Power Systems

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Editors

Smart Power Grids 2011

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Preface

System and network integration on a smart grid that manages hybrid energy sources is on technology road maps for virtually every utility company and independent system operator in recent years. As penetration of renewable increases, the new grid challenges come with integrating intermittent and distributed generation resources into the current electric power system. This book attempts to address the problems that arise with the integration of green-renewable energy sources with market structure into power grids. We focus on the grid integration of renewable energy because it is a driver for a major infrastructure modernization such as power electronics, control, sensor technology, computer technology, and communication systems known as "smart grid".

In each chapter, the contributing authors present a number of important areas of smart power grids. The first chapter covers an overview of smart power grid technology and why it will remain the focus of the twenty-first century. The chapter gives a brief history of the connection between the development of modern industrial societies and the depletion of fossil fuels and why the development of a smart power grid communication system and real-time pricing is an urgent task. It also describes the basic development of microgrids of photovoltaic and wind energy system, and cyber-controlled smart power grids.

In the second topic, the load frequency control in a microgrid is covered. It presents the load frequency control of the distributed generators (DGs) using decentralized control concepts. The control of the system focuses on the voltage magnitude and frequency control and presents the conditions that can lead to system instability or voltage collapse. Three important problems are studied. These include: (a) when the system stability margin is low, (b) when the line impedance has a high R to X ratio, (c) when the system contains unbalanced and/or nonlinear loads.

The third topic covered is a study of a cascaded multilevel inverter. The modeling and control of a multilevel inverter is presented for supplying power to a four-fuel cell system. Both grid-connected and in stand-alone controlled modes are discussed using a fuzzy logic controller by a FPGA. The fourth topic presents the control of a DC-AC PWM inverter in smart microgrid systems; sizing high-speed micro generators; active and reactive power control of grid-connected distributed generation systems; and sliding mode control of inverters. The fifth topic presents the optimal allocation of wind turbines in active distribution networks by using a multi-period optimal method, real-time modeling, and control of smart grid systems; and integration of intermittent resources in real-time scheduling. Overall, most of the chapters are focused on control of power grids and planning.

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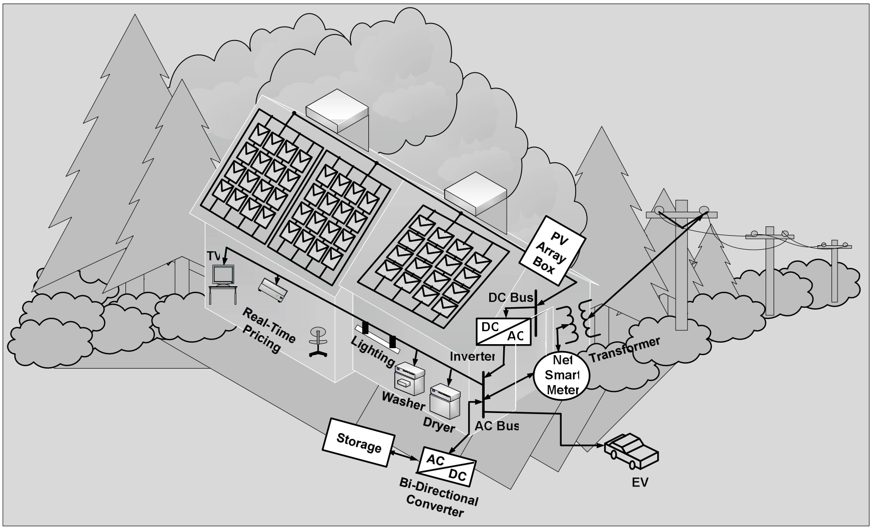

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Ali Keyhani, PhD, is a professor in the Department of Electrical and Computer at Ohio State University. He is a Fellow of the IEEE and a recipient of the Ohio State University, College of Engineering Research Award for 1989, 1999, and 2003. He has worked for Columbus and Southern Electric Power Company, Westinghouse Electric, Hewlett-Packard Co., Foster Wheeler Engineering, and TRW Control. He has performed research and worked as a consultant for Combustion Engineering, TRW Controls, Harris Controls, Liebert, Delphi Automotive Systems, American Electric Power General Electric, General Motors, Ford, and Foster Wheeler Engineering. Dr. Keyhani has authored many articles in *IEEE Transactions in Energy Conversion, Power Electronics, and Power Systems Engineering* . He also recently co-authored "Integration of Green and Renewable Energy in Electric Power Systems" with M.N. Marwali and M. Dai.

