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Smart Hybrid AC/DC Microgrids

Structures and Technical Challenges

1.1 Introduction to Microgrids

1.1.1 Concept of Microgrids

"Microgrids" became jargon in the electrical engineering field at the beginning of the twenty-first century. After nearly two decades of development, the core of this concept keeps expanding and growing along with the development of many other fields, such as power electronics and smart grids. In general, a microgrid refers to a less complex form of an electrical grid, consisting of power generation, energy storage, and consumption as well as essential interfaces. Its functions, on the other hand, entail many more differences than conventional grids [1], e.g. (i) it can work in grid-connected or standalone operation modes; (ii) To the grid, it operates as a self-controlled entity; (iii) it normally features an advanced control strategy to optimally regulate the intermittence from renewable energies, providing high reliability and high power quality; (iv) it is typically located near the users as well as the power generators in a distributed manner, providing high flexibility and cost-effectiveness.

Another important concept closely related to microgrids is distributed generation (DG). DG mainly refers to power generation with distributed forms, differing from the traditional centralized power plant. DG technologies can use sources such as: (i) renewable energy resources such as wind, photovoltaic, micro-hydro, biomass, geothermal, ocean wave, and tides; (ii) clean alternative energy generation technologies such as fuel cells and microturbines; (iii) traditional fossil fuel and rotational machine technologies, such as diesel generators. Due to several benefits of these sources, such as cleanness and simple technologies, compounded with increasing demand for electrical energy and the exhaustible nature of fossil fuels, renewable and clean-energy-based DGs play an essential role in microgrids. Generally speaking, the microgrid is a key concept to broadly adopt DGs into the conventional electrical grid.

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First Edition. Yunwei Ryan Li, Farzam Nejabatkhah, and Hao Tian.

1.1.2 Development of Microgrids

The affix “micro” in “microgrid” indicates one iconic nature of this technique, which is its scale compared to the utility grid. However, the traditional grid used to be much smaller when the first power plant was constructed in the 1880s – the Manhattan Pearl Street Station. In terms of scale, it is indeed micro, and can essentially fall into the generalized category of microgrids. It was also operated as the very early combined heat and power (CHP) demonstration where steam was used to heat nearby buildings as well as power the generators.

During the dawn of the electrical grid, Thomas Edison’s direct current (DC) grid configuration showed superior performance when supporting power at a short distance. By 1886, Edison’s firm had installed 58 DC “microgrids.” Things quickly changed after Nikola Tesla, with the Westinghouse company, patented an electric motor in 1888. It exploited the rotating field invented by Galileo Ferraris, showing the promising potential of the alternative current (AC) generator. Further enabled by AC transformer technologies, high voltage AC transmission with high efficiency became possible. In 1891, an experiment regarding such an AC-based transmission technique took place in Germany, where a 175 km long, 15 kV transmission line was implemented [2]. The success of this experiment soon gained commercial attention, resulting in the monopoly of AC-type utility grids until now.

During this early stage of the electrical system, power quality issues like harmonic voltages and currents also gained their engineering-perspective investigation rather than pure mathematical problems. The word “harmonic” firstly appeared in electrical research in 1894 by *Houston* and *Kennelly*’s work entitled “The Harmonics of Alternating Current.” The active compensation concept came later during the 1920s [3]: an AC-machine-based compensator was introduced by Boucherot and Kapp. It can adjust the reactive power produced by the machine which shares the similar methodology of modern static compensation equipment.

Alongside the rapid development of a centralized AC electrical system, electricity generation for remote areas (e.g. small islands, isolated mountain settlements, etc.) was challenging based on the traditional grid infrastructure with remote fuel-based power plants and long distance transmission. For those areas, small-scale AC off-grid systems or standalone-only microgrids provided electrical power utilizing techniques such as wind-diesel combinations in the early twentieth century, and even up until now. On the other hand, DC power systems, including DC microgrids, still exist and found their application in systems such as telecommunication systems.

During the last century, worldwide electrical grids experienced significant growth, driven by the everlasting demand for electricity generation. In 1924, the first event of the World Energy Congress was held in London. The concerns regarding limited sources of fossil fuels and dramatically increased energy demand embarked energy experts on exploring alternatives. Solar energy was described as a promising candidate in F. M. Jaeger's article published in *Science* in 1929 [4]. More detailed discussions of alternative energy forms covering water, wind, solar, and nuclear (at that time it was called atomic) were provided in C.C. Furnas's article published in *Science* in 1941 [5]. Similar discussions are scattered in historical publications but rarely conveyed into market driving forces toward sustainable energy eco-systems until the first energy crisis in the twentieth century. The 1973 Arab oil embargo, a turning point for the United States energy strategy, resulted in a chain reaction that soon spread out worldwide. One of the eventual reactions was the establishment of the International Energy Agency (IEA). Born from the oil security crisis, the IEA has evolved through the years, pursuing the enhancement of the reliability, affordability, and sustainability of energy. Another important point of progress in history was the 1992 Energy Policy Act in the United States, further strengthening the cost-competitiveness of renewable energy technologies.

