Chapter 1
Introduction

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Abstract In this chapter, a brief discussion on renewable energy and distributed power generation is presented followed by a discussion on characteristics of power electronics and requirement of power electronics for these energy sources. Brief summary for each of the following chapters are provided to introduce the readers to rest of this book.

1.1 Introduction

Modern societies require significant energy resources that define the way we live. The food we eat, clothes we wear, buildings we live, appliances we use, and cars we drive require different forms of energy in their production or operation. A common metric that describes economic production performance is the ratio of energy consumption per capita income divided by the energy consumed. Today, there is a 200-fold disparity in income per capita between Great Britain and Ethiopia but the ratio of income to energy consumption between these countries is only 0.30–0.32. The fact that the two ratios are nearly identical, suggests that

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increased standards of living will require increased energy in order to maintain such a ratio. Over the past 200 years, developed countries consumed more energy per capita than all the other previous societies throughout the history. Since fossil-fuel resources are limited, a drive toward more energy sustainability leads to renewable energy-based power generation. The costs of renewable resources such as solar, and wind have decreased in recent years due to technology and material production advances. Different forms of renewable energy are available in every country across the globe. For the developed world, a new paradigm of distributed power generation that is less dependent on fossil-fuel resources must be developed, in order to maintain the standard of living and sustainable growth. Developing countries growth and prosperity should increase as they begin to access to electric power through locally occurring natural energy sources providing them a new way of life through energy solutions that are sustainable.

The technology of power electronics is fundamental for renewable energy systems. Many renewable resources are intermittent and, without power electronics, we could not regulate voltage, frequency, and power output characteristics. Depending on the available renewable sources, DC–AC inverters, AC–DC rectifiers, and DC–DC converters are required. A rectifier might be a frontend for an electric grid connected to a load or an inverter can be the interface with local generation. There are other converters for intermediate stages, necessary for adapting the energy produced by the source in such a way that both the energy source and the power conversion operate at their highest efficiencies. Rotating machines are typically used to produce power from sources such as hydro and wind; and storage systems can be used to compensate for intermittency. Resources such as sunlight, hydrogen, and sometimes natural gas require DC–DC conversion, followed by the DC–AC inverter to integrate to the AC grid. In the past 20 years, new energy storage technologies such as ultracapacitors and electrochemical storage have been developed. The output of these devices tends to be DC. A Power electronic converter is needed to convert the power from DC to AC during discharge and AC back to DC during energy storage charging. Energy storage systems can be used to help regulate intermittent renewable energy systems by providing power when the output power is low or by absorbing power when excess power is available.

Power converters for renewable energy integration present a higher complexity when compared with those used in industrial or stand-alone systems because they have to efficiently manage power flow and stay synchronized with the grid. Power electronics for renewable and alternative energy systems require the following attributes:

- High efficiency: A negligible part of the power should be lost during conversion. This requirement is affected by input and output energy fluctuations and by conversion efficiency, changing with the quantity of energy at input/output terminals. The converter has to operate in continuous tracking of the input/output quantities and a subsequent real-time adjustment of the converter operation ensuring the highest energy transfer. This requires two or more power conversion stages (typically AC–DC and/or DC–DC and/or DC–AC).

- Optimal energy transfer: All renewable sources are energy constrained and as such, they need control algorithms to achieve a maximum power point operation. For example, PV arrays must be interconnected with maximum power point tracking (MPPT) in order to optimize their energy transfer.
- Bidirectional power flow: In some cases, the power converter has to be able to supply either the local load and/or the grid.
- High reliability: The continuity of service is a major issue when delivering energy.
- Synchronization capabilities: All power sources connected with the grid have to be fully synchronized and operate in a safe manner thus ensuring high efficiency and reliability, plus conforming to electrical requirements such as the IEEE 1547 interconnection standard for utility grid applications.
- Electromagnetic interference (EMI) filtering: The quality of the energy injected on the grid must respect electromagnetic compatibility (EMC) standards.
- Smart metering: The converter between the local source/load and the grid must be capable of tracking the energy consumed by load or injected on the grid. Real-time information can be passed to an automatic billing system capable of taking into account parameters as the buy/sell energy in real time at the best economic conditions and informing the owner of the installation of all required pricing parameter decisions.
- Communication: Intelligent functioning of power electronics depends on their capability to support communications at the same time that power flows in the systems. Such functions are fundamental for overall system optimization and for implementing sophisticated dispatching strategies.
- Fault tolerance: A key issue for a modern grid is the built-in ability of avoiding propagation of failures among the nodes and to recover from local failures. This capability should be managed by the power converter, which should incorporate monitoring, communication systems, and reconfiguration systems.
- Additional functions capable of making the interface user-friendly and accessible anywhere through Internet-based communications.

