Integration of Green and Renewable Energy in Electric Power Systems

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INTEGRATION OF GREEN AND RENEWABLE ENERGY IN ELECTRIC POWER SYSTEMS

Ali Keyhani dedicates this book to his father:
Dr. Mohammed Hossein Keyhani

PREFACE

During the past 20 years, Ali Keyhani's research was supported by the National Science Foundation.* This book was conceived based on the work supported by these grants. The authors recognized the need for a book where the three areas of electrical engineering—power system engineering, control systems engineering, and power electronics—must be integrated to address the integration of a green and renewable energy system into electric power systems. The approach to integration of these three areas differs from classical methods. Due to complexity of this task, the authors decided to present the basic concepts and then present a simulation testbed in MATLAB to use these concepts to solve a basic problem in integration of green energy in electric power systems in the form of a project. Therefore, each chapter has three parts: First a problem of integration is stated and its importance is described. Then, the mathematical model of the same problem is formulated. Next, the solution steps are outlined. This step is followed by developing a MATLAB simulation testbed for the same problem. Finally, the results of the project are presented; where applicable, the experimental results are also presented. The book can be used as a textbook for instruction or by researchers. Since every chapter presents a project, an instructor can use these projects with some changes in parameters or control objectives as learning exercises for students. It is suggested that this book be used as an undergraduate and graduate course for students who had some background in power systems, power electronics, and control engineering. However, since the projects of this book are goal-oriented, instructors

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can use the book as an interdisciplinary graduate course for electrical and mechanical engineers if the book is supplemented by supporting concepts that students may need.

The book focus is on control of power converters, and we present how the inverters can be controlled to act as steam units and to provide active and reactive power. We will also present the fundamental architectures in design of smart grid distributed generation. In Chapter 1, the two fundamental architectures, namely DC architecture and AC architecture for integration of smart grid distributed generation, are presented. In Chapter 2, we present the inverter control voltage and current in distributed generation systems; in Chapter 3, parallel operation of inverters in distributed generation systems; in Chapter 4, power converter topology for distributed generation systems; in Chapter 5, voltage and current control of a three-phase four-wire distributed generation in island mode; in Chapter 6, power flow control of a single distributed generating unit, in Chapter 7, robust stability analysis of voltage and current control for distributed generation systems; in Chapter 8, PWM rectifier control for three-phase distributed generation system; and in Chapter 9, MATLAB Simulink simulation testbed. In this book, these coordinated control techniques will be presented using a MATLAB Simulink simulation testbed. Throughout the book, we will provide the simulation testbeds used for each chapter in Chapter 9. The instructors can use each chapter to study mathematical modeling with its supporting MATLAB testbed, as well as to provide for students with control projects.

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During the past 20 years, Ali Keyhani's research was supported by the National Science Foundation.* This book was conceived based on the work supported by these grants. This book is the application of body of theoretical work of Davison and Ferguson on multivariable robust servomechanism problem (RSP), Francis and Wonham's work on the internal model principle for linear multivariable regulators, and Utkin's work on the sliding mode control technology. Over the years, many graduate and undergraduate students at the Ohio State University have also contributed to the material presented in this book. In particular, Ali Keyhani would like to acknowledge the contribution of the following people: Professor Charles A. Klein, the Associate Chair and Professor H.C. Ko, past Chairman of electrical and computer engineering at the Ohio State University for his support and guidance. The author also wishes to acknowledge the contribution of Mr. Peter Panfil, VP vice president and general manager of Liebert AC Power, Emerson Network Power for many years of collaborative efforts on problem fourmulation and direction of research for control of power converters and his support of the Ohio State University Mechatronics-Green Energy Laboratory and Mr. Jon L. VanDonkelaar, VP New Product Development, Edison Materials Technology Center, for many of collaborative work on many topics for this book. Finally, the authors would like to acknowledge the support of their family.

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CONTENTS

CHAPTER 1

SMART GRID DISTRIBUTED GENERATION SYSTEMS

1.1 INTRODUCTION

Energy technologies have a central role in social and economic development at all scales, from household and community to regional, national, and international. Among its welfare effects, energy is closely linked to environmental pollution and degradation, economic development, and quality of living. Today, we are mostly dependent on nonrenewable fossil fuels that have been and will continue to be a major cause of pollution and climate change. Because of these problems and our dwindling supply of petroleum, finding sustainable alternatives is becoming increasingly urgent. Perhaps the greatest challenge in realizing a sustainable future is to develop technology for integration and control of renewable energy sources in smart grid distributed generation.