In addition to utility-scale regulation, small scale distributed power generation was also taken care of by national policies, e.g. through the 1978 Public Utilities Regulatory Policy Act, the United States became the first country to establish fixed power buy-back rates (i.e. independent producers are allowed to connect to the grid and sell power). The rapid growth of electricity demand keeps pushing the electrical grids to their design limits. During the 1980s–1990s, the economic value of DG started to be recognized as a good complement to the monopoly of the traditional grid. In addition, DGs can support critical electrical needs in rural areas that are difficult to be covered by the centralized grid infrastructure.

At the end of the twentieth century, distributed-resources-based systems received dedicated research attention, which eventually spawned into the concept of modern microgrids, where power electronics serve as vital interfaces bridging renewable energy generation and the load and grid. In 1999, the United States microgrid research development and demonstration program was established under the Consortium for Electric Reliability Technology Solutions (CERTS). The 2005 Energy Policy Act was more energy legislation that was of great significance not only in the United States but also worldwide. It covers a wide scope of renewable energy forms, emphasizes research and development, and promotes the study of advanced energy technologies such as DG, integrated thermal systems, reliability of energy production, etc.

The following years witnessed intense research of microgrids. The trajectory of microgrid technology is shifting from technology demonstration pilot projects to commercial projects, which have grown into a multi-billion-dollar market. In addition to pure electrical power generation, microgrids with CHP applications brought significant opportunities by optimally regulating multiple energy forms for local customers to achieve much better overall efficiency. This is particularly true considering the much higher efficiency of transmitting electricity over a relatively long distance and the flexibility of DG locations. The concept of "district heating" presented in 1950 is a typical precedent that promoted the combination of thermal/electric stations to generate all the heat and power for a town [6]. In recent years, the philosophy of integration has been further extended to clusters of microgrids for a broader scope of energy generation, forming the virtual power plant (VPP) concept, which is not restricted to physical locations and can include assets connected to any part of the grid.

Moving forward to the third decade of the twenty-first century, a number of countries have announced pledges to achieve net-zero emissions in the future, e.g., IEA 2021 report "Net Zero by 2050" [7]. This is when microgrids as well as their larger interconnected systems will play key roles to better integrate renewable-based DGs with higher reliability, lower cost, and easier accessibility. The challenges are huge but there has been promising progress in recent years. Considerable research efforts have been dedicated to smarter operation for microgrids, e.g. multi-function optimization, fast and reliable power regulation, comprehensive power quality management, advanced communication, etc. Moving forward, microgrids also serve as one of the key enabling techniques for next-generation power systems, i.e. smart grids. These smart grids encompass interconnected microgrids, especially at the distribution level where DGs are increasingly used.

1.1.3 Features of Modern Microgrids

With many years of development of microgrids and the enabling technologies in power electronics, communications, and control, a modern microgrid includes a physical electrical system with renewable and non-renewable-based DGs, energy storage systems (ESSs), and various loads, as well as the communication and control systems as shown in Figure 1.1.

As illustrated, the microgrid has a higher-level control system that monitors and coordinates the physical components through communication systems. Control system information acquisition and command execution are mainly realized by the actuators, such as sensors, relays, and, most importantly, the interfacing converters (IFCs). IFCs are interfaces between the microgrid network and renewable energy, ESSs, loads, or another microgrid network, performing power conversions required for the interconnections. The modern microgrids are expected to have some distinctive features, as shown in the next sections.

High Percentage of Renewable Energy and Energy Storage

Carbon emission and pollution from fossil-fuel-based power generation have been considered as the major challenges confronted by human beings. However,

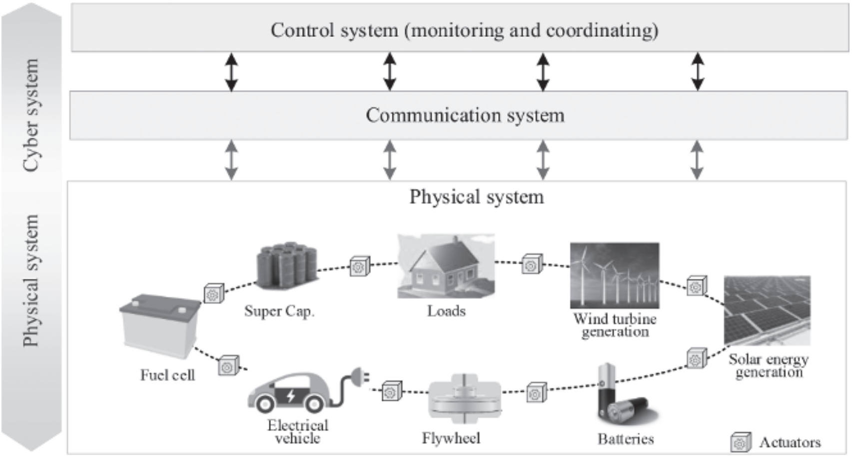

Figure 1.1 Block diagram of modern microgrids.

renewable-based electricity generation, such as the generation from solar and wind, generally suffers intermittencies and lacks complete control. Microgrid technology provides a solution to adopt more renewable-energy-based power generation without degrading the reliability and power quality of the grid through the integration of ESSs, controllable loads, and the corresponding coordination control.

