analysis is thus needed before implementation of such big projects. However, an accurate economic analysis is very challenging because of the uncertainty in the required data. Thus, efficient models are needed for the successful planning of microgrids. Mao *et al.* [5] implemented particle swarm optimization method for energy storage sizing in microgrids to minimize the investment cost considering capital cost, operation and maintenance cost, and emission reduction benefits. The microgrid model proposed by Mohammadi *et al.* [6] attempted to maximize the current value of the grid-connected system by integrating PVs, batteries, and fuel cells with the main grid and electricity market. Chen *et al.* [7] formulated mixed integer linear programming problem by taking into consideration the unit commitment problem and the spinning reserve of the system to optimize the sizing of energy storage system in a microgrid. Solar radiations and wind speeds were forecasted using feed-forward and time series neural network techniques, respectively. Hawkes [8] and Asano *et al.* [9] presented the effects of variations in fuel prices on the planning of microgrids. Mitra and Vallem [10] developed a method for optimal sizing of storage devices needed to maintain the microgrid reliability. Mixed integer linear programming was used by Bahramirad *et al.* [11] to determine the optimal size for DGs in a microgrid.

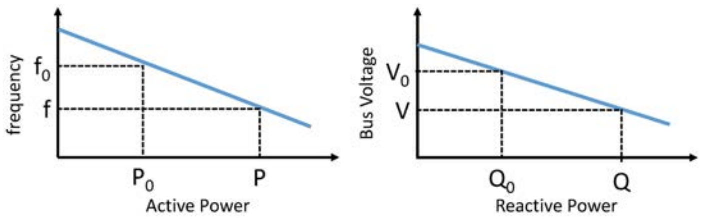

Fig. 2. Droop characteristics of DGs.

Another most needed analysis during the planning stages of a power system is the power flow analysis. For the conventional power system, power flow methods are well established. Gauss-Seidel, Newton-Raphson, sweep methods, and several other efficient power flow methods are available in the literature, and are applicable to a microgrid operating in grid connected mode [12]. The power flow analysis for a grid-connected microgrid can be solved in the same manner as a conventional power system. The DGs, in this case, can be treated as a generator bus (PV bus) or a negative load bus (PQ bus). The variable output of DGs is not considered in power flow problem as they are considered as load buses. Furthermore, since the microgrid is connected to the main grid, the system frequency is assumed to be constant at all times. In the case of an islanded microgrid, conventional power flow methods cannot be applied directly. To implement the autonomous operation of a microgrid, power flow analysis of islanded microgrid is essential. The conventional methods assume the system frequency to be constant. Also, these methods assume a constant y-bus. Furthermore, a slack bus is needed to solve the power flow successfully. Hence, several methods have been proposed in the literature to solve the power flow for islanded microgrids. These power flow methods take into consideration the absence of slack bus and treat the system frequency as a variable. In addition to this, these methods use droop characteristics of DGs which are shown in Fig. 2 [13–15]. The droop characteristics show the relationship of active and reactive power with frequency and voltage, respectively. Power flow for islanded microgrid is solved using Newton trust region method [13]. The method is accurate but complex and computationally intensive. A very accurate, yet simple approach is used in [14], where conventional Gauss-Seidel method is modified and implemented on islanded microgrid. In this method power flow problem is solved in two steps. The first step is same as conventional Gauss-Seidel and involves the calculation of bus voltages. The second step involves the calculation of system frequency, which is done using the droop characteristics of DGs. The modified Gauss-Seidel method is simple and fast but as the size of the network increases the number of iterations required to converge also increases. However, for small microgrids, it can be an efficient tool. Another very effective approach was presented by Mumtaz *et al.* [15], who modified the conventional Newton-Raphson method for solving the power flow for islanded microgrids.

3. Operation and control

In the recent years, DG have become an important part of the distribution system. However, the fluctuation in the output of DGs and varying load demand pose challenges in the successful operation of microgrids. Hence, for the reliable operation of a microgrid, its stability analysis is essential. Fig. 3 shows a typical state space model of a microgrid. In grid-connected mode, the system dynamics are stated by the main grid because of the comparably small size of microgrids. Therefore, the stability analysis of a grid-connected microgrid is not much different from that of the conventional power system. Conversely, in islanded microgrid, the system dynamics are represented by DGs. For the reliable operation of a microgrid in grid connected mode, three levels of supervisory control are employed which include the distribution level, microgrid level, and the unit level. Distribution level involves market operator (MO) and distribution network operator (DNO). Microgrid level involves microgrid central control (MCC), and the unit level involves local controllers (LC). DNO and MO dispatch signals at the distribution level. MCC integrates microgrid with the main grid. It communicates between DNO and LC. The supervisory control can be either centralized or decentralized [16] as depicted in Fig. 3.

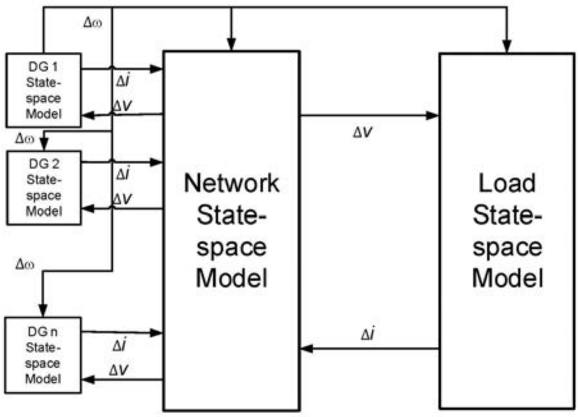

Fig. 3. State space model for microgrid operation.