Muhammad Marwali PhD has experience in various power applications for the de-regulated electricity market. He is currently the on-site manager at the New York ISO where he is the main ABB contact. He also supports the NY ISO project in various areas such as software design, integration of various applications, and design and development of new functions. He is also IEEE Senior Member and adjunct Professor at Ransselaer Polytechnic Institute. Prior to joining ABB, Dr. Marwali held a number of research positions, focusing on areas such as renewable energy, unit commitment, generation and transmission scheduling, state estimation and distributed generation. He has published numerous articles in IEEE and two books.

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Chapter 1
Smart Power Grids

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1.1 Introduction

Energy technology plays a central role in societal economic and social development. Fossil fuel-based technologies have advanced our quality of life, but at the same time, these advancements have come at a very high price. Fossil fuel sources of energy are the primary cause of environmental pollution and degradation; they have irreversibly destroyed aspects of our environment. Global warming [4, 75, 76] is a result of our fossil fuel consumption. Our relentless search for and need to control the valuable fossil fuel resources such as oil and natural gas have promoted political strife. We are now dependent on energy sources that are unsustainable as our energy needs grow and we deplete our limited resources. As oil supplies dwindle, it will become increasingly urgent to find energy alternatives that are sustainable as well as safe for the environment and humanity.

The restructuring of the electric power industry was a critical step for individual stakeholders, facilitating their wide participation in the production, delivery, utilization of energy and efficient use of electric energy. The restructuring is facilitating integration of internet technology in protection, control and real-time pricing. Furthermore, the worldwide awaking of global warming has created a market for integration of renewable and green energy sources. Now, technology is rapidly moving in a direction where every energy user can become energy producer.

Amin [43] coined the term "smart grid" in 2005. Shahidehpour integrated many definitions of smart grids in his forward section of Keyhani's [1] book on smart power grids as "The smart grid has further offered alternatives to participants looking to enhance the reliability, sustainability, and capability for customer choices in energy systems. The smart grid has made it possible to set up microgrids that could be operated as stand-alone islands in critical operating conditions. Such small installations can enhance the reliability of regional electric power systems when the larger grid is faced with major contingencies. There are several practical examples of microgrid installations which have demonstrated that

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the use of smart switches in distributed power grids could reduce the number and the duration of outages. In addition, the smart grid allows microgrids to optimize the use of volatile and intermittent renewable energy resources and enhance the sustainability of regional power systems. The applications of solar photovoltaic, which mostly follows the daily load profile for power generation, on-site or local wind energy, along with storage devices for microgrid installations could provide an inexpensive and sustainable means of supplying microgrid loads. The principles of a widespread utilization of energy storage can also be found in the emerging market of plug-in electric vehicles, which would utilize wind energy at off-peak hours. Such microgrid applications could also eliminate the need for extensive additions of high voltage lines for the transmission of renewable energy across densely populated regions of the world. However, the evolutions in the electric power industry that I believe will truly revolutionize the way we deliver electricity to individual consumers are smart grid applications related to real-time pricing, hourly demand response, and the expansion of customer choices for promoting energy efficiency. The use of new smart grid innovations would make it possible for consumers to prioritize their energy use according to their daily schedules, needs, and preferences, taking into account a variable cost of electricity to save money. Smart grid advancements would also enable automated control systems to optimize energy use at home or for businesses, identifying the most appropriate times for device operation to reduce the cost of electricity. Customer participation will offer a number of incentives for the optimization of electric power operations, including lower operation costs by eliminating the commitment of costly generating units at peak hours, mitigating mandatory system upgrades that are required for responding to a few hundred hours of annual peak loads, and reducing the chance of transmission congestion, which could otherwise operate the power system at a state close to its critical point of collapse. Demand response could also offer a less fluctuating and flatter daily profile, which would make it possible to forecast the daily load profile and schedule fuel and hydro consumption more comprehensively and efficiently for power generation." This description of a smart power grid ushers the design and development of electric energy system for centuries to come.

1.2 Solar Energy

Solar energy is a readily available renewable energy; it reaches earth in the form of electromagnetic waves (radiation). Many factors affect the amount of radiation received at a given location on earth. These factors include location, season, humidity, temperature, air mass, and the hour of day. *Insolation* refers to exposure to the rays of the sun, i.e., the word "insolation" has been used to denote the solar radiation energy received at a given location at a given time. The phrase *incident solar radiation* is also used; it expresses the average irradiance in watts per square meter (W/m^2) or kilowatt per square meter (kW/m^2). The surface of the earth is coordinated with imaginary lines of latitude and longitude. Latitudes on the surface of the earth are imaginary parallel lines measured in degrees. The lines subtend to the plane of the equator are called *latitudes*. The latitudes vary from 90° south (S) to 90° north (N). The longitudes are imaginary lines that vary from 180° east (E) to 180° west (W). The longitudes converge at the poles (90° north and 90° south). The radiation of the sun on the earth varies with the location based on the latitudes. Approximately, the region between 30° S and 30° N has the highest irradiance as depicted in Fig.1.1. The latitude on which the sun shines directly overhead between these two latitudes depends on the time of the year. If the sun lies directly above the northern hemisphere, it is summer in the north and winter in the southern hemisphere. If it is above the southern hemisphere, it is summer in the southern hemisphere and winter in the north.

