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Overview of Technical Challenges, Available Technologies and Ongoing Developments of AC/DC Microgrids

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Abstract

Gradual depletion of fossil fuel resources, poor energy efficiency of conventional power plants, and environmental pollution have led to a new grid architecture known as smart microgrid. The smart microgrid concept provides a promising solution that enables high penetration of distributed generation from renewable energy sources without requiring to redesign the distribution system, which results in stable operation during faults and disturbances. However, distributed generators/loads and interaction between all nodes within a microgrid will substantially increase the complexity of the power system operation, control, and communications. Many innovative techniques and technologies have been proposed to address the complexity and challenges of microgrids including power quality, power flow balancing, real-time power management, voltage and frequency control, load sharing during islanding, protection, stability, reliability, efficiency, and economical operation. All key issues of the microgrids, different solutions, and available methods and technologies to address such issues are reviewed in this chapter. Pros and cons of each method are discussed. Furthermore, an extensive comprehensive review for researchers and scholars working on microgrid applications is provided in this chapter to help them identify the areas that need improvements and innovative solutions for increasing the efficiency of modern power distribution grid.

Keywords: AC microgrid, DC microgrid, microgrid power quality, power management, microgrid modeling, power electronics, renewable energies

1. Introduction

The smart microgrid concept was first developed in Refs. [1, 2]. The capability of integration of a large number of distributed power generation sources and high penetration of renewable sources such as photovoltaic panels, wind turbines, and fuel cells within a smart microgrid made it very attractive. In fact, management of multiple distributed power generation sources including renewable energy sources in a smart microgrid offers many advantages such as significant reduction in the need for a transmission and high voltage distribution system, satisfying the growing demand of electricity, and improving energy utilization efficiency and reliability. However, interaction between all nodes within a microgrid including both conventional and renewable energy generation sources will not only increase the complexity of the power system considerably, but it will also raise challenging issues of reliability and power quality due to intermittent nature of renewable sources. Therefore, many technical challenges must yet be overcome to ensure safe, secure, reliable, optimized, efficient, and cost effective operation of the microgrid.

Academic scholars and industry experts offered many innovative techniques and technologies to address the challenges of microgrids such as power quality and power flow balancing [3–12], voltage and frequency control [13–35], power management [36–48], optimization [49–62], stability [63–66], reliability and protection [67–77], and dynamic modeling [78–95]. In this chapter, the concept of microgrid is first presented. All key issues of microgrid and the proposed innovative techniques addressing these issues are then briefly reviewed. Finally, dynamic modeling and control of microgrid in different circumstances is discussed.

The rest of this chapter is organized as follows: Section 2 presents the microgrid concept. Power quality and power flow balancing of microgrid is discussed in Section 3. Section 4 reviews different control methods, power management strategies, and optimization techniques for microgrid. The key issues and technical challenges of microgrid stability, reliability, and protection are then summarized in Section 5. Section 6 discusses dynamic modeling of microgrid. Finally, conclusion and discussion are presented in Section 7.

2. Microgrid concept

A microgrid is a local group of electricity sources and loads that are intelligently managed through power electronics interfaces. A microgrid normally operates in parallel with utility electrical macrogrid, which is denoted as grid-tied mode of operation. It is capable of operating independently in islanded mode. In grid-tied mode, the microgrid becomes part of the main utility grid, and serves the grid with the excess power from distributed renewable generation sources. In this mode of operation, system control and scheduling a transition to islanded mode are done based on the system operation information such as generation outputs, demands, voltages, and the status of protection relays. In islanded mode, however, the microgrid must provide load balance by load shedding and load management. In this mode of operation, some loads might be shutdown to guarantee that there is enough power for

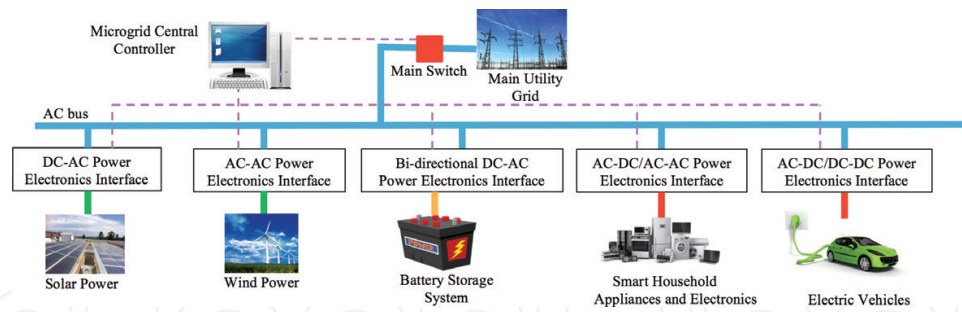


Figure 1. Schematic of an AC microgrid.

critical loads. To restore the transition back to grid-tied mode, the frequency, voltages, and phase angles should be within acceptable limits and must be synchronized.

