1

An Introduction to Modern Power Systems

1.1 Introduction

Power systems are complex structures composed of an enormous number of different installations, economic actors, and – in smaller numbers – system operators. In the traditional approach, the system is dominated by economies of scale. This means that for steadily increasing consumption, a large power generation capacity is installed, mainly nuclear, coal- or gas-fired thermal, and hydroelectric. In order to guarantee the reliability of such a system, a meshed transmission grid at high voltage has to be installed, into which the generators feed. Underlying this transmission system, function of the distribution grid is to conduct the power flow at lower voltage levels to customers, at medium or low voltage. The described power flow is mainly unidirectional, from the generators to the customers, who are connected at medium or low voltage. Only a few customers are connected at high voltage, due to their high loads. Such a system is easy to control, as most of the players (the customers) are passive, only a few actors (generators and system operators) are needed to centrally control the system, and the interfaces are well defined. The most extended economic model in this context is the vertically integrated utility. However, some of the deep fundamentals on which this structure is based can be envisioned, moving from these vertically integrated utilities to the Smart Grid distribution system [1]:

- Economies of scale are no longer applicable to the power system generation, due to the dramatic growth of distributed generation.
- The costs of the various renewable energy technologies have declined steadily due to technological advances.
- Increased environmental concerns on the part of customers and legislators.
- Regulation is enabling the emergence of different players on the electricity market (retailers, energy service providers, etc.)

Energy Storage in Power Systems, First Edition. Francisco Díaz-González, Andreas Sumper and Oriol Gomis-Bellmunt.

These fundamental changes are causing a shift from the vertically integrated approach with few control actors towards a system with a high penetration of renewable (and intermittent) generation and, as a consequence, a system that needs to be highly controlled at all voltage levels. The increasing use of renewable energy not only helps to alleviate fuel poverty, but also promotes decentralized power generation, thereby reducing the dependence on conventional grid-based energy sources. It provides electricity from small-scale generation and microgeneration; working towards reducing the increasing electricity consumption and supplying any surplus generation to the grid. Therefore, microgeneration is a key power generation trend for smart communities, both rural and urban. Distributed generation from micro–combined heat and power (CHP) installations and renewables such as small-scale wind turbines and solar photovoltaics (PV) plays a strong role in this ecosystem. New generation units from renewable energy sources must be established; however, as a result of stochastic generation, those energy resources are intermittent, and possible output fluctuations have to be balanced [2]. Energy storage applications will be used to cope with this problem [3]. All of this leads to the approach to make the grid intelligent: the Smart Grid. A Smart Grid is an electricity network that can intelligently integrate the actions of all of the users connected to it – generators, consumers, and those that do both – in order to efficiently deliver sustainable, economic, and secure electricity supplies [4]. A Smart Grid uses sensing, embedded processing, and digital communications to enable the electricity grid to be observable (able to be measured and visualized), controllable (able to be manipulated and optimized), automated (able to be adapted and to self-heal), and fully integrated (fully interoperable with existing systems, and with the capacity to incorporate a diverse set of energy sources) [5].

One prominent set of actors in modern power systems are “prosumers” (“proactive consumers”). Prosumers are common consumers who become active to help to personally improve or design the goods and services available in the marketplace, transforming both it and their own role as consumers [6]. The strategic integration of prosumers into the electricity system is a challenge. As prosumers are acting outside the boundaries of the traditional electricity companies, ordinary approaches to regulating their behavior have proved to be insufficient. The aggregated potential of flexibility makes the role of the prosumer important for energy systems with high and increasing shares of fluctuating renewable energy sources. To involve different prosumer segments, both utilities and policy need to develop novel strategies. The benefits for prosumers in modern power systems can be summarized as follows:

Economic. The Smart Grid offers the possibility of involving customers, their flexibility being used as an instrument to shed loads and secure stability. It is assumed that customers will allow the distribution system operator (DSO) access to their home automation systems, and that a value chain that links households with the transmission system operator (TSO) via the DSO will be created in such a way that the flexibility can be used systematically, as can the compensation flowing in the other direction.

Incentives. Incentives may attract customers into a demand–response regime and into distributed energy resources (DER) programs without the need for a proper compensation structure. Poor quality of supply can also be a trigger, especially when there is only one utility operating. Local DER solutions are thus a good option, although the levelized energy costs could be much higher than the supply costs from a centralized utility. Other incentives, such as environmental and social sustainability concerns, comfort, convenience, and so on, could also be drivers.

Technical. Energy storage for electricity is the main key to assuring the stability of a system with intermittent generation, at least for short periods. Ownership models and options for placement in the grid will drive very different solutions. It will be possible for electric cars to supply to the grid (vehicle to grid), which will add to the additional power system storage capability. As long as the distribution operator is in control of, or owns, these facilities, they will be operated in a different manner than if the storage is owned and operated by the community or by a third party working partly on their behalf.

