Energy Storage for Sustainable Microgrid

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FOREWORD

The modern power grid is one of the most complex man-made engineering systems delivering close to 1000 GW of electricity in the United States alone. Power generation in the traditional power grid is highly centralized with power and energy flowing unidirectionally from synchronous generators through a transmission/distribution network to end users. However, technological issues of traditional electric utilities as well as environmental problems caused by the combustion of fossil fuels have stimulated the research and development of new power system technologies. With the emergence of distributed energy resources (DER), for example, wind, photovoltaic, battery, biomass, microturbine, fuel cell, etc., microgrid technologies have attracted increasing attention as an effective means of integrating renewable distributed generation (DG) into power systems.

A high level penetration of renewable energy resources (e.g., wind, PV) in microgrids can make maintaining grid stability and delivering reliable power challenging due to intermittency and fluctuation issues. In such cases, a distributed energy storage (DES) can play an essential role in improving stability, strengthening reliability, and ensuring security. This monograph is dedicated to fundamentals and applications of energy storage in renewable microgrids. With limited page budget, this book covers the following topics, which are summarized in the following paragraphs: basic concepts and control architectures of microgrids; applications of energy storage systems (ESS) in renewable energy microgrids; interfacing between ESS and microgrid; coordinated frequency regulation of battery energy storage systems (BESS) with renewable generation in microgrid; and sizing of ESS for microgrids.

Nowadays, DG technology is becoming increasingly mature, and is deployed as active distribution networks working cooperatively with conventional power grids. In addition, the issues of exhaustible natural resources, fluctuating fossil fuel prices, and the security of electricity have encouraged governments around the world to hold positive attitudes toward the development of emerging microgrids. Future microgrids will allow high renewable penetration and become building blocks of smart grids thanks to advanced communication and information technology. As the underlying scientific and engineering research questions are being answered, there is no doubt that microgrids will play an extremely important role in future sustainable power and energy systems.

There are several applications of ESS including aggregated and distributed ESS in renewable energy microgrids. The microgrid energy management system includes load leveling and peak shifting features, which are widely used to mitigate load fluctuations and improve power quality. ESS is typically used to suppress fluctuations in renewable sources, with methods such as constant power control, output filtering and ramp-rate control. Uninterruptible power systems (UPS) are another important application of ESS in microgrids, especially for the islanded renewable microgrid. ESS in a microgrid also provides benefits for power quality, voltage regulation, reactive power support, and operating reserves.

Interfacing circuits are needed for an ESS to connect to the microgrid. It is beneficial to provide an overview of structures and basic principles of several power converters such as DC-DC converters, AC-DC rectifiers, DC-AC inverters, AC-AC converters. This is done in Chapter 3. The most important DC-DC converter for an ESS is the bidirectional buck-boost DC-DC converter, which is responsible for the charging and discharging of ESS. For DC-AC converters, the voltage source inverter (VSI) is the most widely used converter in practice. A VSI can be used to integrate an ESS or solar photovoltaic into the microgrid. With dq control method, real power and reactive power are controlled independently. There are different configurations of battery management systems (BMS). Within a BMS, cell balancing is important for reliable operation of the BESS.

Compared with frequency regulation by wind generation system, a BESS is a better alternative for providing frequency regulation and inertial response in a faster, more accurate and flexible manner. So, participation of BESS in an islanded microgrid frequency regulation can assist renewable DGs in operating at their maximum efficiency without excessive power curtailment. In Chapter 4, coordinated frequency regulation of BESS with renewable generation in an islanded microgrid or microgrid clusters is discussed. The objective of microgrid frequency regulation is to regulate the frequency of an islanded microgrid to the specified nominal value in the event of frequency disturbance, and at the same time to maintain the tie-line power interchange among different microgrids within a microgrid cluster, or between two virtual areas within a single islanded microgrid at the scheduled value by coordinating the outputs of wind power generation and BESS through virtual inertial response, frequency droop control, and load frequency control.

Energy storage sizing is an important aspect of the cost-effective functioning of microgrids. In the last chapter, different ESS sizing technologies are evaluated. Cost-benefit analysis is a very common method to determine optimal storage sizing. The implementation of an expansion planning method for optimal storage sizing is included. The objective of this method is to minimize the operating cost, maintenance cost and investment cost of the entire microgrid system. In the case study, an optimization problem for determining both the optimal power rating and energy rating of ESS in a microgrid is formulated and solved with mixed integer linear programming (MILP).