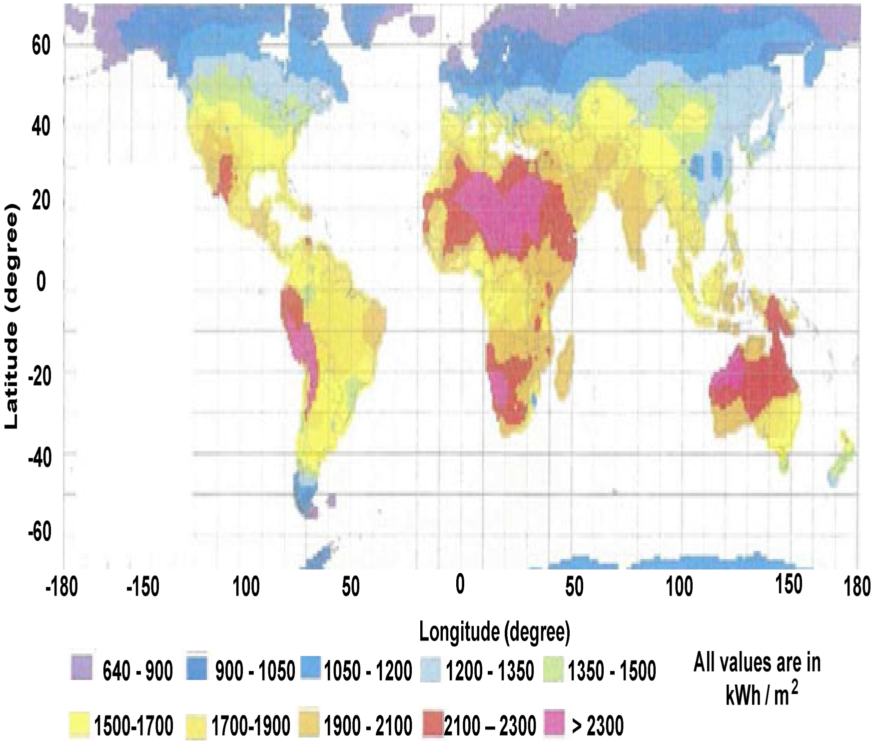

Fig. 1.1 The Global Irradiation Values for the World (kWh/m^2) [44]

1.3 Wind Energy

Wind energy, as one of our most abundant resources, is the fastest growing renewable energy technology worldwide as shown in Fig. 1.2. Improved turbine and power converter designs have promoted a significant drop in wind energy generation cost making it the least-expensive source of electricity—from 37 cents/kWh in 1980 down to 4 cents/kWh in 2008. In 2008, wind energy systems worldwide generated 331,600 million kWh, which is 1.6% of total electricity generation—making wind the second highest resource after hydroelectric power (16.6%), while the photovoltaic (PV) technology contribution was only 0.1%.

The United States alone possesses more than 8,000 GW of land-based wind resources suitable for harnessing, and an extra 2,000 GW of shallow offshore resources. With U.S. total electricity generating capacity at 1,109 GW in 2008, the untapped wind sources in United States is almost 8 times as large. Global wind movement is predicated on the earth's rotation, and regional and seasonal variations of sun irradiance and heating. Local effects on wind include the differential heating of the land and the sea, and topography such as mountains valleys. We always describe wind by its speed and direction. The speed of the wind is determined by an anemometer, which measures the angular speed of rotation and translates it into its corresponding linear wind speed in meters per second or miles per hour. The average wind speed determines the wind energy potential at a particular site. Wind speed measurements are recorded for a 1-year period and then compared to a nearby site with available long-term data to forecast wind speed and the location's potential to supply wind energy.