High system efficiency. As mentioned earlier, the flexibility of providing CHP systems can significantly improve the energy efficiency of microgrids. In addition, the adoption of DGs closer to the loads can effectively reduce the losses in the traditional transmission and distribution systems. Moreover, much renewable-based DG such as photovoltaic (PV), fuel cell, ESSs, and modern loads (such as LED lighting) are based on DC technologies, where the many AC–DC conversion processes through IFCs for connecting them to the traditional AC buses can create additional losses. The suitable microgrid configuration where both AC and DC buses exist to interface different types of generation, storage, and load technologies can further improve the system efficiency.

Resiliency. Microgrids are designed to work in both grid-connected or standalone operation modes. This enables the autonomous operation of microgrids when the utility grid suffers from blackouts or major disturbances. In this case, power systems with microgrids are more resilient than traditional ones. Moreover, with more sensors and actuators, such as the controllable and flexible IFCs, microgrids have enhanced the capability for power control and management, leading to sound system operation and higher reliability.

Intelligent. With the development of information and communication technologies, their role in modern microgrid operation and control is becoming more important than ever. Modern microgrids have the capability of system status monitoring, intelligent power and energy management, operation optimization, and outage control.

Superior power quality. With the increasing penetration of interfacing power converters in microgrids, they can be properly controlled to optimize the network power quality in addition to their power management targets. This is a promising idea since most IFCs are not always operating at full rating due to the intermittent nature of renewable-based DGs. Therefore, their available rating can be used in a smart way to support microgrids. Such microgrids will benefit from fewer harmonics, better power factors, lower unbalance, and well-regulated voltage amplitude and frequency.

1.2 Smart Hybrid Microgrid Configurations

According to the type (AC or DC) of buses or feeders to integrate the generation or loads, microgrids can be classified into AC microgrids, DC microgrids, and hybrid AC/DC microgrids. In AC-coupled microgrids, only AC buses or feeders are available and all sources and loads are connected to the AC buses. In a DC-coupled microgrid, all sources and loads are connected to DC buses, and the DC microgrid is interfaced to the main grid through an AC/DC IFC. In hybrid AC/DC microgrids, both AC and DC buses are available, and the microgrid generation sources and loads are connected to the respective buses to minimize the voltage conversion process or optimize the system operation.

1.2.1 AC-coupled Hybrid Microgrid

A simple example of an AC-coupled hybrid microgrid is shown in Figure 1.2. As illustrated, only AC buses are available in an AC-coupled microgrid, and various DGs and ESSs are connected to the AC buses through their IFCs. The ESSs need bidirectional converters to provide the bidirectional power flow capability. In this configuration, both AC and DC loads are also connected to the AC bus where the DC load will require an DC/AC IFC for such integration. This AC-coupled structure is commonly used when dominant generation sources in the microgrid produce grid-level AC voltages directly (such as from diesel generators) or indirectly through interfacing power converters.

In such an AC-coupled system, the control strategy and power management scheme are mainly focused on power generation/consumption balance and AC subgrid voltage/frequency control, especially in standalone operation mode. The

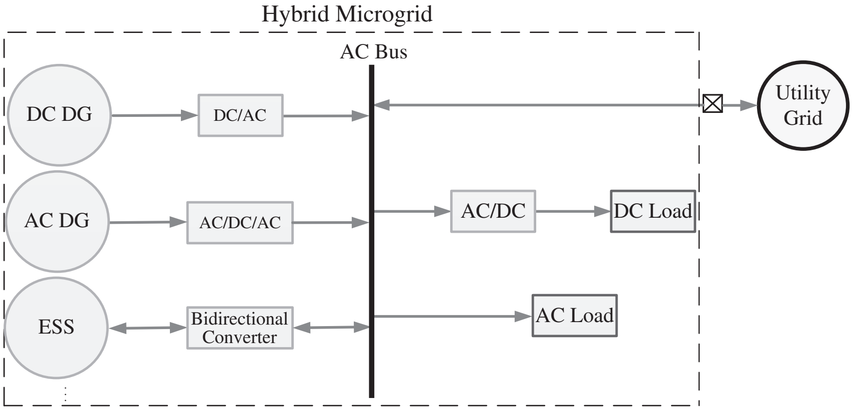

Figure 1.2 A typical example of an AC-coupled hybrid microgrid.

AC-coupled microgrid has been the dominant structure in the past due to its simple structure and simple control and power management scheme.

In some AC-coupled microgrids, instead of using IFCs for each DG or ESS, several power conversion stages can be replaced by multiple-port converters, which combine different power sources in a single power converter. Moreover, in some systems, high-frequency (higher than the power frequency) AC coupling can be adopted for the microgrid, where the microgrid then requires an AC/AC IFC to be connected to the main grid at power frequency.

