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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Integration of Green and Renewable Energy in Electric Power Systems. By A. Keyhani, M. N. Marwali, and M. Dai

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

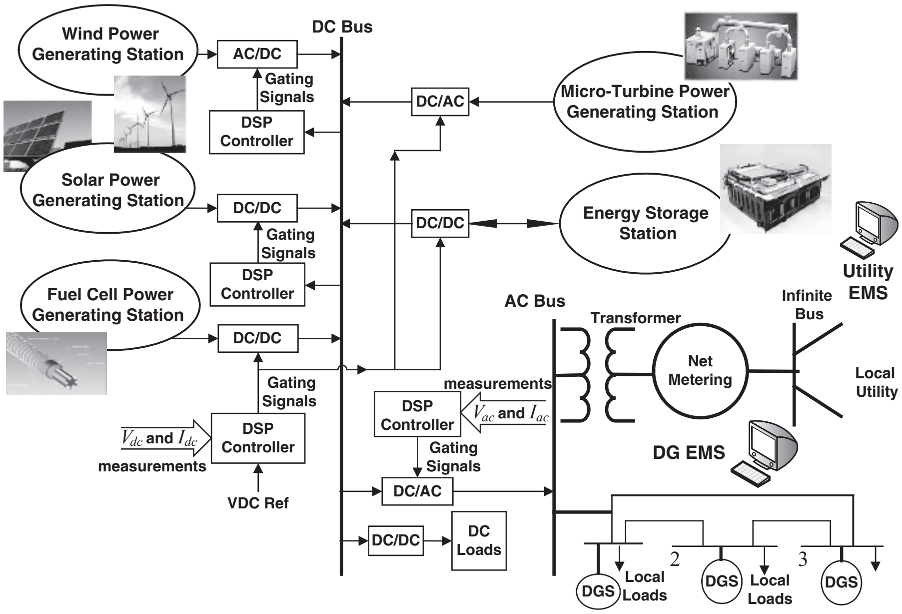

FIGURE 1.1 The DC architecture of green and renewable power grid distributed generation systems.

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

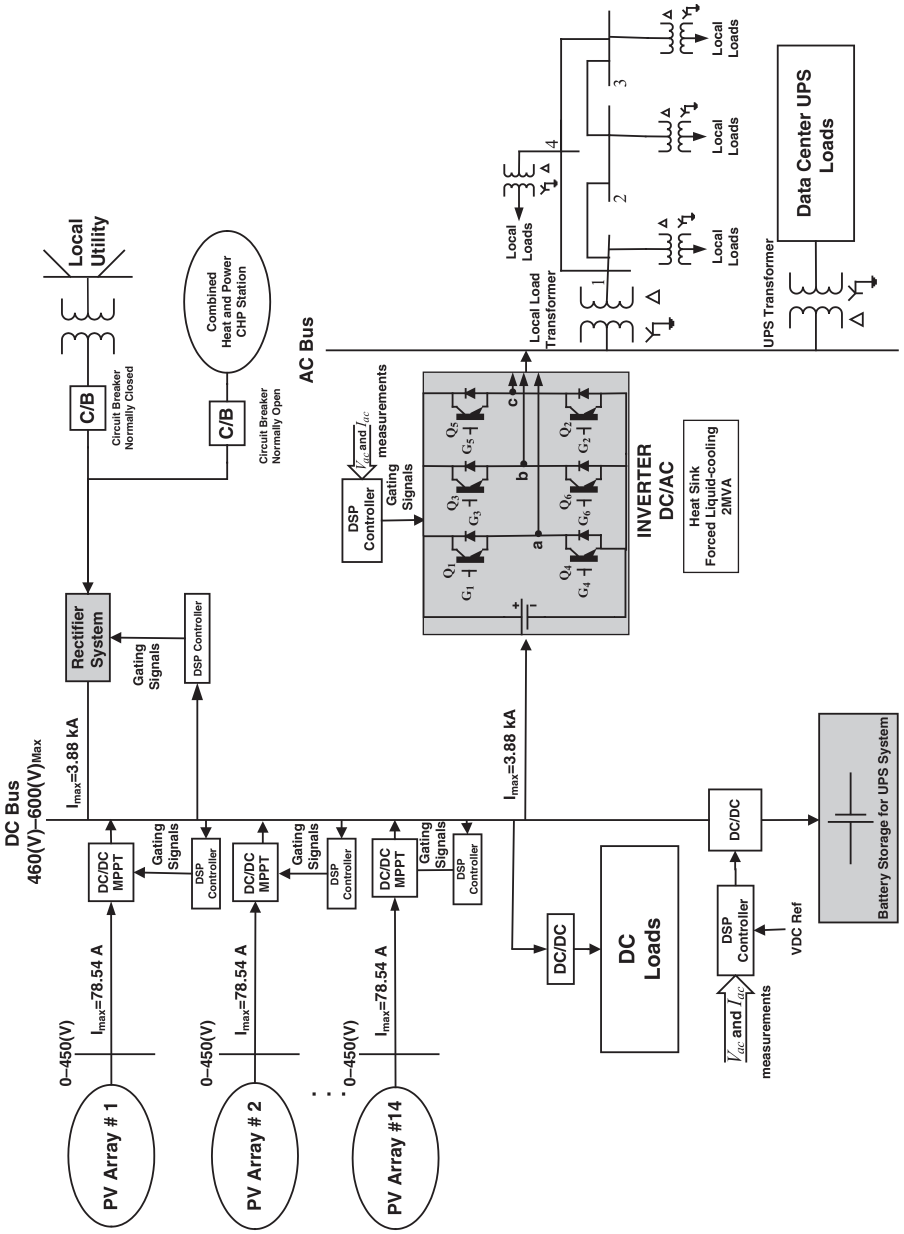

FIGURE 1.2 The DC architecture of a 2-MVA PV station.

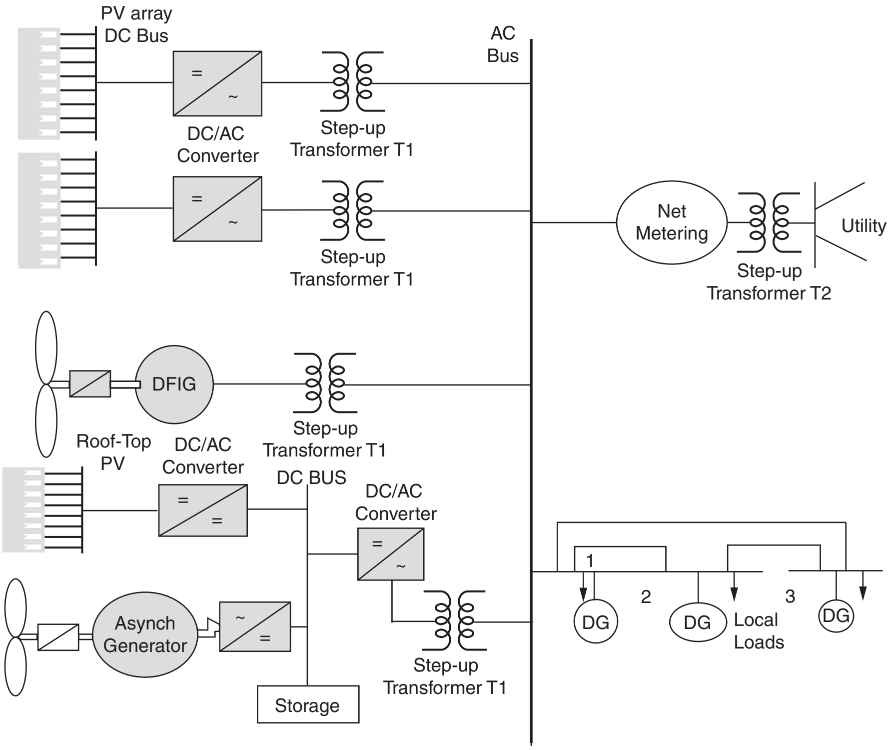

FIGURE 1.3 The Architecture for design of a 2-MVA PV station.