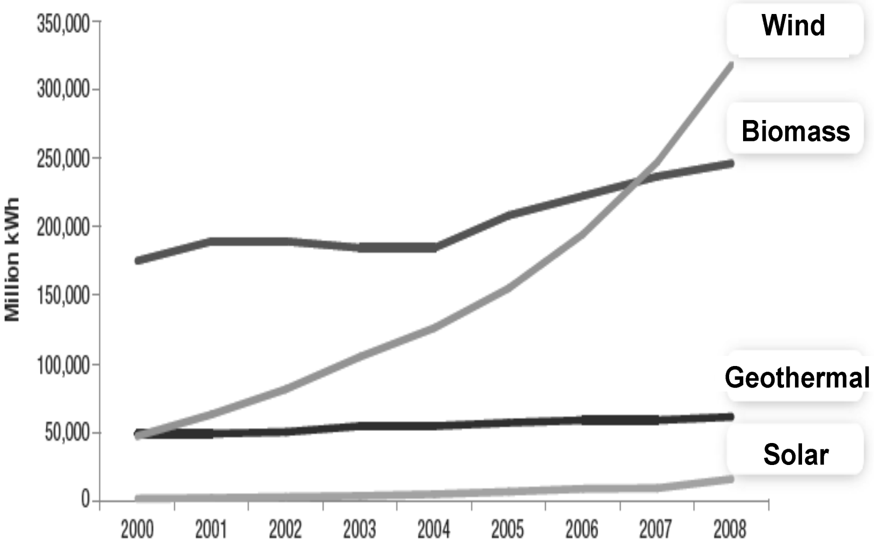

Fig. 1.2 Worldwide Electricity Generations for Wind, Biomass, Geothermal, and Solar Resources, Years 2000–2008 [69]

A wind energy resource map for the contiguous United States from the NREL [80] is shown in Fig. 1.3. This map is based on a location's annual average wind speed and wind power density (in W/m^2) at 60-m (164 ft) tower height; it can be used for initial site assessment. The coastal areas have high wind energy potential; nevertheless, 90% of the U.S. usable wind resources lie in the wind belt spanning the 11 Great Plains states.

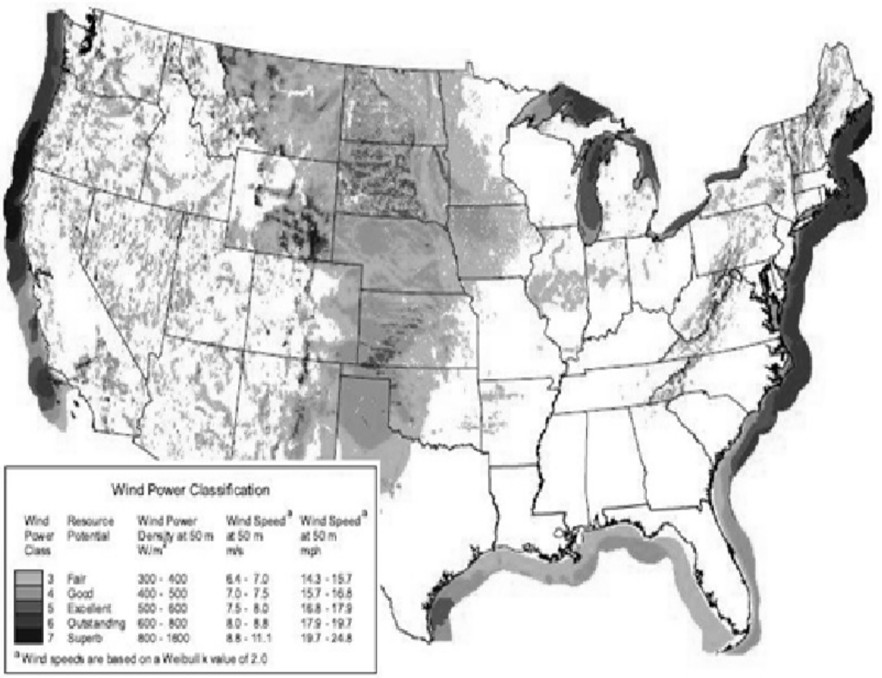

Fig. 1.3 Wind Resource Map of the Contiguous United States with Wind Power Classifications Indicated by Region [69].

Table 1.1. Wind Power Classification.

Wind Power Class	**Resource Potential**	**Wind Power Density at 50 m (W / m^2)**	**Wind Speed[a] at 50 m (m / s)**	**Wind Speed[a] at 50 m (mph)**
3	**Fair**	**300 – 400**	**6.4–7.0**	**14.3–15.7**
4	**Good**	**400 – 500**	**7.0–7.5**	**15.7–16.8**
5	**Excellent**	**500 – 600**	**7.5–8.0**	**16.8–17.9**
6	**Outstanding**	**600 – 800**	**8.0–8.8**	**17.9–19.7**
7	**Superb**	**800 – 1800**	**8.8–11.1**	**19.7–24.8**

[a]Wind speeds are based on a Weibull's [8] value of 2.0.