The smart power grid distributed energy system would provide the platform for the use of renewable sources and adequate emergency power for major metropolitan load centers and would safeguard in preventing the complete blackout of the interconnected power systems due to man-made events and environmental calamity and would provide the ability to break up the interconnected power systems into the cluster smaller regions.

The basic purpose of this book is to introduce the integration and control of renewable energy in electric power systems. Models are important in control of systems because they present the dynamic process of underlying systems. We will present models of green energy systems. These models will be used to develop

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control methods to control the dynamic process of models to accomplish the control objectives.

We present distributed generation (DG) architectures, and then we present the control of converter for utilizing renewable energy sources, such as wind power, solar power, fuel cell (FC) plants, high-speed micro-turbine generator (MTG) plants, and storage devices as local energy sources. This book emphasizes control technology for controlling power converters to supply the loads and to regulate voltage, frequency, and power oscillations. The control technology for the robust global stabilization, tracking, and disturbance attenuation algorithm that are applicable to distributed energy systems will be presented. As part of this objective, we present a MATLAB/Simulink simulation testbed for presenting the control technology. We will use the time learning approach by introducing the building blocks for analysis and modeling, and then we will present the control technology. We will also present the control methodology to study parallel operation of multiple DG units in low-voltage distribution systems and to mitigate circulating power, the effects of nonlinear loads such as power pre-regulated power-factor-corrected (PFC) loads, voltage and power oscillation due to sudden drop of loads, startup, and loss of local utility. Furthermore, this book will open new vistas for simulation studies and experimental work to address the critical need of industry in expanding the knowledge base in green energy systems, power electronics, and control technology.

Figures 1.1 and 1.2 depict the direct current (DC) architecture and alternating current (AC) architecture of green and renewable power grid DG systems consisting of FC plant, wind turbine, solar arrays, high-speed MTG, and storage systems. The FC and solar power outputs are low-voltage DC that are steps up to a higher-level DC power for processing using DC/DC converters. However, the output power of wind turbines is variable-frequency AC power, and the output power of MTG is high-frequency AC power. For these two sources, the AC/DC or AC/AC converters are used.

In the architecture of Fig. 1.1, the DG sources are connected to a uniform DC bus voltage including the storage system. This will facilitate plug-and-play capability by being able to store the DC power and use DC/AC converters to generate AC power. Today, commercially available storage devices such as flow batteries and battery–flywheel systems can deliver 700 kW for 5 sec to 2 MW for 5 min or 1 MW for up to 30 min, while 28-cell ultra-capacitors can provide up to 12.5 kW for a few seconds. The DG sources of the low-voltage distribution system of Figure 1.3, designated as DGS, is representing a power-generating station that may contain one or all DG sources of Figs. 1.1 and 1.2. These DG units are connected in parallel. The DG system can be operated as an island system or in parallel with the local utility network. In islanding operation the DG system uses the local utility as backup power. First, depending on the availability of the renewable energy sources, the renewable is used to support all or part of the base load, and the remaining DG sources are used to regulate the system voltage and power. However, the island distribution network and its DG sources not only need to be designed to support its own daily load cycle, but also need to be designed with an assumed reliability criterion such as the loss of the largest DG unit. That is, upon occurrence of a large disturbance, the storage devices in conjunction with regulating units are to control