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:

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

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:

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

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

1.4 ARCHITECTURE FOR DESIGN OF A 2-MVA PV STATION

Figure 1.3 represented an AC architecture of DG system. For example, a PV system with 2-MW capacity cannot be economical processed at low-voltage DC due to high power losses. The DC system can be used if the DC converters are used to step up the DC voltage of PV system to higher voltages to reduce the power losses. However, today, it is more economical to step up AC voltage to higher voltages for injection to utility system. As shown in Fig. 1.3, the step-up transformer T1 will step up the voltage from the DC/AC converter to a higher voltage. All PV arrays are connected in parallel to the PV system AC bus. In addition, to provide regulating capability for the PV station, a number of PV arrays and wind power energy are processed in DC and the energy is stored in a flow battery or battery–flywheel system. The DC power of storage system is used for regulating the load voltage and load frequency control. The size of the storage system is specified by the regulating requirements of the PV station when it has to operate as an island. The PV station voltage is stepped up with the transformer T2 for parallel operation of the PV station as part of the utility system.

Disturbance due to sudden outage of utility system can cause severe power system stability of the DG system. Furthermore, upon occurrence of faults, the FC and MTG plants fault current could reach a high level, and hence they must be disconnected. Also, after the FC unit is reconnected, the MTG unit may experience instability. Therefore, appropriate control actions need to be taken to stabilize the DG system.

Because of the intermittent nature of renewable energy sources and the slow electrochemical reaction of fuel cells, the need for energy storage devices is inevitable. The energy storage devices will provide operating reserve as fast-acting energy sources when sufficient power can not be provided during load transients and disturbances. Figure 1.4 depicts operation of multiple DG systems connected in parallel in a local network, with the local network connected to the local utility system.

To elaborate on the control methodology, it is essential to recognize that the DG sources, energy storage devices, and the low-voltage network that serve the loads represent multiple entities with conflicting interests. The DG sources are constrained by their dynamic response to disturbances, whether natural or man-made. Upon a major disturbance, the dynamic energy demand may exceed the stored DC bus power reserves, resulting in severe power and voltage oscillation and collapse. Since the loads are mostly power electronics and industrial, their stability margins are relatively close to their stable operating point. Thus, only a finite amount of stored energy in the DC bus (see Fig. 1.1) is available in the DG system. In-depth attention has been given to the needs for storage devices. This problem can be addressed by studying the relationship between energy storage system reserve, demand side management, and the dynamic response of the mix of DG sources in maintaining the DG system stability. MTG plants are fairly fast, and their time responses can change in a fairly wide range. For high-speed MTG the rotor mass is very small; however, since speed is very high, the H constant is in the range of 0.3–1.2; However, there might be other H values out of this range as well. For medium- and low-speed MTG

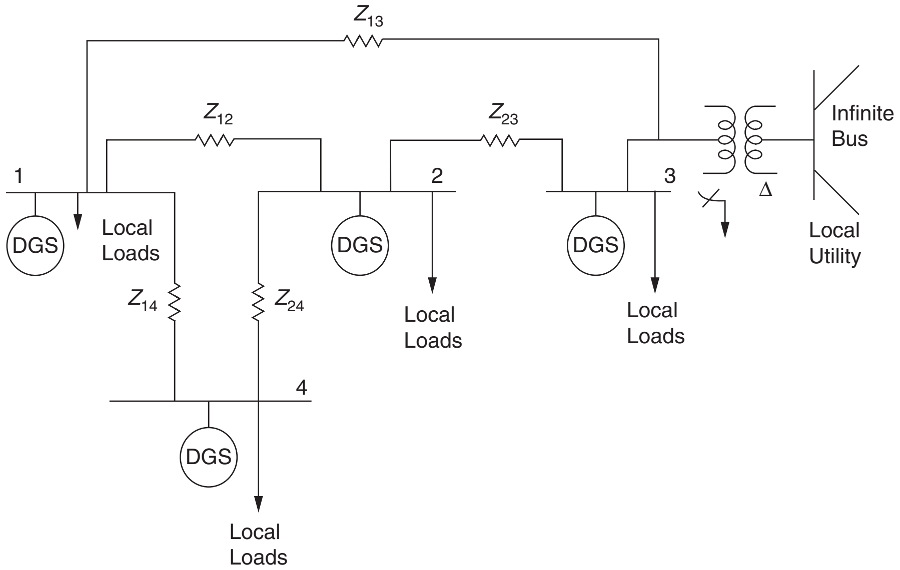

FIGURE 1.4 Low-voltage distributed generation system.

(12,000–50,000 rpm), the H constant can be in the range of 0.5–1.5. MTG plants usually use permanent magnet synchronous machines and thus there is no field time constant is associated with them either. FC plants have dynamic response on the order of 5–10 min. Furthermore, the power generated by the renewable generation resources could vary widely, and their operation must be coordinated with amount of DC power storage devices with FC and MTG units that can adjust their generated power in response to disturbances. This coordination is essential for maintaining stable voltage and mitigating the power oscillations. Figures 1.5a and 1.5b depict parallel operation of FC units. Figure 1.6 depicts the control architecture of fuel cells supplied from hydrogen tank. To understand load frequency control and voltage control coordination between various DG sources problems, we need to determine how fast we can control the set points of the MTG and FC plants as soon as the DC bus voltage begins to drop. Furthermore, the use of the advance predictive control can be investigated by using the one-step-ahead load prediction to change the output power of FC and MTG units and to rid through the disturbance and stabilize the DG system. Such a study will also increase understanding the regulating potential of DG system and will minimize the size of DC storage system and demand-side dynamic load-shedding requirements upon disturbances. In fact, we are also trying to determine the mix of DG sources and stored reserve energy. The same problem needs to be investigated when the cluster distributed DG sources lose its connection to the interconnected systems as depicted by Fig. 1.2. Here again, we need to develop control strategy to mitigate the power oscillations and maintain stability. The development of this control system technology is vital to ensure a sustainable

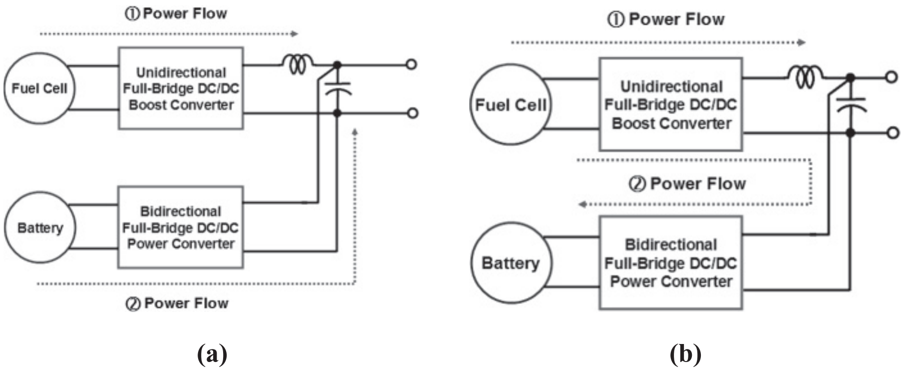

FIGURE 1.5 Block diagram of paralleled-connected FC sources. (**a**) Battery discharge. (**b**) Battery recharge.