Several methods have been proposed in the literature to solve for the stability analysis of islanded microgrids using small signal model [17-20]. Small signal stability for parallel connected inverters was proposed for islanded microgrids [17]. However, dynamic analysis for an islanded microgrid was performed assuming an ideal inverter [18]. The small signal model developed in [18] used droop characteristics of DGs in the outer power loop, while current and voltage were inner controllers to filter higher frequencies. Droop control method was developed for the multi-inverter microgrid yet it assumed inductive impedance of DGs [19]. A more generalized approach, which considered complex output impedance of DGs was used [20].

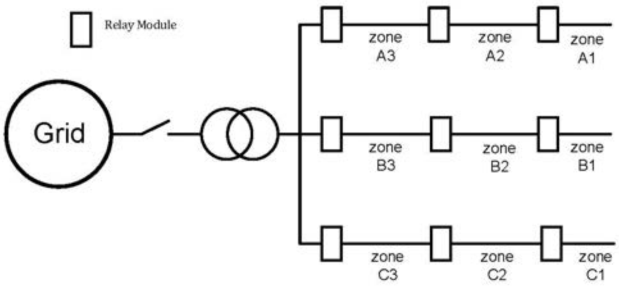

Fig. 4. Microgrid with Protection Zones and Relay Module.

4. Protection

Power flow in a conventional distribution network is unidirectional. However, with the integration of DERs the power flow in the distribution systems can be bi-directional. Faults current path may change depending upon the location of the fault. Constant relay settings may be invalid in case of microgrids (especially for the microgrids with an inverter based DGs). Hence, the conventional protection schemes are not valid in the case of microgrids. Microgrids with the ability to operate both in grid connected and islanded mode impose more challenges, and hence, more sophisticated protection schemes are needed for the successful operation of a microgrid.

Protection issues (e.g. bidirectional flow, fault current path, relay settings, short circuit capacity) of microgrids have been discussed in literature where several protection schemes have been proposed. In the case of an inverter based DG fault current is limited (maximum 2 p.u.). Conventional relay systems are not suitable in case of inverter based DGs. Protection strategies can be based on communication, time grading, and other techniques. Time grading technique is used when the primary relay fails to operate during the occurrence of a fault. In such cases, backup relays operate after a specific time delay defined in the settings of the relay. Usually, the network is divided into zones, with each zone having its own protection relay system. Fig. 4 shows a microgrid with several protection zones and relay modules. Protection scheme for radial distribution systems was presented [21]. A protection scheme that uses microprocessors for the protection of microgrids operating in either grid connected or islanded mode was also presented [22]. Adding communication can help improve the level of protection of microgrids but at the expense of additional cost. In this type of protections system, the circuit breakers and protection relays are connected with a central control unit via a communication network. Optical ethernet communication network which connects the relay devices with the protection and control unit was proposed [23]. Flywheel inverter system was proposed to increase the fault current so that the relays can detect and can clear the fault. Use of fault current limiters is proposed in [24], where these limiters are used in combination with over-current relays to solve the protection issue [25]. A protection scheme was proposed for inverter based DGs in which differential relay measures the difference in the current between two points [26]. Differential protection is one of the most reliable protection schemes for the protection of microgrids (in both grid-connected and islanded mode). Different protection scheme incorporated with digital communication relays was proposed [27]. Another protection scheme based on communication is the wide area protection (WAP). Protection strategy based on WAP was proposed [28]. Most of the faults in the system are temporary and are automatically removed. Autoreclosing relays give the best protection against such faults. At the time the relay senses the fault, it sends the signal to the circuit breaker to trip. After few milliseconds (or nanoseconds) the relay closes the circuit automatically to check whether it was a temporary fault or not. If yes, the network continues to operate in normal mode. If no, the reclosure relay trips, senses it as the permanent fault and opens the circuit permanently. Adaptive differential overcurrent protection was proposed in which the numerical directional overcurrent relays with directional interlocking capability was used for the protection of radial networks [29]. Its implementation cost is high because of the requirement of a communication network. A multi-agent protection scheme was proposed, where the network was divided into zones and wavelet coefficients of transient current were used for fault location [30]. The proposed scheme did not require any central data processor or voltage transformer. Also, the computational time was lower making it more efficient but this requires high-speed communication.

5. Conclusion

Development of microgrids and the integration of renewable energy resources are the key components in the transition from the conventional power system to smart grid system. In this paper, major challenges in planning, operation, control and protection of islanded microgrids are presented. A review of existing technologies and methodologies to overcome the issues for reliable operation of islanded microgrids was also presented. Modified power flow approach was identified as the solution for the planning and operation of islanded microgrids. Bidirectional and differential relays can be an effective solution for the protection of microgrids. Finally, energy storage devices are the key technology for the intermittent renewable energy resources. Most of the challenges in the implementation of microgrids have been addressed in the literature. However, a significant research is still needed especially for the islanded microgrids (microgrids for rural and remote areas). Furthermore, small-scale experiments are also essential before implementation of a real system.

Acknowledgements

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