1.2.2 DC-coupled Hybrid Microgrid

Figure 1.3 shows a DC-coupled hybrid microgrid, where only DC buses are available for integrating the DGs, ESSs, and loads. The AC-based source and loads will then require IFCs to be connected to the common DC bus. This DC-coupled configuration is typically adopted when DC power sources (e.g. PV or battery systems) are the major power generation units in the microgrid. Note that in this structure, all the DGs and ESSs are connected to the DC bus. In this DC-coupled microgrid, a variable frequency AC load such as adjustable speed motors can be connected to the DC bus with a DC/AC converter. In this case, the traditional front-end AC/DC grid side rectifier for AC bus connection can be removed, which brings obvious benefits in control, power quality, and efficiency. In this system, the microgrid DC/AC IFCs provide bidirectional power flow between the DC bus and AC bus. Depending on the power exchange requirement between DC and AC buses, parallel IFCs are typically used with increased rating and reliability.

The DC-coupled microgrid features a simple structure and does not need any frequency and phase angle related synchronisation when integrating different DGs.

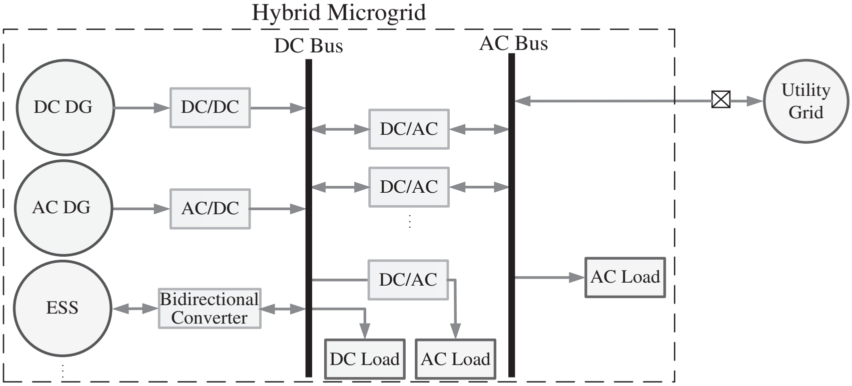

Figure 1.3 A typical example of a DC-coupled hybrid microgrid.

The control and power management of parallel microgrid IFCs, and their AC terminal voltage synchronization (with each other or with the grid in grid-connected mode) can present some challenges. Moreover, both DC and AC voltage control and subsystem power management are necessary for a DC-coupled system. In some DC-coupled hybrid microgrids, ESSs are connected to the DC bus directly without converters.

Similar to an AC-coupled hybrid microgrid, in DC-coupled hybrid microgrids, multiple-port power converters can be used to connect different input power sources to a common DC link in a unified structure.

1.2.3 AC-DC-Coupled Hybrid Microgrid

The structure of an AC-DC-coupled hybrid microgrid is shown in Figure 1.4. As seen, both DC and AC buses are available in such a system to integrate the DGs, ESSs, and loads. The AC and DC buses (or subgrids) are linked by IFCs. Different from the DC-coupled system, the AC-DC-coupled hybrid microgrid has DGs and ESSs on the AC subgrid too, which requires more coordination for the voltage and power control between the DC and AC subgrids. On the other hand, similar to the DC-coupled microgrid, parallel IFCs are desired to link AC and DC subgrids with increased capacity and reliability. In general, this structure is considered if major power sources include both DC and AC powers. This structure improves overall efficiency and reduces the system cost with a reduced number of power converters by connecting sources and loads to the AC and DC subgrids with minimized power conversion requirements.

Considering these benefits, AC-DC-coupled hybrid microgrids will be the most promising microgrid structures in the future.

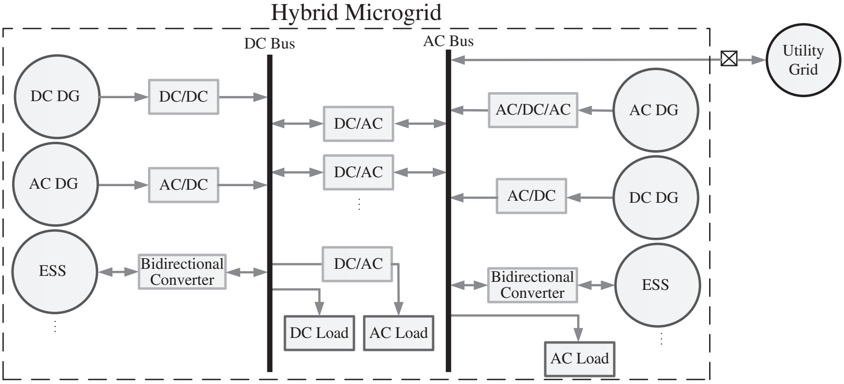

Figure 1.4 A typical example of an AC-DC-coupled hybrid microgrid.