network with a significant renewable energy supply contribution. In this book, we use the perfect robust servomechanism problem (RSP). The RSP method had not been applied to practical problems because it requires extensive real-time computations. However, by use of advanced digital signal processors (DSP), this problem has been resolved. We will present this control technology in later chapters. The RSP control guarantees exact asymptotic tracking of the fundamental frequency reference and error regulation of the load disturbance at each of the harmonic frequency included in the servocompensators. The perfect RSP guarantees this property independent of any perturbations in the plant as long as they do not destabilize system. However, it is important to analyze the stability property of the controller under large disturbances and the power-factor-corrected (PFC) loads to ensure proper operation of the converter over its intended operating range. In this book, the stability robustness of the system with the controller will be investigated using structured singular values under nonlinear PFC loads. Specifically, a simulation test bed will be presented for

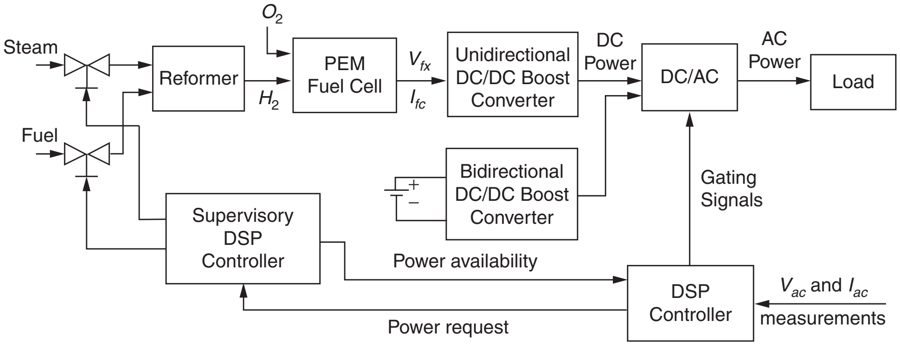

FIGURE 1.6 Fuel cell coordinated control.

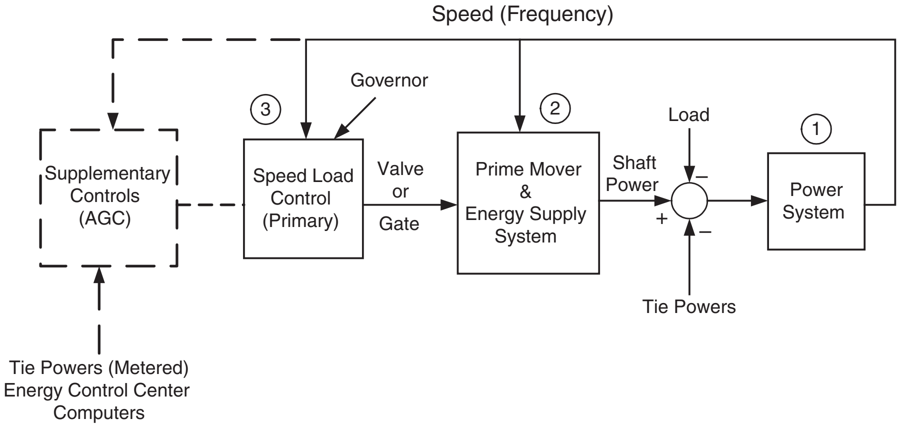

FIGURE 1.7 The automatic generation control of power system (AGC).

the students to study perturbations due to load variations and parameters uncertainties of the system components. A quadratic cost function with separate weighting scalars for plant states and servocompensator states will be used to find solutions to the perfect RSP. Finally, the stability robustness and transient response of the resulting control system will be presented for the systems depicted by Figs. 1.1 and 1.3. Figure 1.7 depicts the architecture for the regulating and control of power disturbances. In this architecture, the primary objective is to control the DC bus voltage as the DC bus voltage drops/increases in response to the fluctuating power demand by the sending control signal to the regulating energy sources to increase/decrease the input power.

The smart grid can be operated in two modes of operations:

1. Synchronized operation with the local utility system.
2. Island mode of operation upon loss of the utility system.

1.5 A DG SYSTEM OPERATING AS PART OF UTILITY POWER SYSTEM

The architecture of Figs. 1.1 and 1.3 satisfy Renewable Portfolio (R/P) laws that have been mandated by many states. This architecture allows selling and buying energy from local utilities. When a DG grid system is connected to a utility, the DG system bus voltage—that is, the infinite bus voltage—is maintained by the local utility. Furthermore, the system frequency is controlled by the power system operator. If the DG inverter has a large capacity in the range of MVA rating, then it will be connected to the subtransmission voltage of the local power system. For example, a system has more than 20,000-MVA capacities feeding its transmission system; if a smart grid DG system is connected to the subtransmission system of this system, the DG system cannot change either the bus voltage or the system frequency. The high-MVA DG grid system will become a part of the utility network, and it will be subjected to power system disturbances. To understand why this is the case, we need to understand the control system that is used by power system operators.

Fig. 1.7 illustrates the energy management system (EMS) of the power system (it is also called the Energy Control Center). The EMS system has two computers that are operating in parallel. Two computers are used to increase the reliability and security of the power system. The function of the energy management system is to control the interconnected system, load and frequency, system voltages, and economic operation of power systems.

The load frequency control system is designed to follow the system load. That is, as load changes—let's say as the load increases (or tie line powers)—the inertia energy stored in the system supplies the deficiency in energy, to achieve a balance between load and generation. This energy is supplied by prime movers (stored energy in rotors). The balance between load and generation must be maintained for a power system to remain stable. When the balance between generation and load is disturbed, the dynamics of generators and loads can cause the system frequency and/or voltages to vary; and if this oscillation persists, it will lead to the system collapse. If the load changes are rapid and the power system frequency drops, then steam units and hydro units control loops will open the hydro gates, and/or turbine steam valves to supply energy to stabilize the system frequency. This action takes place regardless of the cost of energy from generating units. All units that are under load frequency control participate in the regulation of the power system frequency. This is called "governor speed control," as shown in Fig. 1.7. Clearly, the cost of generated energy is not the same for all units. Every 1–2 min, "supplementary control loop," under automatic generation control (AGC), will economically dispatch all units to match load to generation and, at the same time, minimize the total operating cost. Therefore, the AGC will change the set points of generators under its control. This control cycle can be on the order of one minute to several minutes. Figure 1.8 shows the time scale of the power system control.