A microgrid can be generally classified into AC and DC types. The AC microgrid is the main type of microgrid where all distributed power generation sources and loads are connected to a common AC bus through power electronic interfaces as shown in **Figure 1**. However, in DC microgrids a DC bus is used as a common bus especially for small-scale commercial and residential applications, due to higher efficiency and controllability as the extra power conversion stages are eliminated and synchronization and reactive power compensation are not needed in this configuration [96–101].

Integration of various distributed generators/loads and interaction among them within a smart microgrid remain in place regardless of the type of microgrid due to the complexity of power systems technologies, control and communication techniques. In the following sections, many challenges raised by smart microgrid applications such as power quality, protection, stability, reliability, and efficiency are briefly discussed.

3. Microgrid power quality

Power quality is an important issue in a microgrid due to intermittent nature of the integrated distributed renewable energy sources within the microgrid, the transition between grid-tied and islanded modes of microgrid, nonlinear loads, injected current harmonics by power electronic devices, and loads with considerable reactive power demand.

Energy storage, filtering, and proper control schemes are three main categories utilized by scholars to improve the power quality of a microgrid. In Ref. [3], a two-level and a three-level controlled voltage structure were developed as the active power conditioners (APC) to improve the power quality. Their satisfactory results validate the ability of the controlled APCs in improving the power quality even in a weak microgrid context with strongly nonlinear loads and voltage unbalance. A micro-source grid-connected inverter control method based on an advanced f - P , V - Q droop control was proposed in Ref. [4] for microgrid power quality management. Authors in Ref. [5] employed a digital power processor in a closed loop scheme to remove and compensate for unwanted harmonic content of power system

variables such as voltages and currents, and thus improve the power quality. Zhang et al. [6] took advantage of both energy storage and filtering by combining a flywheel energy storage system and an active power filter for power quality improvement of microgrid. Their simulation results show that the combined system can maintain short-term uninterrupted power supply and meet harmonic content standard. Belov et al. [7] created a virtual prototype of a microgrid including AC/DC/AC converters and energy storage devices. They developed a mathematical model of the converter with energy storage device on the basis of the bridge-element (B-element) concept. Their experimental results demonstrate low-voltage distortion caused by the AC/DC/AC converter. In [8], a cooperative control approach is applied to distribute switching power interfaces in a low-voltage residential smart microgrid to optimize exploitation of local energy sources and improve power quality. It is assumed that the low-voltage residential smart microgrid has limited or no communication capability to neighbor units. Cheng et al. [9] employed distributed multiple active filter system to remove power system's harmonics. They used multiple active-filter units instead of a centralized large-rated active filter to reduce the harmonics in the power system and thus improve the power quality. In Ref. [10], Pulse Width Modulation (PWM) converters are utilized to improve the generators' power factor and produce less harmonics. By changing voltage amplitude and phase of PWM converters, generators' active and reactive powers are controlled to meet the required power quality. A combined system of active power filter and static var compensator is employed in Ref. [11] to reduce the harmonic current produced by power electronic devices and load with considerable reactive power demand, and thus improve power quality of microgrid. In Ref. [12], an optimal power control strategy is presented for a microgrid operating in islanded mode. The proposed control strategy is based on particle swarm real-time self-tuning method.

4. Microgrid control strategies, power management, and optimization

Generally, the control strategies of microgrid can be classified in three different levels including primary (local), secondary (power management), and tertiary (optimization) control level [13].

Primary control, which is also known as local or internal control, is simply based on local measurements. In this local control level, no communication is needed [14]. The frequency and voltage deviation in microgrid depend on active and reactive power mismatch, the load characteristic, and the droop model of distributed generation sources. Therefore, frequency/voltage droop control and inverter output control strategies are the general methods being utilized in the primary level of control [15–26].