1.2.4 Examples of Hybrid Microgrids

A hybrid microgrid can exist in many different forms, such as a community, campus, institutions, commercial center, or even a microgrid in the sky or ocean like more electric aircraft (MEA) or electrified ships. Considering the rapidly increasing online activities and demand of data centers as well as the wide acceptance of electric vehicles, two examples of hybrid microgrids, data centers, and electric vehicle charging stations, are briefly presented here.

Based on an EPRI report, data centers will consume 20% of electricity in the United States by 2030, and power quality issues are a significant concern in such systems (in the United States, low power quality and unreliable power supply of data centers can result in millions of dollar losses annually). In general, data center structure can be AC-coupled or DC-coupled, which are shown in Figure 1.5. The traditional configuration of the data center is an AC-couple structure, where the AC/DC and DC/DC voltage conversion happens right before the server load. In recent years, the research and implementation of DC data centers (400 V DC distribution) have seen increasing demand. This DC-based structure effectively reduces the current and losses in the system. They also have better performance compared to AC architecture in terms of reliability, efficiency, and power quality.

The charging stations of EVs can have AC or DC structures, which are shown in Figure 1.6. For commercial EV charging stations, level 2 (single/three-phase AC charger, around 20 kW) and level 3 (typically DC-based fast charger greater than 20 kW) chargers are popular. In the AC-coupled structure, all fast DC chargers are connected to a common AC-bus through AC/DC converters, while in a

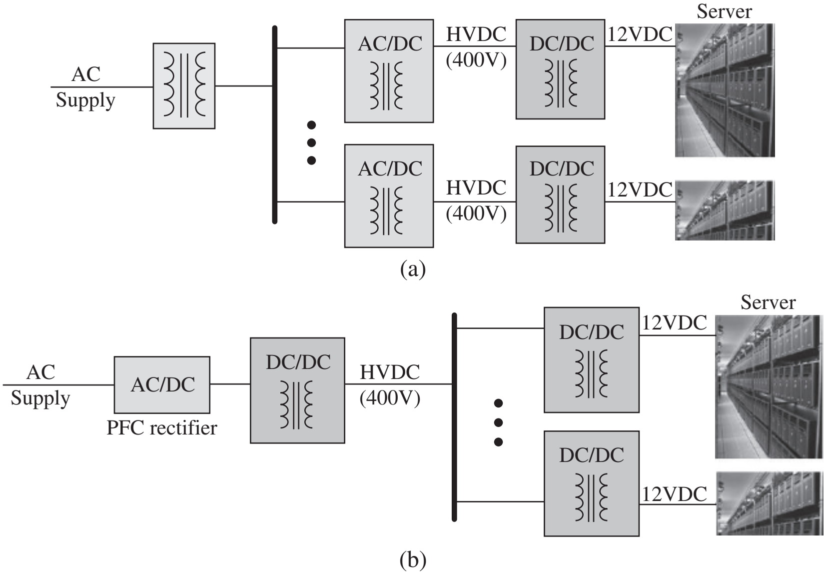

Figure 1.5 Examples of a data center: (a) AC-coupled structure, and (b) DC-coupled structure.

DC-coupled structure they are connected to a common DC bus. Considering the DC voltage requirement for EV batteries, the possibility of integrating renewable energy sources, higher efficiency, and better power quality, DC structures are more promising for charging stations.

Moreover, EV charging stations with level 2 or 3 chargers can easily consume power in the MW level, introducing significant peak power and stress to the station's electrical system (with potentially costly upgrades required). One solution for this is to also include local energy storage to reduce peak power demand. Again, the DC-coupled microgrid solution will ensure less AC/DC voltage conversion is required in such a charging station with battery energy storage.

As mentioned earlier, some standalone microgrids in the sky exist in the form of an MEA with a high-frequency AC bus. In Figure 1.7, an example of an MEA structure is shown. As can be seen, in this AC-coupled hybrid microgrid, the loads and power generators are connected to a common AC bus. The traditional loads such as starter, deicing, etc., are also powered by an electrical system to improve the overall system efficiency. The AC bus is a high-frequency bus with variable frequency