Different aspects of these attributes are covered in the 14 chapters written by well-known educators, engineers, and scientists who have developed products and prototypes in their respective areas of expertise and with a focus on renewable and distributed energy applications. The book provides background knowledge for the reader to understand how to enable efficient interconnection and economical operation of dispersed installations to the utility grid. Achieving one of the tenets of the smart grid initiative—enabling active participation of consumers in the demand response using timely information and control options.

Chapter 2 gives a description and overview of power electronic technologies including a description of the fundamental systems that are the building blocks of power electronic systems. Technologies that are described include: power semiconductor switching devices, converter circuits that process energy from one DC level to another DC level, converters that produce variable frequency from DC sources, principles of rectifying AC input voltage in uncontrolled DC output voltage and their extension to controlled rectifiers, converters that convert to AC from DC (inverters) or from AC with fixed, or variable output frequency (AC controllers, DC–DC–AC converters, matrix converters, or cycloconverters). The chapter also covers pulse width modulation control techniques in detail.

Chapter 3 discusses photovoltaic systems and describes how semiconductor devices can directly convert solar energy into direct current. PV cell technology is explained and a description of how, incident light spectrum, panel tilt, cell temperature, panel design, surface deposits, shadows, and materials on the solar cell can influence performance. In order to have modules or arrays for higher voltage or current, the cells must be associated, and control algorithms must be implemented in order to make the system operate with high efficiency. Descriptions of power electronics, digital controls, sun tracking, and remote monitoring are provided as the basis for the modern PV energy systems.

Chapter 4 presents wind energy systems, with coverage on the basic energy conversion from wind, wind turbines, and their aerodynamic and control issues. The chapter continues with a discussion on how wind energy systems can be isolated or grid-connected and the difference between onshore and offshore applications. Specific power electronics for wind turbine applications include: partially rated power electronics, full scale power electronics, FACTS, and advanced topologies. The chapter concludes in how wind turbines can be controlled and integrated.

Chapter 5 gives examples and applications of small hydropower systems. A small hydropower can be used as stand-alone cost-effective solution to provide remote power or enhance grid connected power systems. This chapter provides a discussion of basic principles of hydropower resources, how to find the best places to site hydropower in rivers. Power turbine system technologies that can be used for small-hydro applications are also discussed. Systems such as fixed-speed with induction generator, variable-speed with a cage-bar induction generator or synchronous generator, variable-speed with a multiple-pole synchronous generator or multiple-pole permanent magnet synchronous generator; and variable-speed with a doubly-fed induction generator are described.

Chapter 6 introduces fuel cell systems and their associated power electronic converter topologies. The introduction includes a description of different fuel cell technologies and the physics behind the characteristic polarization curve and dynamic behavior. Two models for control applications are discussed, one for a proton exchange membrane fuel cell (PEMFC) and another for the solid oxide fuel cell (SOFC) with detailed equations. The chapter presents specific power converter topologies used for fuel cell systems highlighting their advantages and drawbacks.

Chapter 7 explains how variable (adjustable) speed generation systems provide reduction of fuel consumption and improve electrical power generation systems. Two basic topologies are presented; one is based on the application of permanent magnet generator and another one on slip-ring induction machines. A description of how power is controlled from engine driven generators is described. A variable-speed power generation with the slip-ring induction machine system is introduced that utilizes a control method based on space vector theory. In the chapter, discussions were provided showing how the reference stator voltage vector, rotor current amplitude, frequency, and phase are controlled to provide a stable sinusoidal three-phase stator voltage.