The community. With DER and Smart Grid technologies, communities will gain substantial market power. Traditionally, the utility was in charge of upgrading the infrastructure in order to cater for a sufficient supply capacity and to assure quality. To build a community solution for local supply by means of Smart Grid technologies and DER seems to be the solution for future expansion, at least in rural areas.

Market and trading. New local markets and trading will arise, based on real-time trading, in order to balance the system. The flexibility of customers, local generators, and storage systems will create value on the market to balance the intermittency of renewable generation.

Social. A new form of social cooperation and commitment can be created. For example, customers could start to cooperate to assure that surplus energy that cannot be fed into the system is provided to neighbors and others who are in a position to benefit.

1.2 The Smart Grid Architecture Model

The Smart Grid Architecture Model (SGAM) framework has been developed by the Joint Working Group on standards for Smart Grids, from CEN/CENELEC/ETSI. Its methodology is intended to present the design of Smart Grid use cases by a

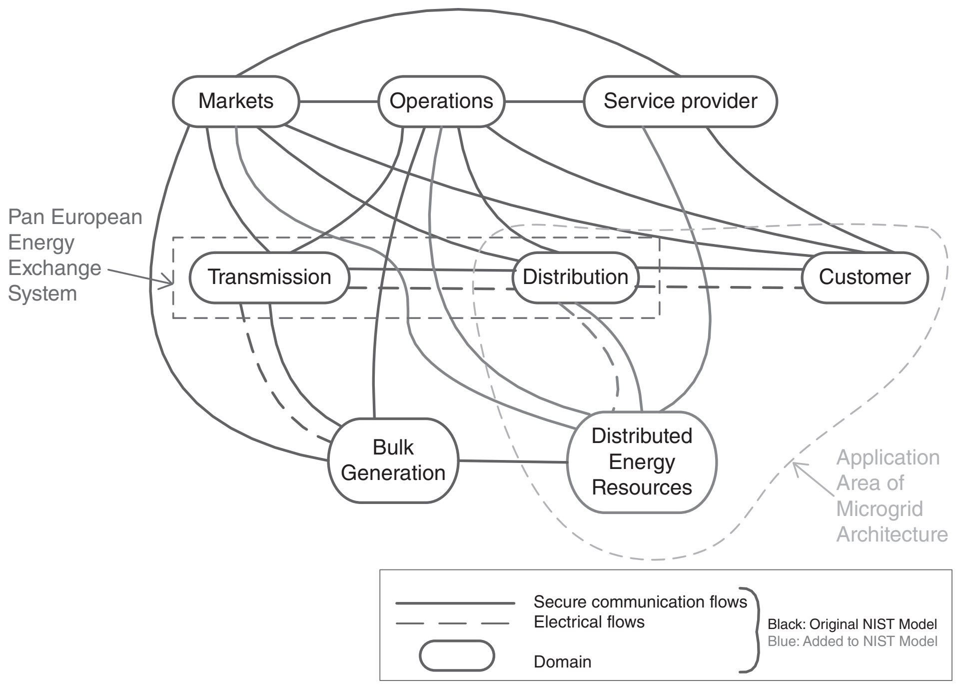

Figure 1.1 The European Conceptual Model, modified from NIST.

holistic architectural definition of an overall Smart Grid infrastructure. Apart from addressing the system architecture through a reference architecture, it also provides an overarching standardization process. The major elements of the described reference architecture are as follows:

1. A high-level framework model (the European Conceptual Model) that is an adapted version of the US NIST (National Institute of Standards and Technology) model, and which bridges between the two models, as shown in Figure 1.1.
2. The SGAM framework as a three-dimensional model with interoperability layers and Smart Grid zones and domains, and that will assist in the architectural design of Smart Grid use cases.
3. Representations of stakeholder views of Smart Grids.

The core of the framework is the Smart Grid plane. In this plane, the power system equipment and energy conversion (electrical processes) viewpoints are linked with the information management viewpoints. These viewpoints can be divided into the physical domains of the electrical and energy processes and the hierarchical zones (or levels) for their management. Figure 1.2 shows the domains and zones of the Smart Grid plane in two dimensions.