When a smart grid DG is connected to a utility, then the smart grid DG-generating station operates, using a master-and-slave control technology. The master is the EMS of the utility system. EMS controls the infinite bus voltage and system frequency. It should be observed from Fig. 1.1 that the smart grid DG is connected to the utility system by a transformer. The slave controller controls the AC bus voltage of the inverter (magnitude and phase angle) and inverter current. Therefore, the slave controller of the DG inverter controls active and reactive power. The DG inverter can operate as a unity power factor and leave the voltage control—that is, reactive power (Var) control—to the EMS of the utility system, or it can operate with a leading power factor or a lagging power factor. The digital signal processor (DSP) of the inverter controls the DG inverter. The EMS of the smart grid DG system is interfaced with a DSP controller and a smart net metering system to display the activity of the DG system. If the smart grid is suddenly separated from its local

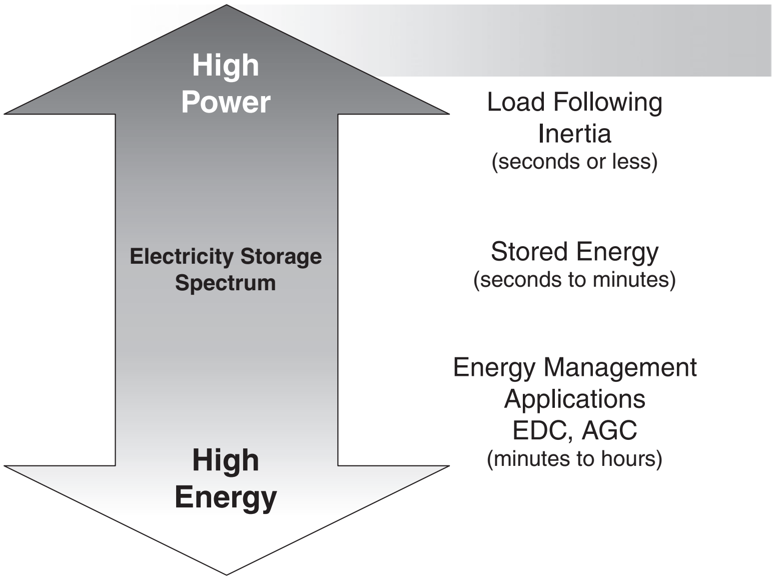

FIGURE 1.8 The energy management time scale of power system control.

utility and the system stability is maintained, then the slave controller takes over load frequency control and voltage control. However, for small rooftop PV sites, the inverter is controlled to produce active power. The VAR support is provided by the local utility. However, for high-MVA generating stations, there will be a purchasing agreement between the utility and DG generating stations on active and reactive power transfer. The word “smart” means that DG generating stations can control their loads and can accept “price signal” and/or “emergency operation signal” from its local utility to adjust their active and reactive power generation. Other designs are also possible. These may include net smart metering communication between the EMS of the local utility and the EMS of DG system. The smart grid DG systems have hardware in place to shed loads, in response to price signal or to rotate nonessential loads and to keep on critical loads. However, since disturbances of a utility system cannot be predicted, it is quite possible that, upon the loss of the utility system, its DG grid systems would be not rapidly disconnected from its utility system, and the stability of DG systems would not be maintained. In this case, DG systems would collapse. However, DG systems can be restored by shedding noncritical loads, and DG systems can return to normal operation in a short time. This problem of stability is a function of how strongly a DG grid system is connected to a utility system. This problem must be studied as system parameters are defined and as voltage level of connecting a DG system to a local utility is defined. Figure 1.9 presents how EMS is controlling load and frequency, system bus voltages, and economic operation of a power system.

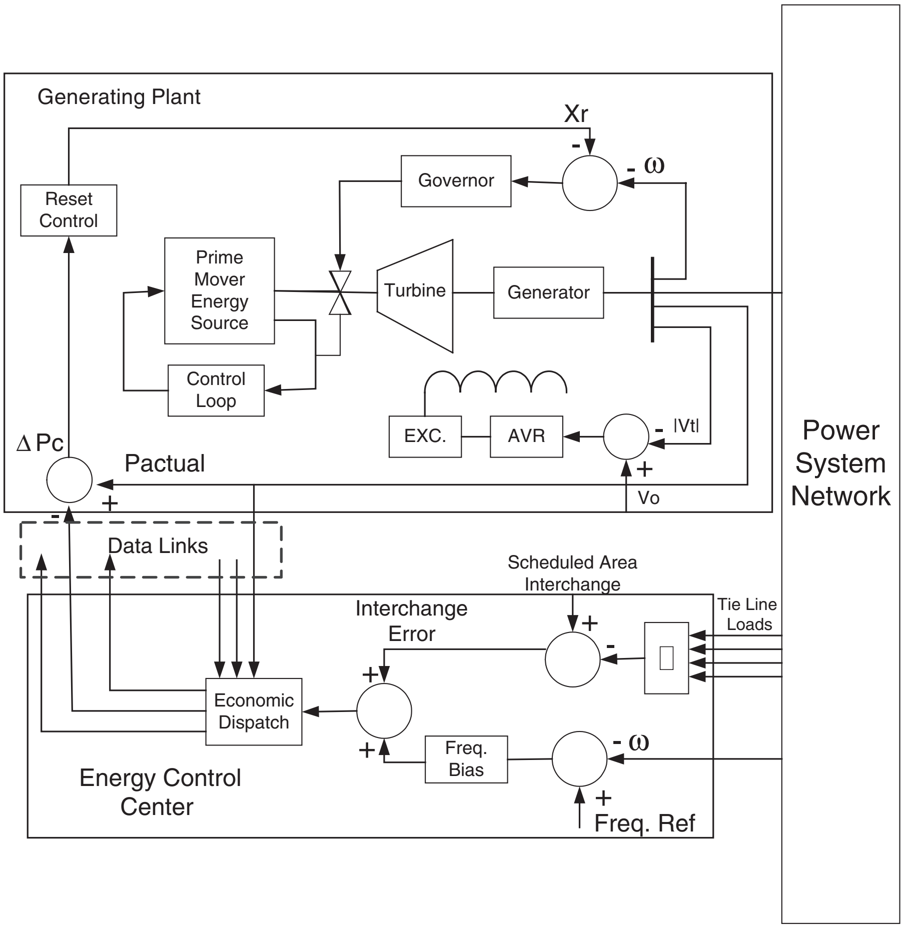

FIGURE 1.9 The energy management system (EMS).

1.6 POWER SYSTEM REACTIVE POWER (VAR) CONTROL

To ensure that power system bus voltages are controlled at their rated values, the power system operators control system Var support. This can be stated as follows: Reactive power generated by generators, plus reactive power generated by capacitors and synchronous condenser, must be equal to reactive power consumed by load, plus system net reactive losses.

To accomplish stable bus voltages, the power system operators control the generator bus voltages by adjusting the field currents of generators. This is done by measuring the terminal voltages of generators and comparing them with set references, as shown in Figs. 1.7 and 1.9. A generator can be operated in three modes by controlling its field current: (1) the overexcited mode, (2) the unity power factor, and

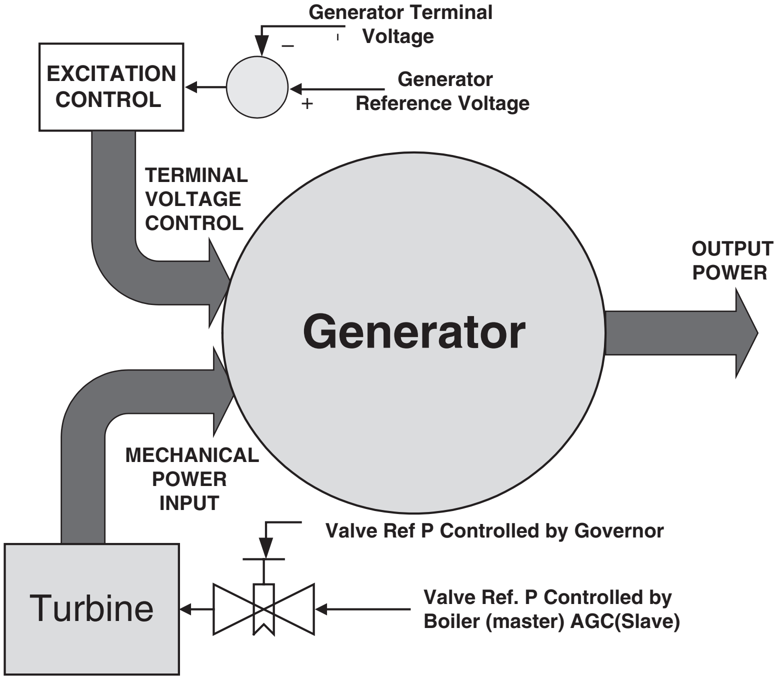

FIGURE 1.10 The operation of a generator as a three-terminal device.