Unlike the primary control, the secondary control level approaches strongly need fast and reliable communication systems set by IEC 61850 standard [34, 35]. Both centralized and decentralized control approaches can be used in secondary control level [27–30]. Non-model-based fuzzy and neural network controllers [30, 31] and model-based predictive controllers are the examples of centralized control approaches. Multi-agent based control approaches [32, 33] are the examples of decentralized control methods in secondary control level of microgrid. Also, peak shaving, load following, frugal discharge, state of charge set-point, full power/

minimum run time, and ideal predictive dispatch strategies [36–38] are other examples of secondary level control algorithms that have been proposed based on the main power management strategies.

Coordination of multiple microgrids based on the requirements of the main utility system is done in the tertiary control level. Tertiary control is not done by the microgrid itself, and is normally considered part of the main utility grid.

In addition to the developed control strategies for secure, reliable, and stable operation of microgrid, many energy management approaches have also been proposed to handle the characteristics of different power generators and storage systems within the microgrid. In Ref. [39], a microcontroller-based power management system is utilized for the online operation of an experimental low-voltage microgrid to control the battery state-of-charge. In Ref. [40], a dynamic energy management strategy is proposed for a photovoltaic (PV)-based micro grid with combined energy storage. The combined storage system includes batteries and super capacitors. Batteries have low power density and their charge and discharge rate are low causing severe stress under quick load fluctuations. Super capacitors, on the other hand, have high power density and they can easily tolerate quick load fluctuations, but cannot be used as an energy storage system alone as they cannot supply load for a longer time. Combining batteries and super capacitors provides a high-power density storage system. In Ref. [41], authors developed an online power energy management strategy for a hybrid fuel cell/battery as another type of energy storage system utilized in a microgrid. Their proposed method includes three layers, where in first layer, all possible operation modes of microgrid are captured. The power split between batteries and fuel cells is done in the second layer by a fuzzy controller. The set points of each subsystem are regulated in the third layer. In Ref. [42], an energy management system is proposed for a microgrid, including advanced PV generators with embedded storage units and a gas microturbine. The power management is done both centrally at the microgrid side and locally at the customer side by exchanging data and order through a communication network. The proposed power management strategy relies on PV power predictions, load forecasting, and distributed battery storage system. In Ref. [43], an overall power management strategy is proposed to manage power flows among the different energy sources and the storage system within the microgrid in which the primary power sources of the system are wind and PV, and a fuel cell-electrolyzer combination is used as a backup and a long-term storage system. Katiraei and Iravani [44] investigated three power management strategies based on voltage-droop characteristic, voltage regulation, and load reactive power compensation to address real and reactive power management of a multiple distributed generation microgrid system.

In addition to control and power management, optimization is the other pillar of efficient and reliable operation of the microgrid. An optimal allocation methodology and economic analysis of energy storage system within a microgrid is proposed in Ref. [45] using genetic algorithm on the basis of net present value (NPV). In Ref. [46], the optimization is done by a coordinated control approach in two layers including the schedule layer and the dispatch layer. The schedule layer ensures the economical operation of microgrid based on forecasting data, and dispatch layer provides power and voltage regulation based on real-time data. The control and coordination between two layers satisfies both the economical benefit and technical

constraints of microgrid on long-time operation. Authors in Ref. [47] optimized a microgrid economically by considering a multi-objective cost function including the operational cost of distributed generators, start-up and shut-down costs, and the cost of interrupted loads. A multi-objective optimization is also implemented in Ref. [48] in order to minimize the emissions of the three main pollutants coming from the gas turbines, i.e., CO_2 , CO and NO_x . Another multi-objective multi-scenario optimization method is presented in Ref. [49] to evaluate and optimize the performance of the microgrid under various scenarios from different aspects consisting of construction and operation cost, customer outage cost and environment. In Refs. [50, 51], a centralized hierarchical optimization strategy is presented for economic evaluation of a typical microgrid. A decentralized agent-based strategy is also developed in Refs. [52–54] for microgrid power management and optimization. In Ref. [55], an optimization scheme is developed based on the heuristics using a fuzzy neural network. Another neural network-based optimization method is presented in Ref. [56]. Genetic algorithm [57], particle swarm optimization (PSO) [58–61], and ant colony optimization (ACO) [58, 62] are also utilized as intelligent computational methods for microgrid power management and optimization.

Despite all scholarly works and proposed strategies, it is still necessary to develop a comprehensive control and power management strategy to consider all aspects of energy managements such as different modes of microgrid operation and transition modes, voltage and power flow, coordination of controllable units, economical operation, and stability due to the complexity of microgrid.