I would like to thank those who have provided help and support during the preparation of the monograph. I am grateful to members of the Renewable Energy and Power Electronics Laboratory at the University of Denver, who have devoted a lot of effort and assistance during the book preparation. Special thanks go to these members: Ibrahim Alsaidan, Xiao Kou, Ibrahim Krad, Qiao Li, Siyang Liao, Shruti Singh, Ziping Wu, Weihang Yan. My thanks also go to all the reviewers and staff members of Elsevier for their timely efforts and support. Last but not least, I would like to appreciate the constant support and guidance from Professor Bikash Pal of Imperial College London.

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For additional information on the topics covered in the chapter 4, visit the companion site: http://booksite.elsevier.com/9780128033746/

CHAPTER 1

Basic Concepts and Control Architecture of Microgrids

1.1 INTRODUCTION

This chapter discusses the basic concepts and control structures of microgrids. Nowadays, distributed generation technology is becoming more and more mature, and is deployed as key elements of active distribution network working cooperatively with conventional power grids. In addition, the issues of exhaustible natural resources, fluctuating fossil fuel prices and security of electricity have encouraged governments around the world to hold positive attitudes toward the development of emerging microgrids. Future microgrids will allow high renewable penetration and become building blocks of smart grids thanks to advanced communication and information technology. As the underlying scientific and engineering research questions are being answered, there is no doubt that microgrids will play an extremely important role in future electric power and energy systems.

1.1.1 Concepts of Microgrids

Power generation in the traditional power grid is highly centralized, with power and energy flowing unidirectionally from large synchronous generators through a transmission/distribution network to end-users. However, the technological issues associated with traditional electric utilities, as well as the environmental problems caused by the combustion of fossil fuels, have stimulated research and development into new power system technologies. With the emergence of distributed energy resource (DER) units, e.g., wind, photovoltaic (PV), battery, biomass, micro-turbine, fuel cell, etc., microgrid technologies have attracted increasing attention as an effective means of integrating such DER units into power systems. However, there is no clear definition of a microgrid, and the concept varies in different countries and regions. Based on the European Technology Platform of Smart Grids [1], a microgrid is a platform that facilitates the integration of distributed

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generators (DG), energy storage systems (ESS) and loads to ensure that the power grid can supply sustainable, price-competitive and reliable electricity. Figure 1.1 shows a typical microgrid structure, comprising DGs, such as combined heat and power unit (CHP), micro-turbines, PV systems, wind power systems, fuel cells; a distributed energy storage (DES) facility such as battery banks, super-capacitors, flywheels, electric vehicles; flexible loads and control devices.

Microgrids can be classified as AC and DC types. AC microgrids can be integrated into existing AC power grid, but they require quite complicated control strategies for the synchronization process in order to preserve the stability of the system. On the other hand, DC micro-grids have better short circuit protection and significantly improved efficiency. Furthermore, some synchronous units (e.g., diesel generators) and some non-synchronous units (e.g., micro-turbine machines) are usually connected in the same microgrid system. As the penetration level of more DC loads (especially Plug-in Hybrid Electric Vehicles) increases, hybrid AC/DC synchronous/non-synchronous microgrids via multiple bi-directional converters will become increasingly attractive. Figure 1.2 shows a typical system structure for a hybrid AC/DC microgrid that contains power electronic interfaces and multiple DER units.

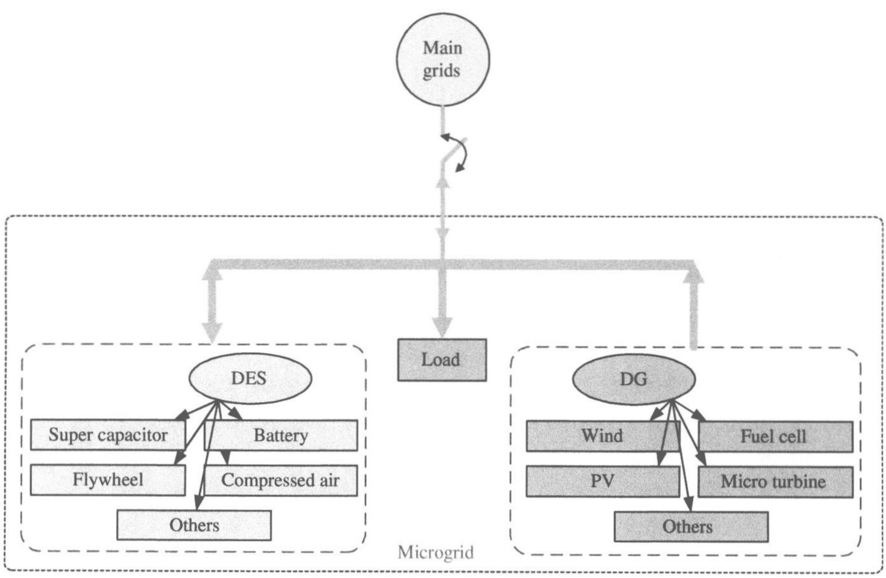

Figure 1.1 Typical structure of a microgrid.