(3) The underexcited mode. The terminal voltages of the generators are set by the system operator to provide active power and reactive power as specified above. By adjusting the generator power factors, the generator's active and the reactive power generation are specified. Then, the turbine valves of the generators are set at a position that will control pressure and steam flow demand, and the positions of the valves correspond to the active power provided by the generators. Therefore, as can be seen in Fig. 1.10, a steam turbine generator is a three-terminal device; that is, the mechanical power is inputted, the generator terminal voltage is controlled, and the generator delivers active power and reactive power.

1.7 AN INVERTER IS ALSO A THREE-TERMINAL DEVICE

Recall that by adjusting the field current, the operator decides on the operating power factor of a generator (that is, active and reactive power production). An inverter can be made to operate in the same three modes and provide active power and reactive power in the same way as a generator.

The operation of the three terminals of an inverter is as follows (Fig. 1.11): (1) input power is supplied from a DC source (battery storage); (2) AC power is supplied to the load; and (3) DSP controller, based on its control technology, computes the switching

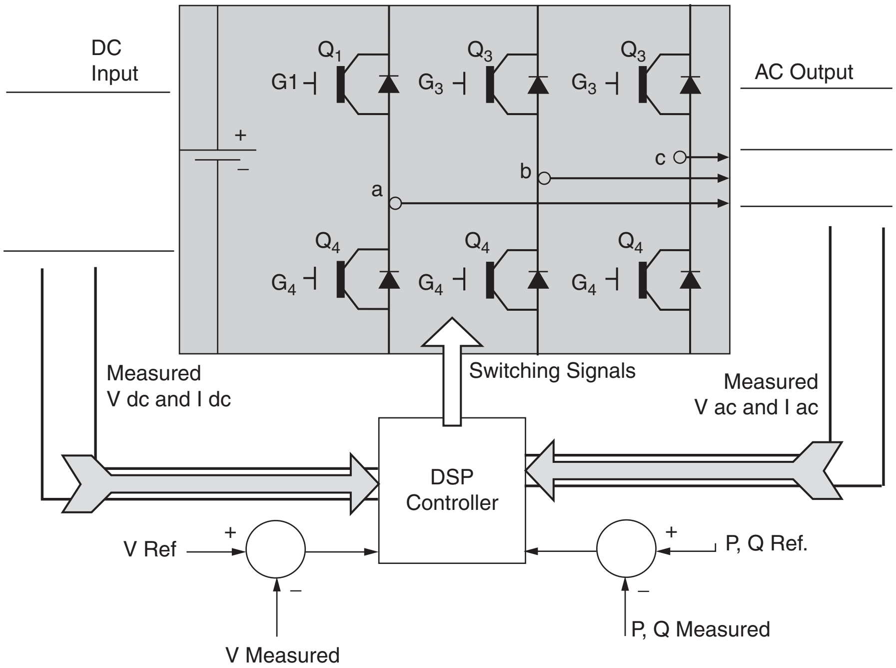

FIGURE 1.11 The operation of an inverter as a three-terminal device.

policy that ***controls the phase angle between the terminal voltage and current, that is, the power factor.*** Therefore, using the appropriate control technology, we can operate an inverter, such that, it can produce active power and reactive power. The frequency of generated power is set by pulse width modulation (PWM). The details are given in Chapter 2.

In Fig. 1.12, we have multiple control loops. The first control loop controls the DG AC bus voltage, that is, the load bus. The second control loop controls the AC bus current (i.e., the load current). This is accomplished by controlling the phase

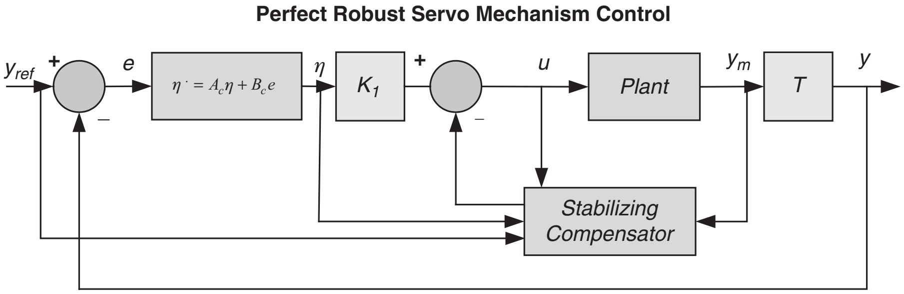

FIGURE 1.12 The inverter control system.

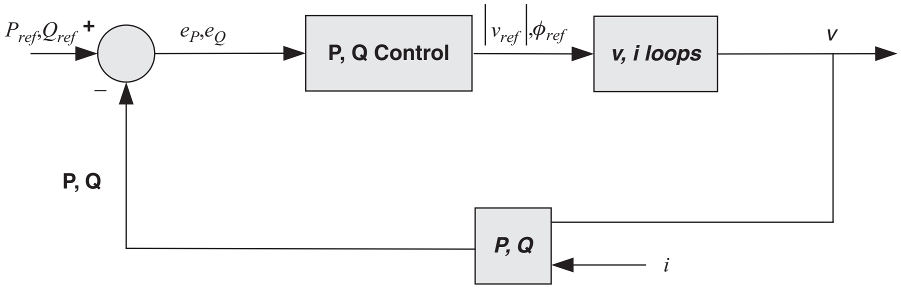

FIGURE 1.13 The grid-connected inverter P and Q control.

angle of the load current with respect to DG AC bus voltage. Finally, the stabilizing compensator eliminate the unwanted harmonics.

In Fig. 1.13, the desired active and reactive power to be injected into the local utility is specified by the P ref and the Q ref. The AC bus voltage and current, the P and Q injected to the local utility, are calculated and compared with the reference active power and reactive power. The P–Q control loop determines the desired control actions for the amount of power to be transferred to the AC bus. Therefore, the inverter is controlled to deliver active power and reactive power per the purchased agreement or based on “price signal” from a power system operator. If a utility system is subjected to a major disturbance such as faults, it can pull down DC bus voltage if the DG system is not rapidly disconnected from the utility. This problem must be investigated by modeling the battery system and developing an equivalent coherent generator model of the utility power network.

1.8 THE SMART GRID PV-UPS DG SYSTEM

When combining the integration of green energy sources with un interruptible power supply (UPS), the architecture presented by Fig. 1.14 will increase the security of the system by attempting to isolate UPS loads from utility disturbances. In this architecture, two power converters are used. First, a bidirectional converter is used to charge the battery system and inject power into the local utility. A second inverter is used to support UPS loads and local smart grid loads.