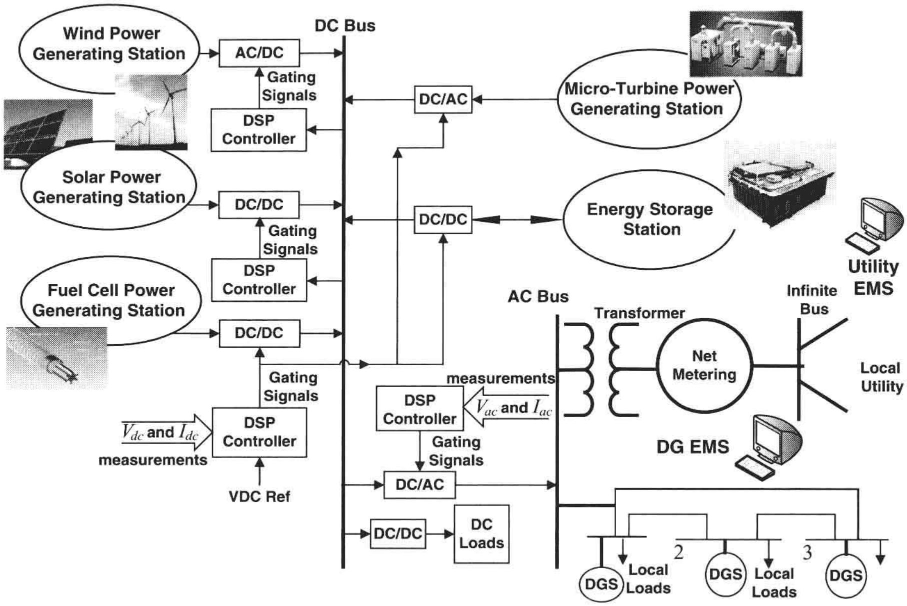

FIGURE 1.1 The DC architecture of green and renewable power grid distributed generation systems.

and to stabilize the low voltage and power oscillations. In the island mode, the stabilization can be achieved using local frequency droop and providing DC power to the DC bus by controlling DC bus voltage and current and charging the storage devices (e.g., battery, flywheel, etc.) as soon as the disturbance is controlled.. To better understand this problem, studying the mix of DG sources with respect to the loss of the largest DG unit in the island network is essential. The proper mix of DG regulating units such as MTG plant (on the order of fraction of seconds), FC plant (on the order of minutes), and storage devices (instantaneously) can be designed to control and to provide their proportional share of power to maintain frequency load regulation and voltage stability. Furthermore, as a last resort, the demand side load management should be used to stabilize the system. However, the system needs to be designed to be sectionalized by switching part of its load to the local utility and continuing to operate as an island with its remaining loads. Another important issue that needs to be investigated is the effects of nonlinear loads that have been increasing their penetration in electric power systems. Today, most loads in hospitals (MRI, CAT scan, etc.) and communication systems (digital signal processing DSP and microcontroller) are pre-regulated PFC. There are many reasons for the PFC technology: (a) The input current waveform is sinusoidal, and hence the injection of current harmonics to the line is very low during the steady state operation. (b) Since the power factor in these types of loads is almost unity, the converters operate at minimum possible operating temperatures. (c) All manufacturers of power converter systems, namely DC power supplies and electric drives, are required to comply with