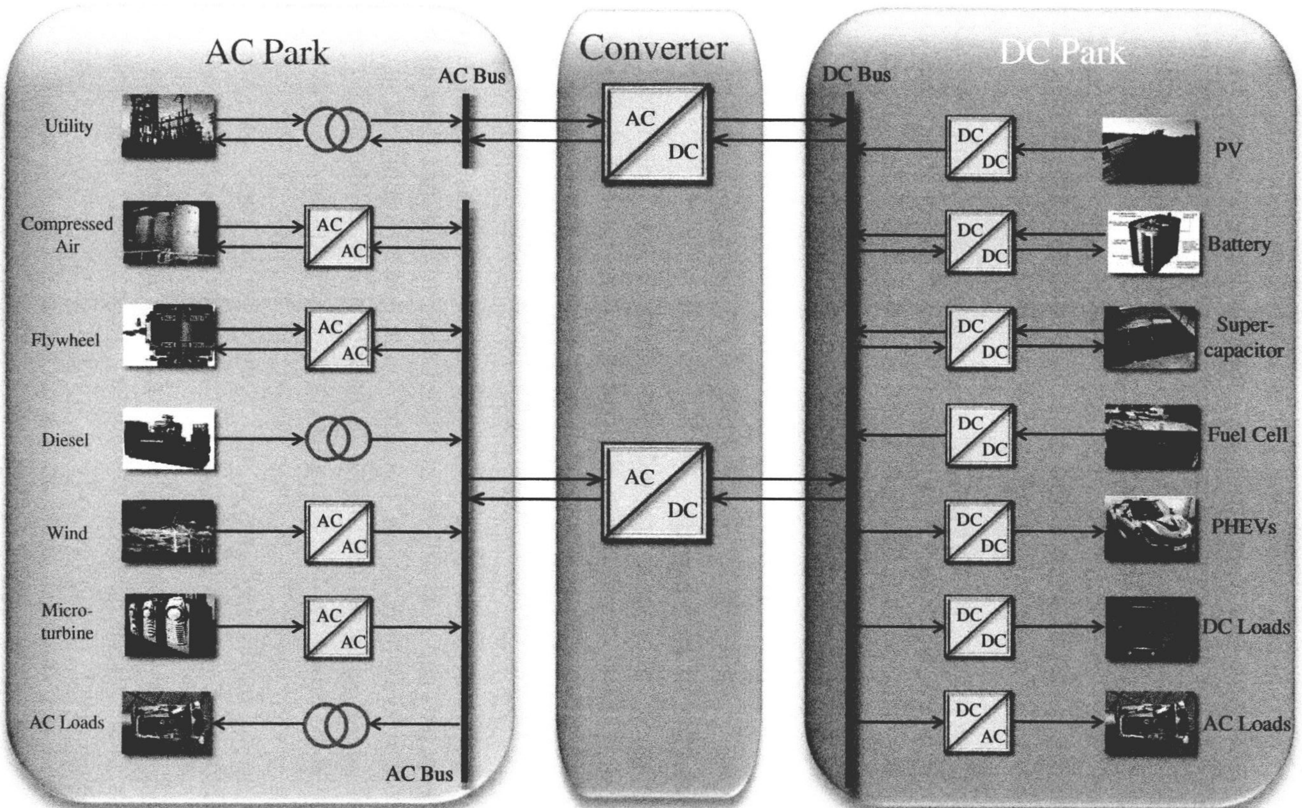

Figure 1.2 Typical system structure for a hybrid microgrid.

Although many types of DG units are more sustainable, a high level penetration of renewable energy resources (e.g., wind, PV) in microgrids can make maintaining grid stability and delivering reliable power challenging due to intermittency and fluctuation issues. In such cases, a DES can play an essential role in improving stability, strengthening reliability, and ensuring security. Not only can DES units be used for smoothing the fluctuations from the output of DG units, but they can also contribute to the stable operation of microgrids. Advances in material science and power electronics technologies have facilitated the effective employment of new DES facilities.

The development of microgrids will bring many benefits but does present significant challenges. For instance, the voltage and frequency disturbance problems in unpredictable weather conditions when integrating renewable energy, monitoring and managing local power generation and loads, designing protection devices to cope with bi-directional power flow and so on. More research needs to be conducted to solve these problems.