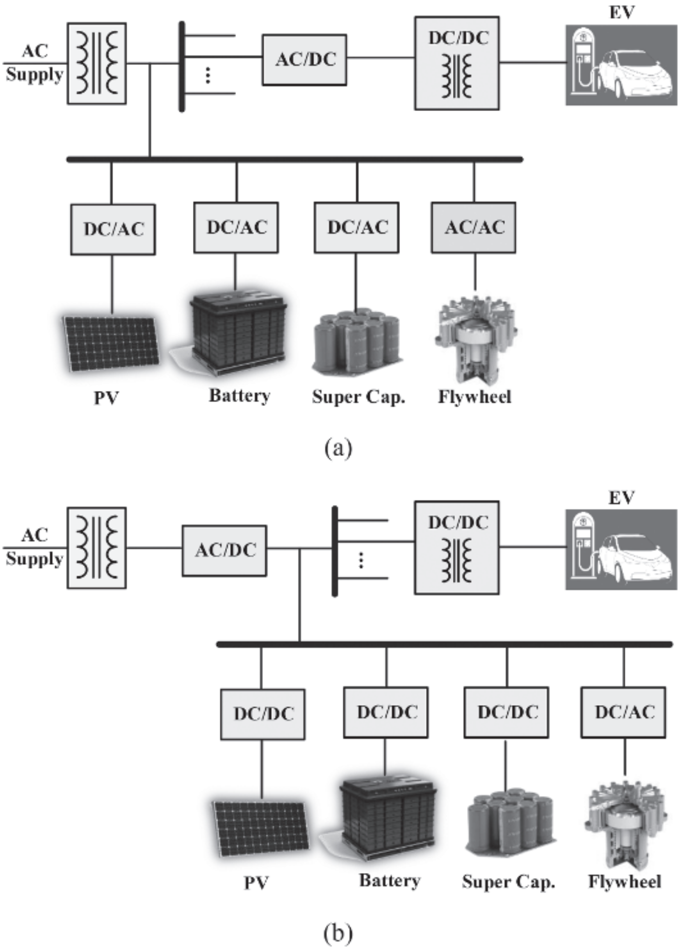

Figure 1.6 Examples of the electric vehicle charging station: (a) AC-coupled structure, and (b) DC-coupled structure.

in the range 350–800 Hz. Compared to the traditional 400 Hz fixed frequency, the variable frequency allows more efficient engine operation.

Similarly, electric ships can be considered as a standalone microgrid in the ocean. In an electric ship, the generators and loads are connected to the medium voltage DC bus on the ship to allow maximum controllability of the generators and loads to optimize the system operation with significant fuel savings.

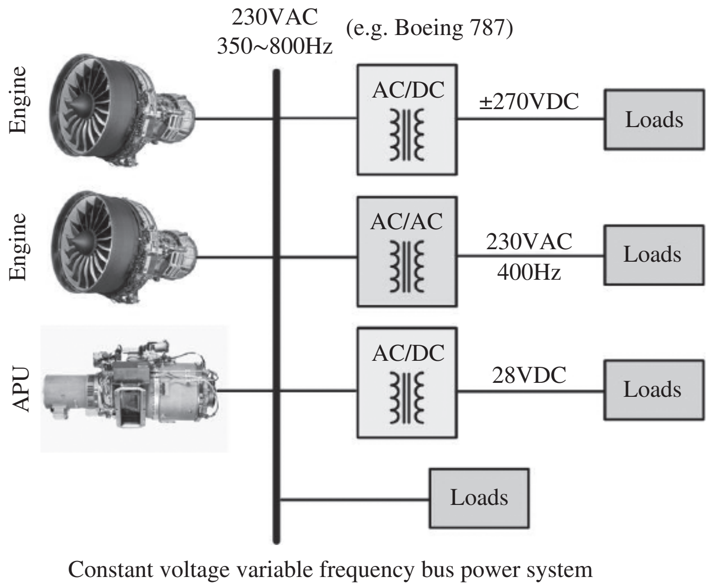

Figure 1.7 The more electric aircraft as a high-frequency AC-coupled microgrid.

1.3 Smart Hybrid Microgrid Operations

Different operation aspects or functions of a smart microgrid are executed at different time scales. For example, the primary control functions of IFCs (i.e. voltage and current controls) must be executed over a very short time (with control bandwidths of hundreds or thousands of hertz), especially when harmonics regulation is needed. The power and power quality management functions are also mostly waveform-based control and need to be implemented with a high control bandwidth. On the other hand, the energy management functions with long-term optimization objectives can be done over a relatively long time scale.

Figure 1.8 shows the basic and smart functions of smart microgrids with their expected time scales. The basic functions mainly focus on individual IFC operations while the smart functions improve smart microgrid stability, reliability, energy efficiency, and power quality. In the following, the key aspects of smart microgrid operation are briefly introduced.

1.3.1 Distributed Generation and Energy Storage Systems

Renewable and non-renewable energy-based DG systems are now widely adopted in microgrids. They can supply loads without long-distance power transmission,

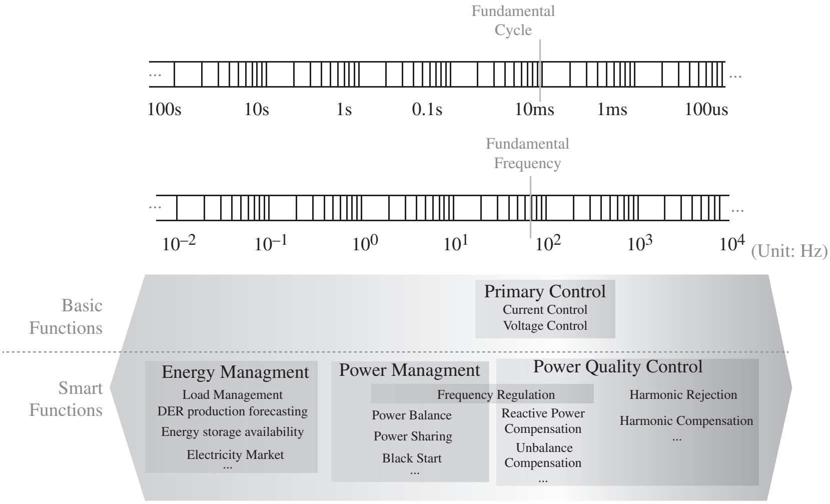

Figure 1.8 Functions of a smart microgrid.