5. Microgrid stability, reliability, and protection

Stability, reliability, and protection are the key issues of microgrids due to reverse power flows of distributed generation units, local oscillations, transient modes of microgrid, severe frequency deviations in islanded mode operation, and economical and supply-demand uncertainties of microgrid. To address these issues, various strategies have been proposed and developed [63–66]. In Ref. [63], the stability constraints imposed by droop characteristics in an islanded microgrid are identified using a small-signal approach. It was shown that droop gains have significant impact on the stability and microgrids dynamic performance. In Ref. [64], an adaptive feedforward strategy is proposed to change the dynamic coupling between a distributed resource unit and the host microgrid in a way to make the system stability less sensitive and more robust to the droop coefficients and network dynamics. The conflicting goals of proper load sharing and stability of an islanded microgrid is investigated in Ref. [65]. Suitable load sharing requires high values of angle droop specially under weak system conditions. However, overall stability of the system is negatively impacted by high droop gains. To stabilize the system while ensuring proper load sharing, a supplementary control loop around the primary droop control loop is proposed in this chapter. Stability issues of high gains of droop controller are also investigated in Ref. [66]. In this chapter, a reduced-order mathematical model of the microgrid is proposed for prediction of stability of microgrids with large number of inverters. The results show that the stability of the microgrid can be analyzed with each inverter transformed into an equivalent network separately assuming that the interconnection cables are predominantly inductive and the droop laws can be decoupled.

Protection is another major challenge for microgrids. An overview of microgrid's protection techniques and strategies is presented in Refs. [67, 68]. All the proposed protection systems ensure to respond to both main grid (utility) and microgrid faults as fast as possible for proper isolation of the microgrid from the main grid. Fast operation of protection system plays a crucial role in stability of microgrid after transition to islanded operation. Protection against overcurrent is one of the fundamental elements of electricity grid. However, this is a challenging task in microgrid as the total short-circuit current capacity of a microgrid in islanded and grid-tied modes is different. In fact, in grid-tied mode of operation the protection is simplified by the potentially large fault currents, whereas these fault currents may have relatively low values in islanded mode due to integrated power electronics interfaces in microgrid. This low current capacity in islanded mode is not sufficient to trip conventional overcurrent protection. Therefore an adaptive protection system is needed to change relay settings in real time to guarantee that the microgrid is always protected [69, 70]. Another solution is utilizing digital relays equipped with a communication network [71] to protect the microgrid. An easier solution to the protection issue is designing the microgrid to enter islanded mode in a faulty situation before any protection action could take place [72]. To prevent the flow of large line currents during a voltage sag, two current-limiting algorithms are employed in Ref. [73]. These algorithms are used with a voltage-source inverter (VSI) connected in series between the microgrid and main utility grid to imitate a large virtual RL or L impedance for limiting the large line current during utility voltage sags.

To address the issues and limitations of traditional relaying overcurrent protection techniques in microgrid with bidirectional power flow, a voltage-based fault detection and protection strategy is proposed in Ref. [74]. The proposed protection scheme provides reliable and fast detection for different types of faults within the microgrid in which any output disturbance is detected and the strategy for the isolation of the faulty section is initiated. A state observer is utilized in Ref. [75] to detect and identify faults that occur within the protection zone. Fault detection in a DC microgrid and the method for discriminating the stable abnormal operating condition from the faults is presented in Ref. [76]. In Ref. [77], different fault-detection and issues associated with grounding aspect of protection system is discussed.

6. Microgrid modeling and dynamic characteristics

Dynamic characteristics and suitable mathematical model of the microgrid is needed to design an efficient control and power management strategy. However due to high order model of microgrid and its complexity, many studies are performed based on digital computer simulation software packages such as Power Systems Computer Aided Design (PSCAD)/Electromagnetic Transients including DC (EMTDC) and MATLAB/Simulink/Simpowersystem to select appropriate control parameters on a trial and error basis [78–83]. These scholarly works emphasize that simulation-based modeling approaches facilitate a powerful tool to investigate the behavior of microgrid. However, simulation-based models cannot provide a comprehensive prediction of all microgrid scenarios resulting in poor power quality or instability.