Chapter 8 provides the basics of micro turbines operation and integration techniques. Microturbines are a relatively new technology for generation of electric power, and are commercially available in ratings from 30 kW up to 1 MW or more. This chapter describes how microturbines perform, and how they differ from other more traditional forms of electric power generation. Emphasis is placed on the power electronics and control features of typical microturbines.

Chapter 9 provides a discussion on the various technical components that are used for battery energy storage systems for utility-scale energy storage and how these technical components are interrelated. A basic description of how battery energy storage systems work is provided with several examples to illustrate how battery energy storage can be used in large-scale applications. An overview of how the storage system's power electronics work is given in the chapter followed by a more detailed description of possible power electronic topologies and power electronic controls that are used to ensure that the system can be properly integrated with the generation source and, if necessary, the load. Battery management and monitoring through the power electronic controls are discussed and a detailed example of battery energy storage system integration is provided.

Chapter 10 introduces the concept of fast response energy storage systems that have the ability to provide or to absorb a high amount of electrical energy in a short period of time without diminishing the lifetime of the storage device. Major technologies discussed in this chapter are: electric double layer capacitors (EDLC) that store energy in the electrical field of a capacitor; Flywheels that utilize kinetic energy, and superconducting magnets (SME) where energy is kept in the magnetic field of a lossless inductor. Fast storage technologies show promise to allow increasing penetration of renewable energy sources and support Smart Grid. In this chapter, the power converters that are used to manage power delivered and stored for these fast response energy storage systems are provided along with descriptions of how to integrate these technologies for renewable energy system applications.

Chapter 11 covers application of modular power electronics for renewable and distributed energy applications. The chapter starts with basics of modular power electronics such as power electronics building block (PEBB) and integrated power electronics module (IPEM). A description of common power electronics topologies for different renewable and distributed energy applications are given showing that generalized power electronic topologies can be formalized to design building block modular power electronics interfaces. The chapter concludes by giving examples suggesting that such modular power electronics can eventually improve the overall life-cycle cost and reliability for renewable and distributed energy systems.

Chapter 12 provides a fundamental description of microgrids. The current and future capability of microgrids for aggregating multiple resources is described. Concepts such as plug-and-play technologies need to be developed to accommodate the addition or removal of different sources and loads without a need to develop complex interconnection, load flow, and dispatch studies. Dynamic microgrid interactions between different aggregated resources and their power electronic controllers are discussed.

Chapter 13 focuses on the role that power electronics will have in future smart-grids. The operation of future electricity grids will be multi-disciplinary in nature with merging of energy and communication infrastructures, and interaction of state-of-the-art technologies such as power electronics, computational intelligence, signal processing, or smart metering. The chapter provides good background information of emerging distribution systems, evolutionary changes, and enabling the technologies that will be needed. Power electronic-based interface systems with smart topologies and controls are explained. Three examples of smart interface control systems are described including smart inverters, smart power router, and the concept of the virtual synchronous generator.

Chapter 14 explains practical issues for commercialization of current and future plug-in hybrid electric vehicles and focuses primarily on power electronics-based solutions for both current as well as future electric vehicle technologies. New plug-in hybrid vehicle power system architectures are discussed in detail together with key battery technologies that are used for transportation applications. Advanced power electronics battery management techniques and charging infrastructures for electric vehicles and plug-in hybrid electric vehicles are also described in this chapter.

Chapter 15 introduces a new distributed control paradigm for power system control, called multi-agent systems (MAS). The development of advanced communication infrastructures can provide power electronics interfaces with the ability to control complex power systems in efficient and scalable ways and in real-time. Multi-agent systems (MAS) are based on distributing information and computing algorithms for complex networks, and are an excellent technological solution for power electronics applications. This chapter focuses on applications of MAS in power systems and provides applications how MAS can be used with other artificial intelligence techniques in order to make the grid smarter and more flexible.