reducing power losses compared to traditional power grids. However, despite the benefits of DG systems, challenges are also raised due to their integration. For example, the power flow within the microgrid is bidirectional, leading to complexity in operation control and system protection. Also, the output powers of DGs are usually not compatible with the grid; thus, appropriate power converters structures with high reliability, efficiency, controllability, and power quality are essential. As another challenge, the intermittence of renewable energy-based DG systems, such as wind or PV power systems, could lead to power fluctuations, power quality issues, or even stability problems, especially in high penetration levels.

Due to the intermittent nature of such renewable energy-based DGs and their low inertia, the load demands and their variations cannot be satisfied at all times, particularly in standalone operation. Therefore, ESSs are required, such as batteries, fuel cells, pumped-hydroelectric, flywheels, and supercapacitors. Some ESSs require proper power converters to be integrated into the microgrid. The ESSs should be appropriately sized to deal with the DG output variations and load demand variations. They should also be placed in a proper location, where different objectives such as improving voltage profile, reducing the system power loss, or reducing the occurrence and levels of abnormal conditions (overloads and over/under voltages) can be targeted. Furthermore, ESSs should be appropriately controlled and coordinated with DG systems to ensure system stability in steady-state and transition operation modes of microgrids.

1.3.2 Smart Interfacing Converters

As mentioned, a key component in a modern microgrid is smart IFCs, which enable flexible power flow control and are the actuators of smart functions. Those IFCs connect renewable/non-renewable energy-based DGs, ESSs, and loads to the AC and DC subgrids of microgrids. The main smart functions of IFCs can be classified into three categories: (i) information-level functions, (ii) microgrid-level functions, and (iii) converter-level functions.

The information-level functions of smart IFCs are mainly focused on data communication through a cyber system. In smart microgrids, physical components, such as IFCs, are usually interconnected to cyber systems, and their operations are coupled to cyber system functionality. Smart IFCs can communicate with control centers and each other either by wireline (such as power line communication and low bandwidth communication) or wireless technologies (such as a ZigBee, WiFi, and cellular communication networks). The data communications of IFCs can help to control microgrid operations in steady-state and transient conditions properly. Also, smart IFCs can be controlled remotely. However, as evident, an efficient, reliable, and timely data flow is required, and any cyber incidents can have devastating effects on the microgrid's operation.

The microgrid-level functions of smart IFCs are used to realize power and energy management system objectives in a microgrid. In general, microgrid energy and power management strategies can be realized in hierarchical control. There are three control layers in hierarchical control: primary, secondary, and tertiary layers. The primary control layer contains voltage and current regulations. The objectives of the second layer include system frequency regulations and power quality compensations such as unbalanced voltage compensation, and harmonic compensation. In tertiary control, an optimization problem is usually run to achieve a global optimum operation point and determine the operating power of each power source. The short-term power management system objectives are realized in the primary and part of the secondary control layers, while the tertiary control and part of the secondary control contain the long-term energy management system.

The converter-level functions are focused on proper power conversion. The IFCs track their reference powers provided by the power management and energy management strategies, using current or voltage controls. In addition, microgrid power quality control using IFCs is also part of the converter-level functions.

1.3.3 Cyber Systems

In general, cyber networks are important for smart microgrids to coordinate, monitor, and manage distributed devices, such as power converters, circuit breakers, and meters. In detail, the cyber system provides sensor information to control units (distributed or central) and transfers the control signals to the physical components such as IFCs and relays. Although smart IFC operation in microgrids is generally autonomous, cyber network presence can improve their control performance. Also, the cyber network is critical for the entire microgrid optimal operations (i.e. energy management scheme) and restoration and black start after faults occurrence.

Since the cyber network operation can impact the physical system performance and functionality, the cyber system's high reliability and security are expected. Malfunctions of cyber systems, such as communication failure or cyber-attacks, could adversely affect the smart microgrids' operation and stability.

1.3.4 Power Management and Energy Management Systems

In microgrids, the terms "energy management" and "power management" are different considering control tasks and time scales. The long-term energy management schemes match the total power production to the demand. The energy management strategies use measured data from sensors and predictions data (e.g. renewable sources prediction) and consider microgrid operational requirements (e.g. appropriate level of power reserve capacity) to optimize the microgrid operation. Generally, the energy management system needs to coordinate the various devices, such as power generators, energy storage, and loads in the microgrid, or even coordinate multiple microgrids.