1.4 Microgrid of Renewable and Green (MRG) Power Grids

Figure 1.4 depicts a microgrid of renewable and green (MRG) energy system. The MRG systems consists of PV, wind power of renewable energy sources and green energy sources such as fuel cells and high speed micro turbine generating stations.

The microgrids of MRG are designed to supply power to local grid or import power on prior contract agreements. The combined heat and power (CHP) and micro turbine generating stations and some induction generator based wind generating are directly connected to AC bus of MRG systems. However, PV, variable speed wind, and fuel cell generating stations produced DC power. The PV power can be directly connected to DC-AC inverters to AC bus of MRG systems. Alternative design is based on using a DC-DC boost converter to step up the DC voltage and use higher rating DC-AC inverters. When MRG systems are synchronized to AC bus of the local power grids, the AC bus voltage and frequency are controlled by the local power grid's energy management. However, upon separation of MRG systems from the local power grid, the energy management of MRG must control the MRG AC bus voltage and frequency for stable operation. The load control is essential in proper balance of MRG's loads and generation when the MRG is separated from the local power grid.

1.5 Control Operation of Interconnected Network Bulk Power Grids

Initially designed in the early 1900s, today's power grid has evolved to become a large interconnected network that connects thousands of generating stations and load centers through a system of power transmission lines. A power grid system is designed based on the long-term load forecast of the power grid load centers, which is developed according to the anticipated needs of the community it serves. Then, an analytical model of the system is developed to project the grid's real-time operation. In a smart power grid system, a large number of microgrids operate as part of an interconnected power grid. For example, a photovoltaic- (PV-) based residential system with its local storage system and load would be one of the smallest microgrids in the smart power grid system. To understand the new paradigm of tomorrow's smart power grid design and operation, we need to understand today's electric power grid operation and costs of design.

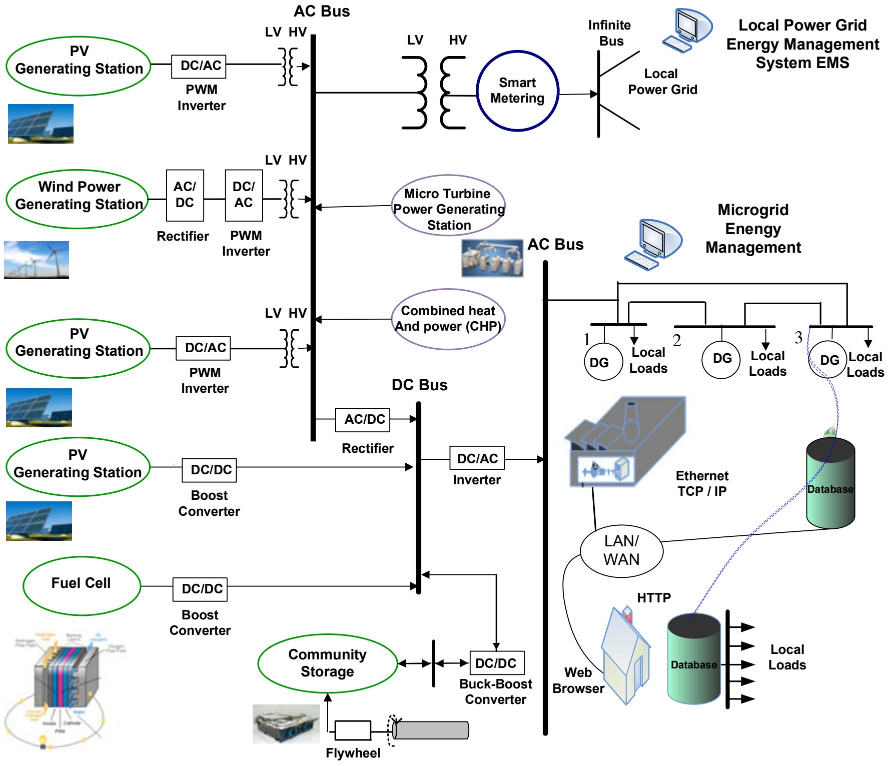

Fig. 1.4 A Microgrid Renewable and Green (MRG) Power Grid

To ensure security and reliability, power plant facilities and resources must first be planned then managed effectively. A large power grid is comprised of many elements including generating units, transmission lines, transformers, and circuit breakers. As new green energy sources are adopted into the power grid and a smart power grid is put in place, additional equipment such as DC/DC converters and DC/ AC converters must be integrated and scheduled for power grid operation. In addition, market structure and real-time pricing of energy need to be evaluated.