The architecture depicted by Fig. 1.14 is essentially the same as in the smart grid DG system of Figs. 1.1 and 1.3. However, this architecture operates at three frequencies. The DC bus operates at zero frequency, the portion of the system connected to the local utility operates at synchronized power system frequency, and the AC bus of the UPS system operates at the inverter frequency. The architecture in Fig. 1.14 provides for the isolation of UPS AC bus from utility system as long as the storage system can provide this isolation. However, if the utility system is subjected to large disturbances that result in rapid discharge of the storage system and the drop in DC bus voltage is excessive, this will result in the collapse of AC bus of UPS system. To understand this problem, let us assume that the UPS-PV system is injecting power

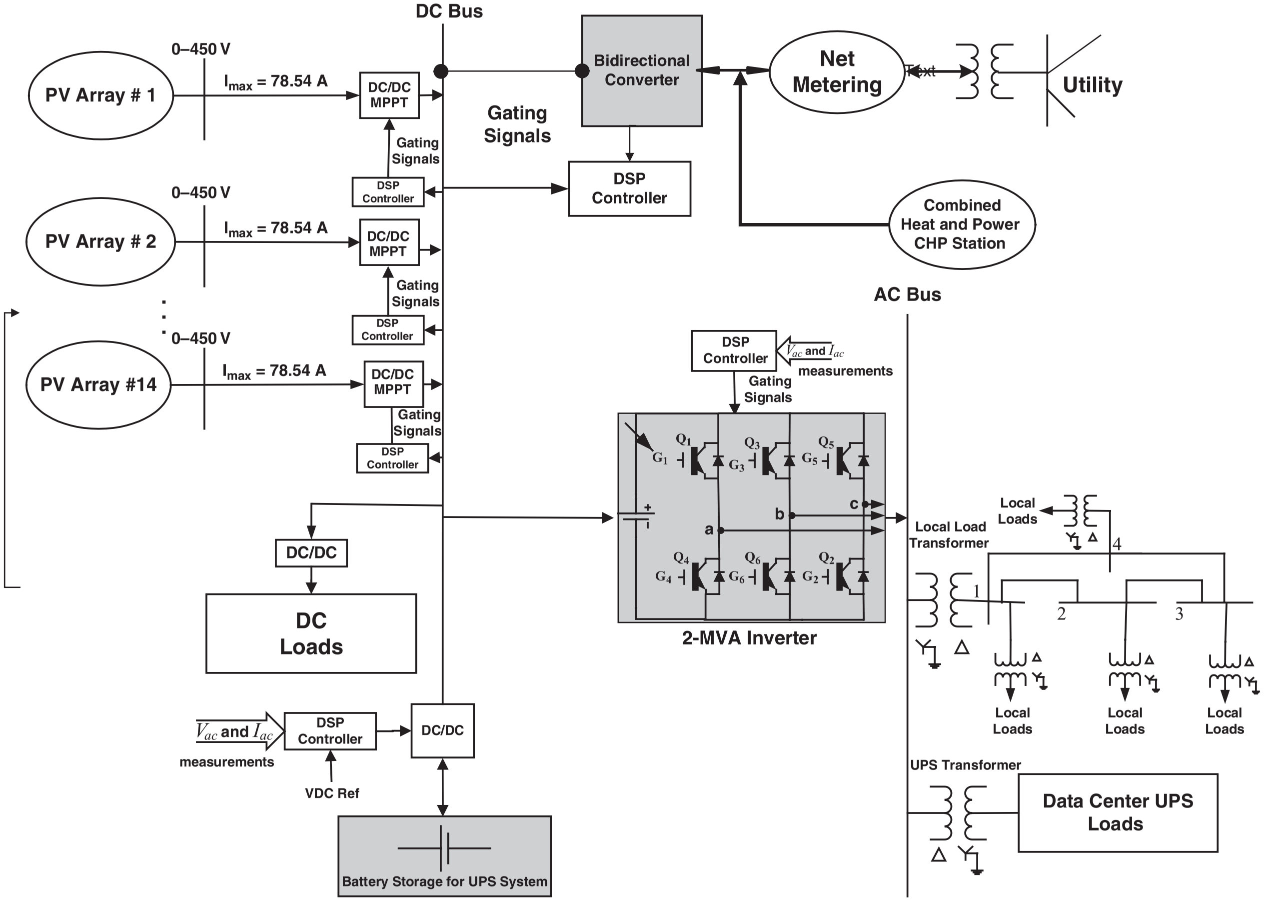

FIGURE 1.14 The smart grid PV-UPS DG system.

into the utility system. Then, unexpectedly, the line that is transferring power into the local utility trips out. Upon this disturbance, the resulting oscillations may result in voltage oscillations of the DC bus and the collapse of the smart grid UPS-PV DG system. The stronger the connection (i.e., the higher the voltage) to the local utility system, the higher the chance that voltage oscillations will penetrate its smart grid UPS-PV. This problem must be studied by modeling the smart grid UPS-PV system and developing a coherent equivalent network for the local utility network in order to determine the protective relay setting for the separation of the smart grid UPS-PV system from the local utility.

1.9 THE SMART GRID SPLIT DC BUS UPS-PV DG SYSTEM

When combining the integration of green energy sources with un interruptible power supply (UPS), the architecture presented in Fig. 1.14 will increase the security of the system by attempting to isolate UPS loads from utility disturbances. However, the stability and the security of UPS loads *cannot* be guaranteed. To isolate the UPS loads, the smart grid DC bus of the UPS-PV DG system is split into two sections as shown in Fig. 1.15 through a normally open circuit breaker. This architecture operates

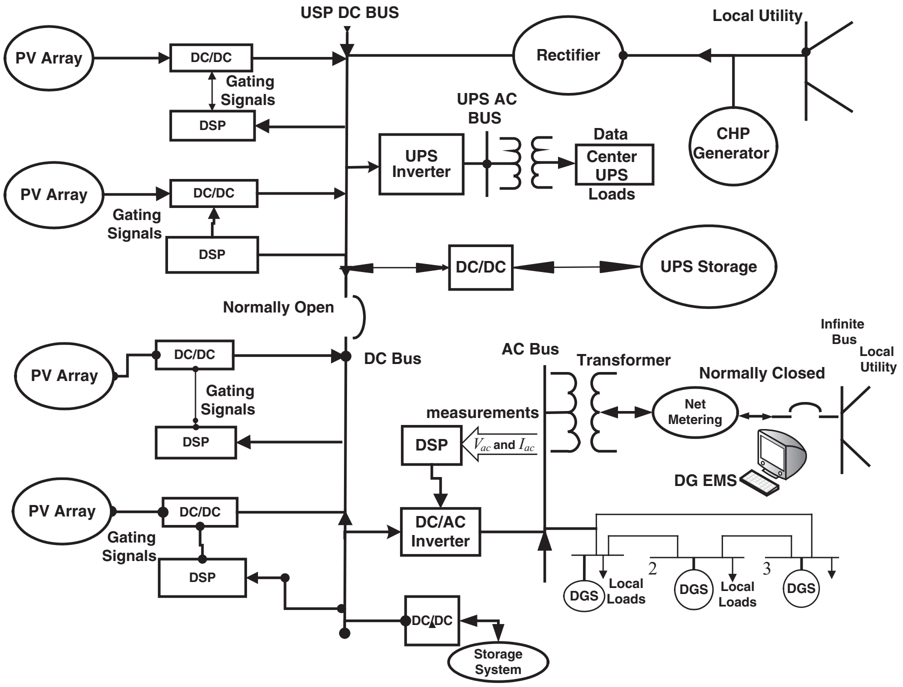

FIGURE 1.15 The split DC BUS UPS-PV smart grid system.

at the following frequencies: (1) The DC bus system operates at zero frequency. (2) The 2-MVA inverter, which connects the DG system to the local utility, operates at the power system frequency (synchronized frequency). (3) Through a separate UPS inverter, the UPS loads are connected to the DG system. The UPS loads operate at the UPS inverter frequency. The split DC bus UPS system would have the same reliability and security as classic UPS technology since it is connected to its utility network, using a rectifier. Therefore, the DC bus voltage of UPS loads is protected from local utility disturbances.