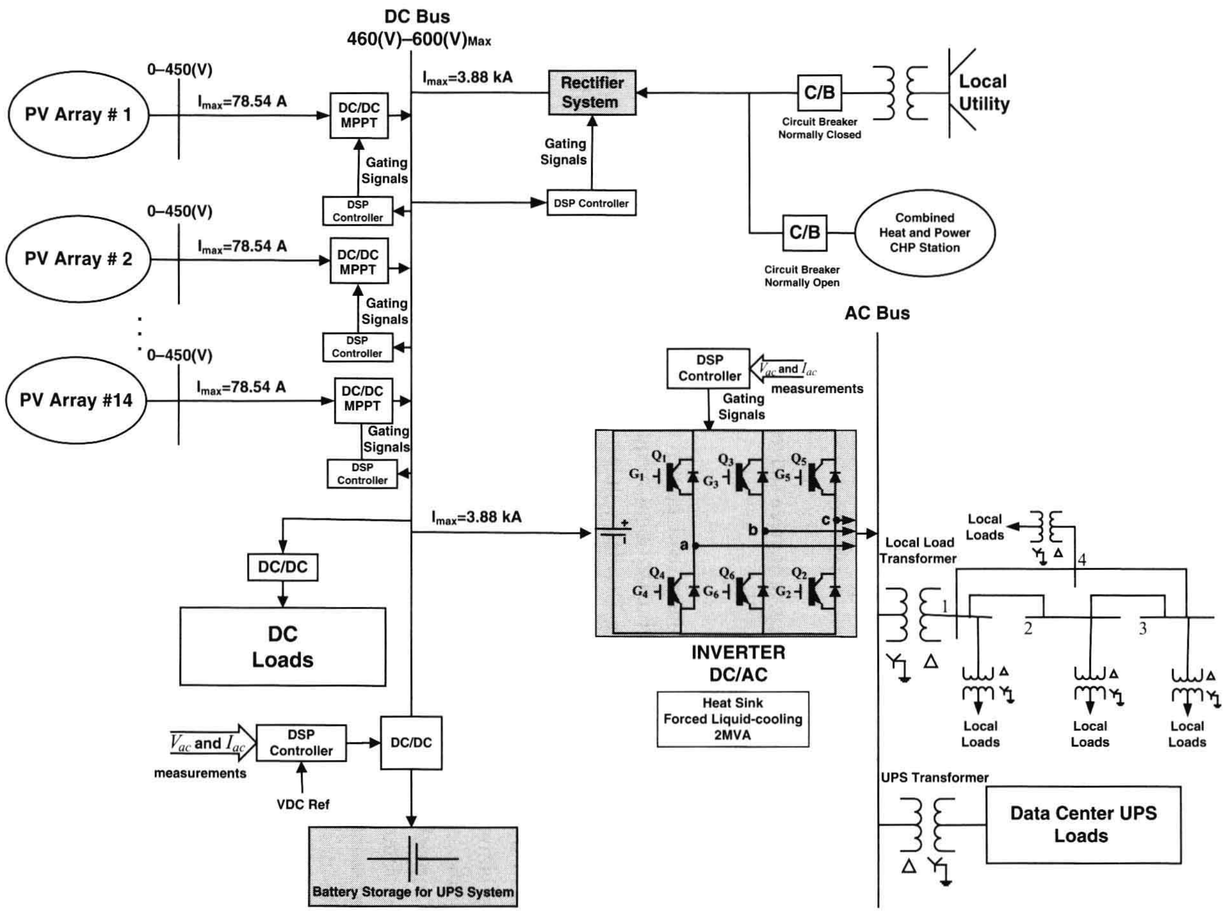

FIGURE 1.2 The DC architecture of a 2-MVA PV station.

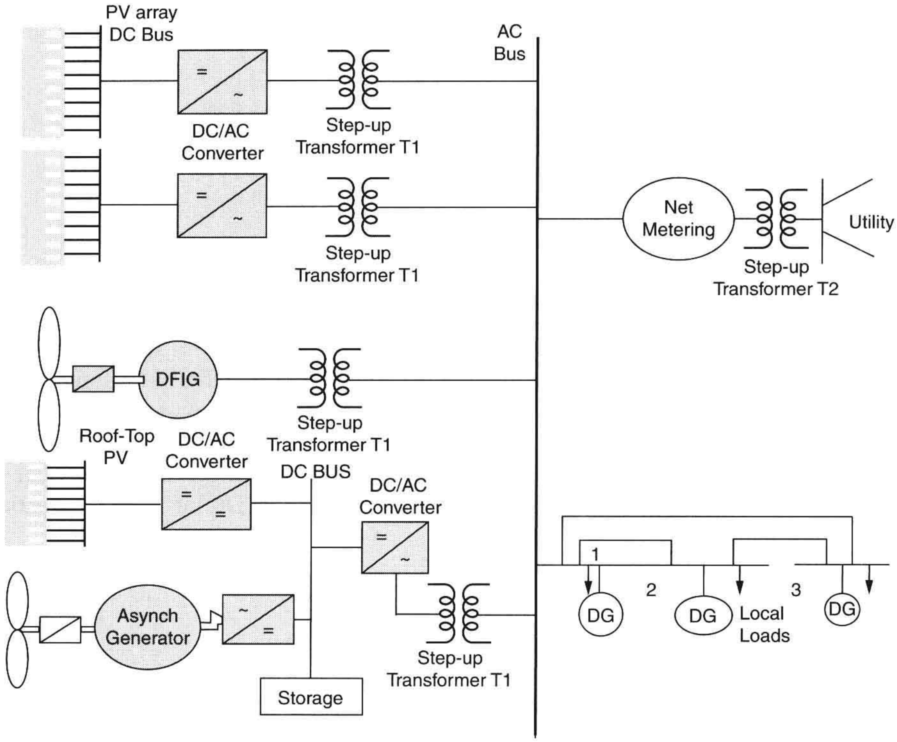

FIGURE 1.3 The Architecture for design of a 2-MVA PV station.

international regulations such as IEC 61000-3-2 and IEEE 519. However, during transient operation or when the power supply system is subjected to a disturbance, such as a drop of loads or the addition of loads or temporary faults, the PFC-type loads would not act as pure resistive loads as they do in their steady-state operations. In fact, these types of loads are highly nonlinear and may act as capacitive and/or inductive loads during disturbances. This type of oscillation has been characterized as bifurcation. The stability study of DGS when they are supplying PFC loads is essential to ensure proper dynamic operation. In-parallel operation with the local utility network creates an important safety issue that needs to be addressed. IEEE standard 1547 spells out DG operation requirements considering the safety issues. However, challenges remain to be addressed in a sudden loss of the utility network.