For stable operation of power grid, we will need to schedule power generation to supply the system loads for every second of the system's operation. The energy resources of a large power system consist of hydro and nuclear energy, fossil fuel, renewable energy sources such as wind and solar energy, as well as green energy sources such as fuel cells, combined heat and power (CHP; also known as cogeneration), and microturbines. These resources must be managed and synchronized to satisfy the load demand of the power grid. The load demand of a power grid is cyclic in nature and has a daily peak demand over a week, a weekly peak demand over a month, and a monthly peak demand over a year. Energy resources must be optimized to satisfy the peak demand of each load cycle, such that the total cost of production and distribution of electric energy is minimized.

Figure 1.5 depicts a 24-hour load variation sampled every 5 minutes. From Fig. 1.5, it can be seen that peak demand is twice the minimum power demand. The power system operator must plan the power grid energy resources and facilities to satisfy the varying load conditions.

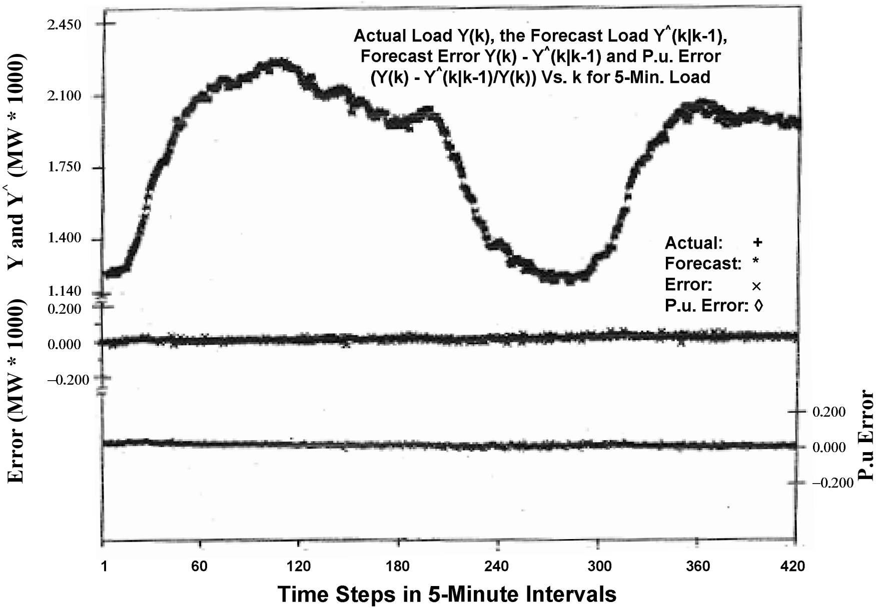

Fig. 1.5 A Twenty-Four Hour Load Variation Sampled Every 5 Minutes

The system load has a general pattern of increasing slowly during the day and then decreasing at night. The cost of generated power is not the same for all generating units. Therefore, more power generation are assigned to the least costly units. In addition, a few lines connect one power grid to another neighboring power grid. These lines are referred to as tie lines. Tie lines are controlled to import or export power according to set agreed contracts. When power is exported from a power system to a neighboring power system through the tie lines, the exported power is considered as load; conversely when imported, it is considered as power generation. The control of the power flow through these lines is prespecified on agreed schedules and they are based on secure operation and economic transactions. To control both the power flow through transmission tie lines and the system frequency, the concept of area control error (ACE) is defined as

$$ACE = \Delta P_{TL} - \beta \Delta f \tag{1.1}$$

where

$$\Delta P_{TL} = P_{Sch} - P_{Actual}$$
$$\Delta f = f_S - f_{Actual} \tag{1.2}$$

P_{Sch} : The scheduled power flow between two power networks

P_{Actual} : The actual power flow between two power networks

f_s : The reference frequency, i.e., the rated frequency

f_{actual} : The actual measured system frequency

β : The frequency bias

The AGC software control is designed to accomplish the following objectives:

1. Match area generation to area load, i.e., match the tie-line interchanges with the schedules and control the system frequency.
2. Distribute the changing loads among generators to minimize the operating costs.

The above condition is also subject to additional constraints that might be introduced by power grid security considerations such as loss of a line or a generating station.