1.10 THE ISLAND MODE OF OPERATION

Upon separation from a utility system, if a smart grid DG stays stable, the inverter of the DG system regulates its frequency. If there is only one inverter in the DG system, load frequency control is accomplished through inverter reference frequency using the Pulse Width Modulation (PWM) technique as part of the DSP controller. The DG system inverter controls its load at the reference AC bus voltage. As load changes, the DSP controller corrects the AC bus voltage. Therefore, as depicted in Figs. 1.1, 1.3, 1.14, and 1.15, the DG inverter follows the load changes and converts DC power to AC, to satisfy active power and reactive power. Again, system load is matched to the generated power from the DG inverter. In short, the DG system is a micro-grid power system that operates like an AC power system.

1.11 THE PARALLEL OPERATION OF INVERTERS

If a smart grid generating station has two and more inverters that are operating in parallel, a new problem would arise. Two inverters in parallel, as shown in Fig. 1.16, would act as two transmission lines with unequal loading, and *circulating zero-sequence current would flow between the parallel inverters*. The circulating current can be excessive when both inverters are sharing nonlinear loads, typically a load consisting entirely or partly of rectifiers—for example, diode or thyristor rectifiers. The sharing of load current harmonics between inverter units is critical. The nonlinear loads cause the distortion of the current supplied by inverters. The load current will have harmonics, in addition to the fundamental frequency. If current harmonics are not distributed evenly between the inverters, there will be a risk of overloading the individual inverter, due to the circulating current that would cause heating. This heating would result in a reduction of lifetime operation of inverters.

This problem must be investigated further as system parameters are defined and the voltage level of the connecting the DG system to its local utility is defined. We will present the operation of parallel inverters in a later chapter.

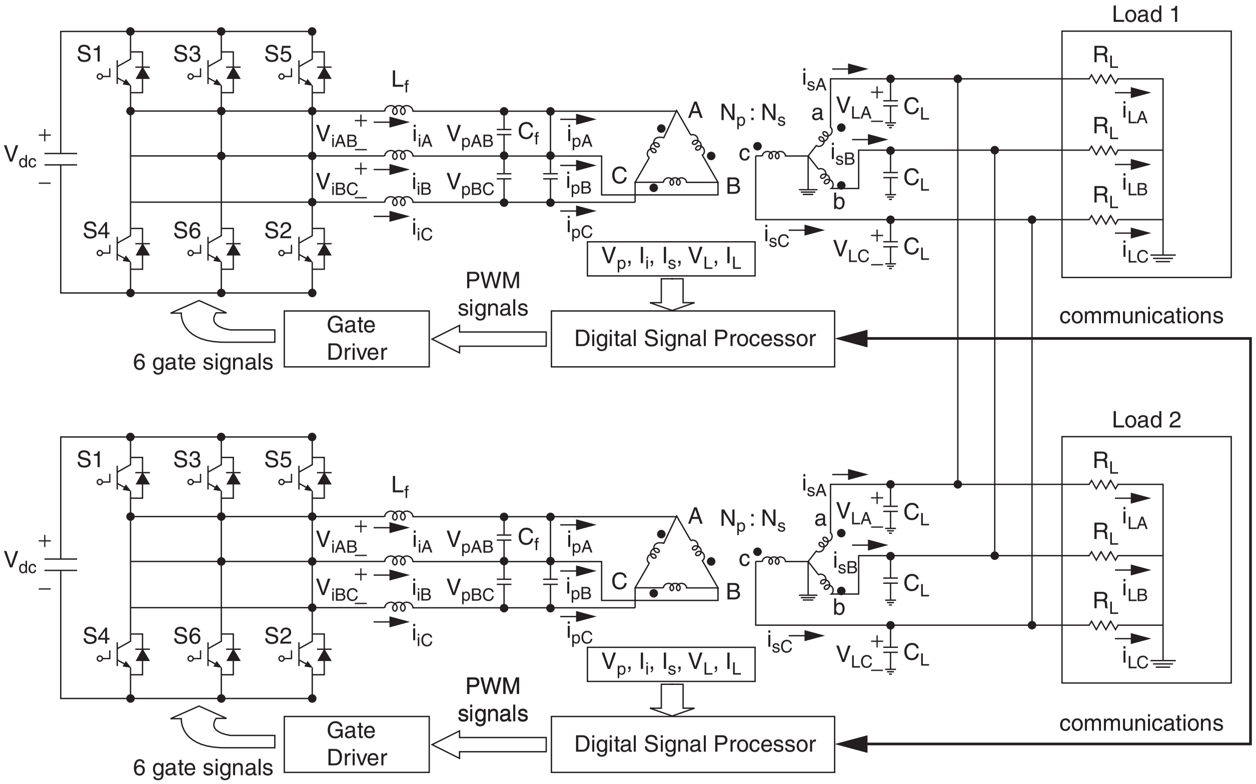

FIGURE 1.16 The parallel operation of two inverters.

1.12 THE INVERTER OPERATING AS STEAM UNIT

If a DG inverter system is designed to operate as a steam unit, then it can participate as part of power system voltage and frequency control. In this case, the DG inverter must have well-defined dynamic response. Such a DG generating station would be very valuable to its local utility, since the excess power can be used as "real-time spinning reserve." If the DG system is designed as a steam power generating system, then it can sell its power to its local utility, based on "price signal," by shedding its own nonessential local loads. If a DG generating system qualifies as provider of real-time spinning reserve, such a DG system would receive payment from its local utility, even if its generated power is not used. But, it must be ready to shed its loads, if needed, and be under the utility EMS to respond to the local utility power system emergency.

The steam power plant has stored energy in its boiler and stored energy in its inertia of rotor. This allows the power system operator to control the frequency of the system. Again, in a power system, the loads are controlled by the end users. The power system operator controls the system frequency to follow the system load demand. This objective is accomplished by comparing the actual system frequency with a reference frequency. Based on the deviation from the set point (i.e., 60 Hz in the United States), EMS opens and closes the turbine valve systems, as shown in Fig. 1.4. However, the opening and closing of turbine valves must follow the boiler's operating condition limits. The drop in steam pressure and steam conditions must not deviate from their set limits, since the drop in steam pressure and temperature will result in water droplets and damage to turbines.

We can make the battery storage system act as a boiler. However, this must be accomplished by following the limits on the discharge rate of battery storage systems, that is, state of charge (SOC). However, as with a boiler, it is necessary to make sure that the battery systems will not be subjected to excessive discharge that damages the battery system or reduces the life of the battery storage system. We can use a battery storage system with a flywheel or a super-charging capacitor to make the combination of a battery–flywheel storage system, with its inverter acting as a steam power plant, as shown in Fig. 1.17. In this architecture, the flywheel system would provide inertia energy rapidly as the DC voltage bus drops; and battery storage system would take over, under appropriate control, to keep the system stable.