The objective of the short-term power management system is to control the instantaneous operational conditions toward specific desired parameters such as voltage, current, power, and frequency within a very short time (e.g. a fundamental cycle). In other words, the power management strategies include voltage and frequency regulations, and real-time power dispatching among the microgrid different power sources. The power management strategies should also provide a seamless and smooth transition during microgrids transition between grid-connected and standalone modes (with minimum voltage and frequency disturbances and deviations, and ensure instantaneous power balancing of generation and demand to prevent DGs overloading and circulating powers).

1.3.5 Power Quality

Power quality issues are becoming urgent for future microgrids. They affect the operation of devices in the microgrid, including power converters, protection devices, and loads, while such device malfunctions can lead to further power quality issues. In microgrids, the integration of unbalanced/non-linear loads and unbalanced distributed sources cause the most significant power quality issues. In addition to conventional methods to improve power quality, IFCs from DGs and ESSs can be appropriately controlled to help address such power quality challenges.

In general, the power quality issues in the DC subgrid of hybrid microgrids can be voltage variations and harmonics. On the other hand, voltage variations (frequency deviation and magnitude change), unbalances, and harmonics are major power quality concerns in the AC subgrid. It is also important to note that in hybrid AC/DC microgrids, power quality issues on the AC or DC side can transfer to the other side through the operation of power electronics DC/AC IFCs.

1.4 Outline of the Book

Considering the most pressing technical challenges, this book focuses on the technologies for smart functions of smart hybrid microgrids, including power management, energy management, and power quality control. The book is organized into three parts:

Part 1: Smart Hybrid AC/DC Microgrids

Part 1 of the book includes Chapters 1–3, which introduce smart microgrid fundamentals and background technologies. Specifically:

Chapter 1 presents the concept, histories, and features of microgrids. The configurations of hybrid microgrids and key operation challenges of microgrids are also discussed.

Chapter 2 introduces the basics of renewable-based DGs and energy storage technologies suitable for microgrids. The widely used renewable generation, such as PV and wind power systems, are presented, and their interfacing power electronics converters and control strategies are discussed. Some power converter-based ESSs, including batteries, flywheels, and superconducting magnets, are also discussed, and their coordination with the renewable generators is studied.

Chapter 3 introduces the fundamentals of information and communication networks. The basic concepts, technologies, protocols, and standards of communication systems are comprehensively introduced. The importance of cyber security and the corresponding standards are also discussed in this chapter.

Part 2: Power Management Systems (PMSs) and Energy Management Systems (EMSs)

Part 2 of the book focuses on IFC control, microgrid power management, and energy management. This part includes the following three chapters.

Chapter 4 presents the control scheme for IFCs in a smart microgrid. In this chapter, the popular IFC control structures are reviewed. In addition, some advanced IFC control concepts for smart microgrid applications are presented, including virtual impedance control, droop control, and virtual synchronous generator control.

Chapter 5 presents power management strategies, such as voltage and frequency regulation and real-time power dispatching, for AC-coupled, DC-coupled, and AC/DC coupled microgrids under different operation modes or during operation mode transitions. The black start of the microgrid is also discussed.

In **Chapter 6**, the energy management strategies for a microgrid under hierarchical control are discussed. The applications of artificial intelligence and the multi-agent control for microgrids are presented. Considering the dependence on the communication system, a detailed discussion of cyber security, consisting of types of attacks, consequences, and solutions, is included in this chapter.

Part 3: Power Quality Issues and Control in Smart Hybrid Microgrids

Part 3 of the book addresses the important power quality issues in smart microgrids. Power quality events, such as grid disturbance, voltage harmonics, and unbalance, can be great challenges for the proper operation of microgrids, where smart IFC control can help address those power quality concerns as important auxiliary functions. This part includes four chapters.

In **Chapter 7,** the various power quality issues, such as transients, harmonics, short- and long-term voltage variations, and momentary power supply outages, are overviewed. Existing solutions based on passive filters and the more flexible power electronic compensation devices are reviewed. Finally, hybrid AC/DC microgrid specific power quality issues and challenges, and their compensation strategies are discussed.

Chapter 8 focuses on the control of IFCs during short-term and severe grid disturbances. The microgrid operation under a grid disturbance can be either switched to islanding operation or remain connected for a disturbance ride-through operation according to different grid codes. The islanding detection techniques, ride-through control strategies, and a protection coordination study considering the ride-through control of DG and microgrids are presented

Chapter 9 presents the strategies for smart IFCs to compensate for unbalanced voltages in a microgrid. These strategies utilize the IFC extra power rating to address the voltage unbalance issues without installing dedicated compensation devices. The control schemes discussed in the chapter include three-phase IFCs and single-phase IFCs. Coordinating multiple IFCs to share the unbalance compensation tasks properly is also discussed.

In **Chapter 10**, IFC control schemes to compensate harmonics in microgrids are presented. Moreover, the harmonic control scheme for IFCs with low switching frequency and the compensation of low-order harmonics in the DC subgrid are also discussed. Finally, control strategies to coordinate multiple IFCs to perform harmonic compensation in a hybrid microgrid are presented.

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