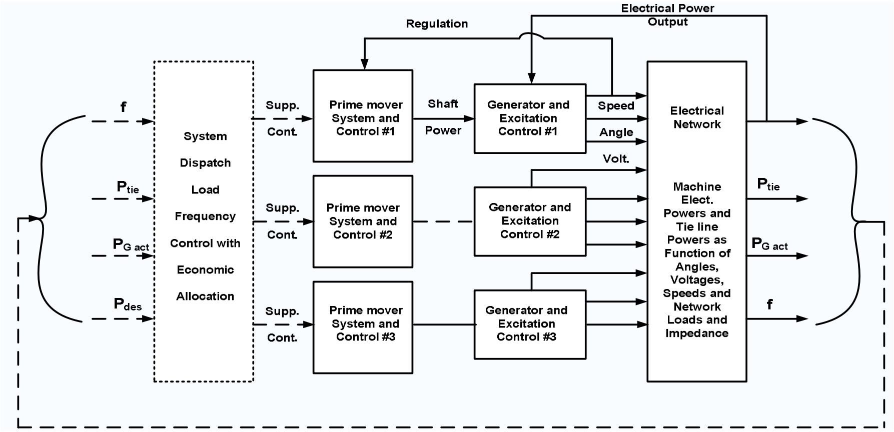

Fig. 1.6 The Automatic Generation Control (AGC).

The first objective involves the supplementary controller and the concept of tie-line bias. The term β is defined as bias and it is a tuning factor that is set when AGC is implemented. A small change in the system load produces proportional changes in the system frequency. Hence, the area control error ($ACE = \Delta P_{TL} - \beta \Delta f$) provides each area with approximate knowledge of the load change and directs the supplementary controller for the area to manipulate the turbine valves of the regulating units. To obtain a meaningful regulation (i.e., reducing the ACE to zero), the load demands of the system are sampled every few seconds. The second objective is met by sampling the load every few minutes (1–5 minutes) and allocating the changing load among different units to minimize the operating costs. This assumes the load demand remains constant during each period of economic dispatch. Figure 1.7 depicts the AGC control block diagram.

The AGC also controls the connected microgrids in a large interconnected power grid. The microgrid concept assumes a cluster of loads and its microsources, such as photovoltaic, wind, and combined heat and power (CHP) are operating as a single controllable power grid. To the local power grid, this cluster becomes a single dispatchable load. When a microgrid is connected to a power grid, the microgrid bus voltage is controlled by the local power grid. Furthermore, the power grid frequency is controlled by the power grid operator. The microgrid cannot change the power grid bus voltage and the power grid frequency. Therefore, when a microgrid is connected to a local power grid, it becomes part of the power grid network, and is subject to the power grid disturbances. Therefore, the AGC control system is designed to follow the system load fluctuations.

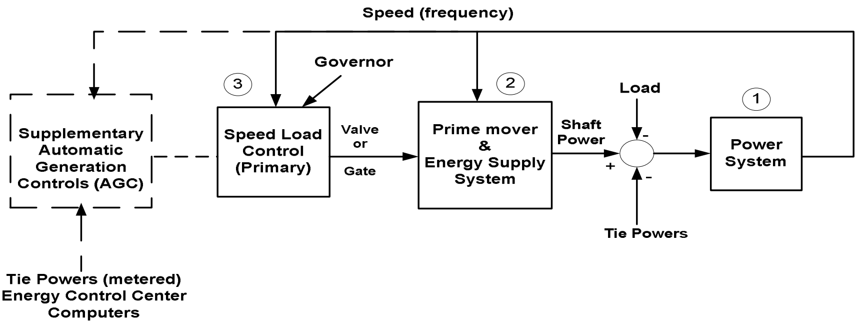

Fig. 1.7 The Automatic Generation Control (AGC) Block Diagram

1.6 Smart Power Grid

In a classical power grid, a fixed price is charged to energy users. However, the cost of energy is highest during the daily peak load operation. The classical power system operation has no control over the loads except in an emergency situation when a portion of the loads can be dropped as needed to balance the power grid generation with its loads. Therefore, most elements of grid are used for a short time during the peak power demand and they remain idle during the daily operation.

For an efficient smart power grid system design and operation, substantial infrastructure investment in the form of a communication system, cyber network, sensors, and smart meters must be installed to curtail the system peak loads when the cost of electric energy is highest. The smart power grid introduces a sensing, monitoring, and control system that provides end users with the cost of energy at any moment through real-time pricing. In addition, the advanced control systems of smart metering provide the energy users with the ability to respond to real-time pricing. Furthermore, the smart power grid supplies the platform for the use of renewable and green energy sources and adequate emergency power for major metropolitan load centers. It safeguards against a complete blackout of the interconnected power grids due to man-made events or environmental calamity. It also allows for the break-up of the interconnected power grid into smaller, regional clusters. In addition, the smart power grid enables every energy user to become an energy producer by giving the user the choice of PV or wind energy, fuel cells, and combined heat and power (CHP) energy sources and to participate in the energy market by buying or selling energy through the smart meter connection.