1.13 THE PROBLEM OF POWER QUALITY

The total harmonic distortion (THD) is an important consideration in power quality and the operation of DG systems. The total harmonic distortion (THD) of a power signal is a measurement of the power harmonic distortion present and is defined as the ratio of the sum of the powers of all the harmonic components to the power of the fundamental power frequency. The impact of harmonics is their effect on power system components and loads. Transformers are major components in power systems. The increased losses due to harmonic distortion can cause excessive losses and, hence,

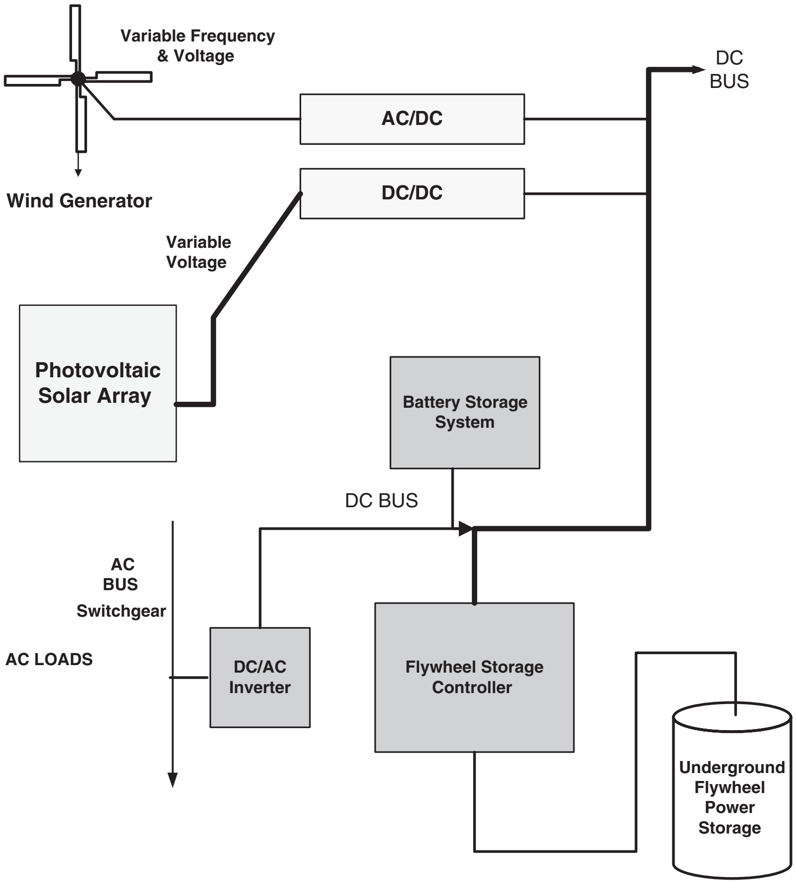

FIGURE 1.17 A DG generating station acting as a steam unit.

abnormal temperature rise. The unwanted harmonics can be eliminated using perfect robust servomechanism control as shown in Fig. 1.12. The control strategy combines the *perfect RSP* controller for low THD output voltages. The discrete sliding mode current controller provides for fast overcurrent protection. In the following chapters, we will present the modeling and control of inverters for integration of renewable and green energy in electric power systems.

The advocated load sharing technique will address the following areas: The technique shall not be sensitive to component mismatches, measurement error, or unbalanced load or wire impedances. We will establish the sharing of harmonic components of the currents without significantly degrading the performance of the output voltages avoiding the existence of a single point of failure in the paralleled units' configuration.

In Fig. 1.18a, the control objective is to control the FC and MTG set points in response to disturbances. In Fig. 1.18b, the control objective is to control DC/DC converters and the DC bus voltage in response to disturbances. Finally, in Fig 1.18c,

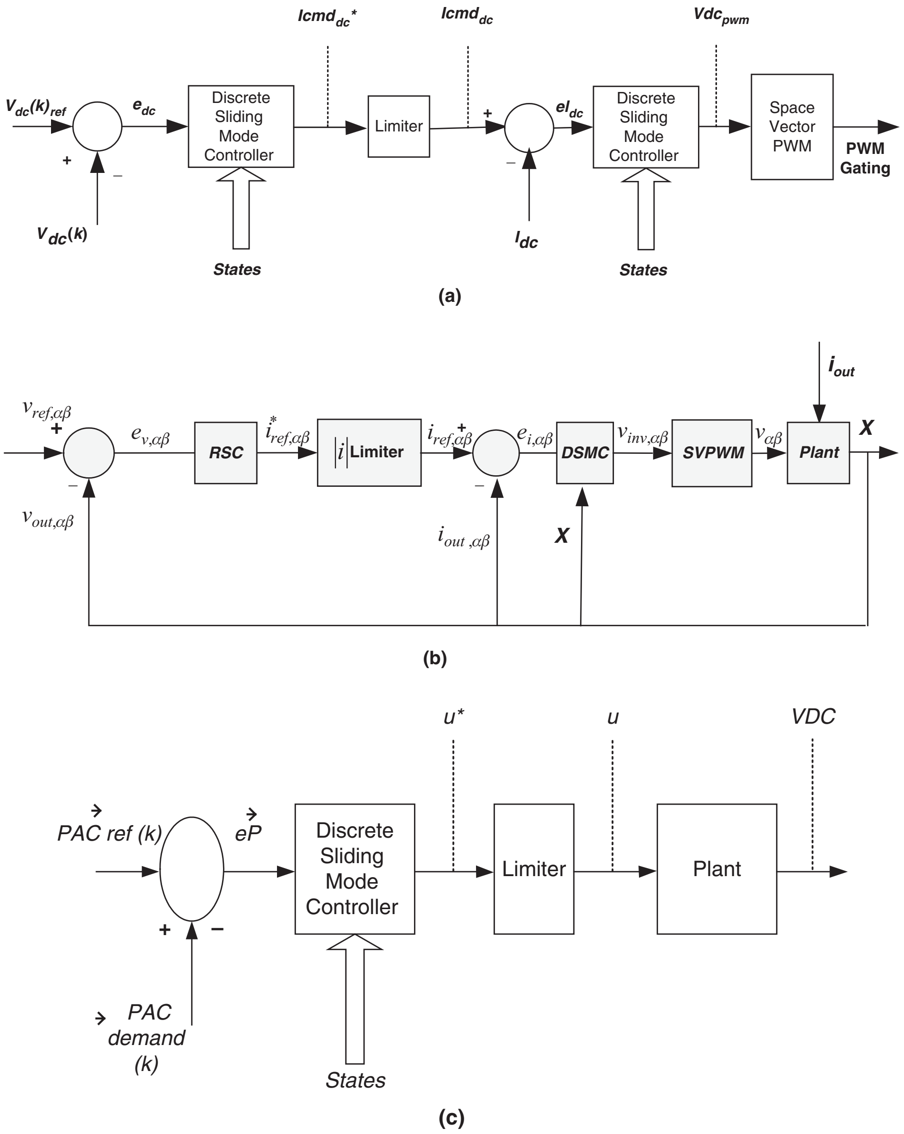

FIGURE 1.18 The block diagram of the proposed coordinated control. (**a**) DC bus voltage control. (**b**) AC bus voltage control. (**c**) Active power control.

the control objectives are to stabilize load voltage and active and reactive power outputs of DC/AC converter in response to disturbances.

The above control technology will be presented in this book. In Chapter 2, we will 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; in Chapter 9, modeling of proton exchange membrane fuel cell; and in Chapter 10, MATLAB simulation testbed. In this book, these coordinated control techniques will be presented using a MATLAB simulink simulation test bed. Throughput the book, we will provide the simulation test beds. The instructors can use each chapter mathematical modeling with its supporting MATLAB to provide students with control projects.