1.1.2 Benefits of Microgrids

As mentioned, microgrids provide an effective way for integrating small-scale DERs in proximity of load into low-voltage distribution network. Microgrids can supply highly reliable power to a wide range of customers, both residential and commercial, such as schools, hospitals, warehouses, shopping centers, university campuses, military installations, data centers, etc. Various research stations (Arctic-based or space-based) can also utilize this technology to enhance their operation since it will provide an uninterrupted power supply. It is also useful for remote places having no or limited access to the utility grid. Further, it is beneficial for customers facing large power outages (for example, hurricane-prone areas). Microgrid technology can also be used in areas facing high stress and congestion in their transmission and distribution systems (for example, the northeastern US).

There are many benefits of implementing microgrids. They help facilitate the integration of distributed generation, most notably, renewable energy resources such as wind and solar. This helps curb the dependency on fossil fuels as a source for electricity, significantly reducing carbon emissions and pollution, and thus promotes energy sustainability. They also facilitate the use of highly efficient generators which utilize combined heat and power technology. They can increase the quality of power at the consumer side. With proper control, microgrids increase electrical reliability by decreasing outage occurrences as well as their duration. Utilities see microgrids as controllable loads, which can contribute to peak shaving during times of peak demand by reducing their own consumption via shedding of non-critical loads and delivering more power to the main grid utility. Microgrids can lower overall distribution system losses by implementing distributed generation located at the demand site eliminating the need for transmission lines and deferring the construction of new transmission lines to a later time. This also results in higher energy efficiency. By using renewable energy resources like wind and solar fuel costs can be reduced. There are also several economic opportunities for microgrids if they can participate in local electricity markets. They can offer several ancillary services to the main grid if properly incentivized to do so. Microgrids can provide active power support via frequency regulation, black start support, system restoration support, and load balancing services. Microgrids can be compensated for these services via fixed payments, payments for service availability, payments based on frequency of usage, and/or payments based on lost opportunity cost. This last is the revenue that the microgrid could have made but was not able to because it had to be available for the main utility grid even if it was not called upon [2].

1.1.3 Integration of Microgrid to Distribution Networks

Conventional DGs are usually directly interconnected to distribution networks at medium or high voltage levels. However, generators in microgrids (e.g., PV, wind turbines, fuel cells) have a relatively small installed capacity (e.g., a few hundred kWs). These generators should be connected to distribution networks at a low voltage level. In conventional power systems, loads are passive and power only flows from distribution substations to customers, but not in the opposite way. But power can flow in both directions between microgrids and the main grid.

In the US, the Federal Energy Regulatory Commission (FERC) provides oversight for constructing electric generation, transmission or distribution facilities. FERC permits various ways of integrating renewable energy resources to facilitate electricity market reform.

The technical requirements for distribution interconnections have been stipulated in IEEE 1547 "IEEE Standard for Interconnecting

Distributed Resources with Electric Power Systems". IEEE 1547 is suitable for all distributed resource technologies, with aggregate capacity of 10 MVA or less at the Point of Common Coupling (PCC).

1.1.4 Basic Components and Operation Strategies in Microgrids

The controllable components in a microgrid include renewable sources, dispatchable sources, ESS and demand side management. All of them work together to maximize the total microgrid profit.

The load control scheme in microgrid can either run in non-automated or automated mode. In non-automated mode, customers can obtain the electricity price and choose whether to switch on or off the loads via remote controls. In automated mode, on-off control is realized by loads themselves through pre-programming or receiving control signals.

The objectives of operating a microgrid depends on the stakeholders' interest. These stakeholders could be microgrid operators, distributed generation owners, distributed generation operators, consumers, etc. To maximize the economic profit, the objective is to minimize total microgrid costs, taking into consideration the impact of the microgrid on the main power grid and the environment. To maximize the technical profit, the objective is to minimize the total power losses and voltage fluctuations, and this option has been adopted by majority of system operators. To maximize the environmental benefits, the objective is to minimize the emissions from the DG in order to meet environmental requirements. The final goal is to combine all the above economic, technical and environment factors to achieve maximum comprehensive benefits [3].

1.1.5 Microgrid Market Models

The microgrid market model consists of consumers, distributed generation owners, the market regulator, retail suppliers, energy service companies (ESCO), distribution system operators (DSO) and microgrid operators. The motivation for using microgrids can be analyzed from either the distributed generation side or the demand side.

On the distributed generation side, since most governments around the world encourage the development of sustainable and clean energy, there are no strict rules for controlling the amount of power output