The bulk power grid of the United States and many other countries are already operating as a large interconnected network. The mission of the North American Electric Reliability Corporation (NERC) is to ensure the reliability and security of the America's bulk power grid. Fig. 1.8 depicts the North American electric reliability centers [75].

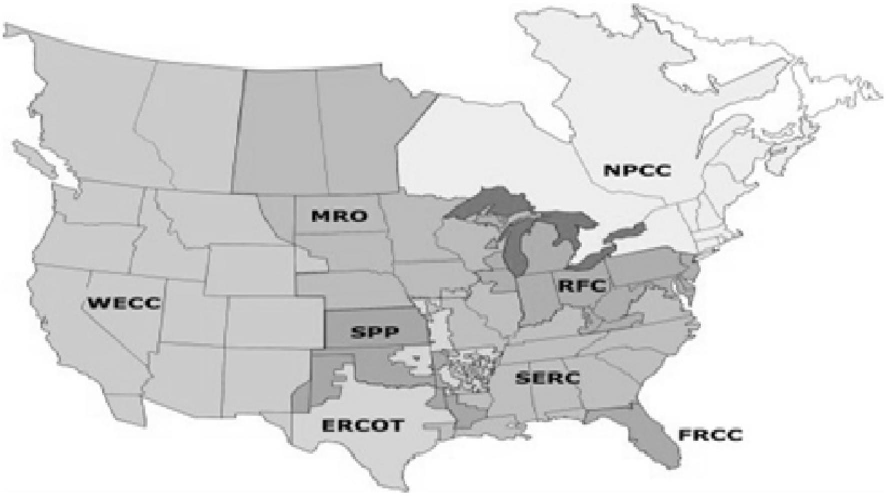

Fig. 1.8 North American Electric Reliability Centers (NERC). ERCOT, Electric Reliability Council of Texas; FRCC, Florida Reliability Coordinating Council; MRO, Midwest Reliability Organization; NPCC, Northeast Power Coordinating Council, Inc.; RFC, Reliability First Corporation; SERC, SERC Reliability Corporation; SPP, Southwest Power Pool, Inc.; WECC, Western Electricity Coordinating Council [25].

The industry is experiencing a gradual transformation that will have a long-term effect on the development of the infrastructure for generating, transmitting, and distributing power. This fundamental change will incorporate renewable generation and green energy sources in a new distributed generation program based on increased levels of distributed monitoring, automation, and control as well as new sensors. The power grid control will rely on data and information collected on each microgrid for decentralized control. In return, the microgrids and interconnected power grid will be able to operate as a more reliable, efficient, and secure energy supplier.

The technology of the power grid and microgrids has a number of key elements. Adaptive and autonomous decentralized controls respond to changing conditions. Predictive algorithms capture the power grid state (phasor measurements) for a wide area and are able to identify potential outages. The system also provides market structure for real-time pricing and interaction between customers, grid networks, and power markets. Furthermore, the smart grid provides a platform to maximize reliability, availability, efficiency, economic performance, and higher security from attack and naturally occurring power disruptions.

The implementation of an advanced metering infrastructure provides real-time pricing to the energy end users. In parallel, the penetration of renewable energy sources is providing a platform for autonomous control or local control of connected microgrids to the local power grid. A distributed autonomous control will provide reliability through fault detection, isolation, and restoration. The autonomous control and real-time pricing also delivers efficiency in feeder voltage to minimize feeder losses and to reduce feeder peak demand of plug-in electric vehicles. The maturing storage technology will provide community energy storage, which becomes yet another important element for microgrid control and allows the energy user to become an energy producer. These interrelated technologies require a coordinated modeling, simulation, and analysis system to achieve the benefits of a smart power grid.

Table 1.2 A Comparison of the Current Grid and the Smart Grid.

	Current Grid	**Smart Grid**
System communications	Limited to power companies	Expanded, real-time
Interaction with energy users	Limited to large energy users	Extensive two-way communications
Operation & maintenance	Manual and dispatching	Distributed monitoring and diagnostics, predictive
Generation	Centralized	Centralized and distributed, substantial renewable resources, energy storage
Power flow control	Limited	More extensive
Reliability	Based on static, off-line models and simulations	Proactive, real-time predictions, more actual system data
Restoration	Manual	Decentralized control
Topology	Mainly radial	Network