1.2 DC ARCHITECTURE FOR DESIGN OF A 2-MVA PV STATION

A 2-MVA PV station consists of PV arrays connected in parallel to provide a 2-MVA power output. Each array consists of certain number of PV panels wired in parallel. Therefore the voltage of the PV panel will determine the voltage of each PV array.

TABLE 1.1 Electrical Characteristics of Schott ASE-300-DGF PV Modules

Rated power (P_{max})	300 W
Open circuit voltage (V_{oc})	63.2 V
Maximum power voltage (V_{mp})	50.6 V
Short-circuit current (I_{sc})	6.5 A
Maximum power current (I_{mp})	5.9 A

Source: Affordable Solar website.

A photovoltaic panel is constructed from a number of PV modules wired in series. These modules have certain current–voltage characteristics. Table 1.1 summarizes the electrical characteristics of the discussed PV modules used in this example.

The PV station consists of a DC bus that is connected to the constructed PV arrays. Each array is connected to a DC/DC converter (boost converter) to boost the voltage level to 460 V and a max of 600 V, which is the voltage of the DC bus. The schematic of this PV station is shown in Fig. 1.2.

1.3 PV MODULES

The DC bus voltage is required to be 460 V; however, it can go up to the maximum value of 600 V. According to this requirement, the designed PV array will have a voltage output of 455 V DC at the maximum power rating. Therefore as discussed before, a boost converter will boost the output voltage of the modules to 460–600 V.

The design is based on the ASE ratings and PV array requirements. These ratings are illustrated in Table 1.2. According to the ratings in the table, each PV panel is constructed of 9 “300 DG/50” modules in series. Therefore the output voltage and

TABLE 1.2 ASE Ratings for PV Arrays

Parameter	ASE
Number of arrays	26
Module type	300 DG/50
Modules per array	450
Modules per string	9
Strings per row	2
Power per string STC	2700 W
Design string VOC	595 V
String operating DC	380–430 V
Design array power STC	135 kW
Module failure rate 2004	0.009%

power of each PV panel will be as follows:

$$P_{max} = 300 \times 9 = 2700 \text{ W},$$
$$V_{max} = 50 \times 9 = 450 \text{ V},$$
$$I_{max} = 5.9 \times 9 = 53.1 \text{ A}.$$

Also, each PV array consists of 450 modules; therefore a total of 50 panels should be connected in parallel to construct an array based on ASE ratings. Therefore, the power rating of each PV array will be as follows:

$$P_{max}(\text{Array}) = 135 \text{ (kW)}.$$

The total required power of the PV station is 2 MVA. Based on this requirement, the number of the PV arrays is found.

$$\frac{2000 \text{ kW}}{135 \text{ kW}} \cong 14 \qquad \text{Number of designed PV arrays required for a 2-MVA station.}$$

Each array is connected to a DC/DC converter to boost the voltage level to the maximum.

Therefore, the maximum current under these conditions is

$$I_{max} = 14 \times 5.61 \times 50 = 3.93 \text{ kA}.$$

If we use a boost converter to increase the current, the maximum current out of the converter is found by the energy balance:

$$P_{out} = P_{in} \rightarrow 3.93 \text{ kA} \times 455 = I_{max_{cnv}} \times 460 \rightarrow I_{max_{cnv}} = 3.88 \text{ kA}.$$

According to this calculation, the cable connecting the DC bus to the rest of the system should be rated for a maximum load current of 3.88 kA. Carrying this current at 460 V DC from a PV field to a DC/AC inverter for processing and injection to the utility will result in high power losses. In the process of reducing losses, the DC voltage can be stepped up to higher voltage. This will reduce the power losses but will add to the cost. In addition, the protection of DC system will be a challenge that needs to be resolved.

The results are summarized in Table 1.3.

TABLE 1.3 Number of Modules, Panels, and Arrays in the 2-MVA PV Station Along with ASE

	Number	I_{max} (A)	P_{max} (W)	V_{max} (V)
PV module	6300	5.61	300 W	50
PV panel	700	5.61	2700 W	450
PV array	14	78.54	135 kW	450