To this end, small-signal dynamic model of a microgrid is presented to provide an accurate and valid representation of microgrid for designing and optimizing the proper control strategies [84–87]. To develop an accurate and valid model of microgrid, individual model of each distributed generation source is obtained in its local $dq0$ reference frame and then all individual models are transformed to the microgrid global $dq0$ frame to form an integrated model of microgrid. For instance, a practical model of energy storage system as one of the most imperative components of the microgrid is developed in Ref. [88].

Although, a comprehensive model of a microgrid provides accurate dynamic characteristics of the grid, it is very complex and increases the computational burden of the designed controller and power management strategy. Therefore, reduced-order model of microgrids is used [89–90] to address the associated issues of complex comprehensive model. It is shown in Ref. [84] that microgrid low frequency modes are highly related to the network configuration and inverter external power loop, whereas the high frequency modes are largely relative to the inverter inner loop, the dynamic characteristics of loads and network. Thus far, a reduced small-signal model of a microgrid operating in islanded mode is derived in Ref. [89] by neglecting the effect of microgrid high-frequency modes. It should be noted that model order reduction and linearization is done around an operating point, assuming small signal variation around the desired operation point, to apply linear system theory to the power grid. However, network variables would not always remain in small neighborhood of the desired operating point. In these cases, nonlinear model [91, 92] or large-scale system model [93] provide a suitable model of the microgrid. In Ref. [93], linearized state variable models of DC-DC converters and system interconnections at different system operating points and changing interconnections are used to develop a large-scale system model of a DC microgrid. Also, a modular and scalable model for a DC microgrid is presented in Ref. [94] which is independent of the type of renewable energy sources. The authors extend the proposed model of 40-house village equipped with PV panels and energy storage system to an islanded DC microgrid. In Ref. [95], the model of a hybrid power generation system is developed using transfer function model of integrated power electronics converters within the microgrid.

7. Conclusion and discussion

The power delivery system has gradually changed from large-scale unidirectional conventional power generation sources to small-scale bidirectional distributed power generation sources/loads including new plugged-in electric vehicles as bidirectional loads and renewable energy sources such as solar photovoltaic and wind energy. The microgrid concept provides promising solution for the transition from a conventional delivery system to the future grid with high penetration of distributed generation from renewable energy sources without requiring to redesign the distribution system. However, distributed generators/loads and interaction between all nodes within a microgrid substantially increases the complexity of power systems technologies, control techniques, and communications among grid's components.

Microgrid challenges	Methods/technologies	Comments/examples
Power quality	Energy storage	Electrical batteries, flywheel mechanical storage, thermal storage
	Filtering	Active power conditioners (APC)
	Proper control methods	$f-P$, $V-Q$ droop control, optimal power control
	Energy storage + Filtering	Flywheel storage and active power filter
Control strategies	Primary (local) control	Frequency/voltage droop control
	Secondary centralized control	Non-model-based fuzzy and neural network controllers and model-based predictive controllers
	Secondary decentralized control	Multiagent-based control approaches
	Tertiary (optimization) control	Part of the main utility grid and not microgrid itself
Energy management	Combined energy storage	Combined batteries and super capacitors, hybrid fuel cell/battery
	Power generation prediction and load forecasting	Managing power flow among the different energy sources and the storage system within the microgrid
	Voltage-droop characteristic	Voltage regulation, and load reactive power compensation
Energy optimization	Multi-objective optimization using intelligent methods	Genetic algorithm, fuzzy neural networks, particle swarm optimization (PSO), and ant colony optimization (ACO)
Stability	Proper control strategies	Supplementary control loop around the primary droop control loop
Protection	Adaptive protection system	
	Digital relays	
	Current-limiting algorithms	
	Voltage-based fault detection	
	State observer	
Modeling	Software-based model	PSCAD/EMTDC and MATLAB/Simulink
	Comprehensive small-signal model	Accurate, but very complex
	Reduced small-signal model	Model order reduction and linearization around an operating point
	Nonlinear model	

Table 1. Summary of different microgrid technologies.

This chapter provided an overall vision of microgrids and their main requirements. An overview of several proposed methods and developed competing technologies for seamless deployment of microgrid and their pros and cons were also presented. **Table 1** summarizes these methods and technologies and their key features. Despite the progresses made over the last few years, technologies remain immature and not yet ready for commercial stage as shown by a large number of different methods, strategies, and policies. To transform the current microgrid into fully commercial, reliable, and cost-effective power grid, a combination of targeted research, development, engineering work, and government incentives is still necessary.

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