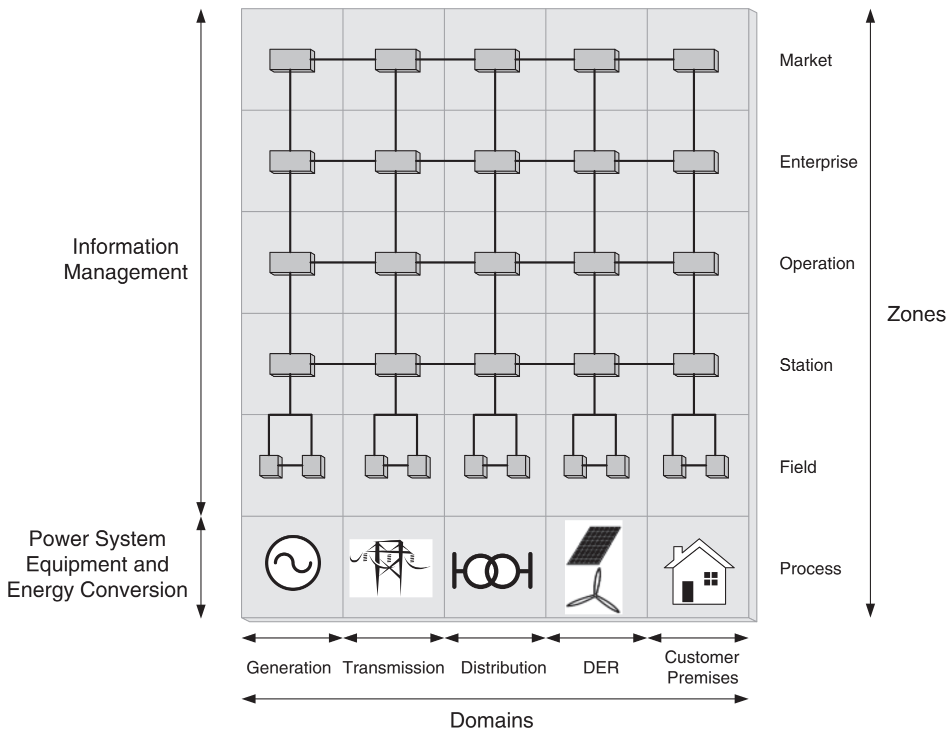

Figure 1.2 The Smart Grid plane.

The different domains represent the power system equipment and energy conversion factors divided into the following subgroups:

1. **Bulk generation**. This domain represents the bulk generation of electricity by power plants. It embodies "classical" power system generation, such as by thermal, nuclear and hydropower plants, as well as large-sized renewable generation such as offshore wind farms and large-scale PV power plants. These facilities are typically connected to the transmission system.
2. **Transmission**. This domain represents the necessary infrastructure and organization for the transmission of large amounts of power over great distances.
3. **Distribution**. This domain represents the necessary infrastructure and organization for the distribution of electricity to the final customers.
4. **DER**. This domain represents generation by means of distributed energy resources, typically using small-scale generation technologies based on renewable energy resources. The range of such generators is typically from 3 kW up to 10 MW; they are connected directly to the distribution grid and can be controlled by the DSO.

5. **Customer premises**. This domain includes the industrial, commercial, and home facilities where the electricity users interact with the distribution system. In the classical approach, this is where the consumers are located (households, industrial plants, shopping malls, etc.). In the prosumer approach, small-scale generation, electric vehicles, demand response, batteries, and so forth can also be hosted.

The Smart Grid plane is also divided into different zones as described below. The idea behind the introduction of zones in the plane is the fact that in modern power systems there are different viewpoints of the same basic processes. Therefore, the aggregation of processes into a particular zone does not interfere with the functionality of the other zones. Apart from the process zone, all of the zones represent information management. The zones are enumerated as follows:

a. **Process**. This zone includes both the primary equipment of the power system, such as the generators, transformers and substation equipment, and the transmission and distribution lines, and loads. It basically represents the classical understanding of a power system. This also includes the equipment for the physical conversion of energy between electricity, solar, heat, water, wind, and so on.
b. **Station**. This zone represents the aggregation level for fields; for example, for data concentration or substation automation.
c. **Operation**. This zone hosts the power system control and operation modules for the respective domains; for example, for the distribution domain, the distribution management system (DMS), for the generation and transmission domain, the Energy Management System (EMS), and so on.
d. **Enterprise**. This zone represents the commercial and organizational processes of an enterprise, including the services (staff training, customer relations management, billing and procurement, etc.) and asset management of the various actors.
e. **Market**. Finally, this zone reflects the possible market involvement of the various actors along the whole production chain.

To complement the Smart Grid plane, five abstract layers are added in order to represent the different viewpoints of the system. This will provide a clear presentation and simple handling of the presented architecture model, enabling the interoperability of the system. Figure 1.3 shows the layer structure above the Smart Grid plane. The different layers are specified as follows:

A. **Components**. In this layer, the physical distribution of all the components participating in the Smart Grid is represented (sensors and actors): system actors, applications, power system equipment, protection and control devices, network infrastructure, and so on.

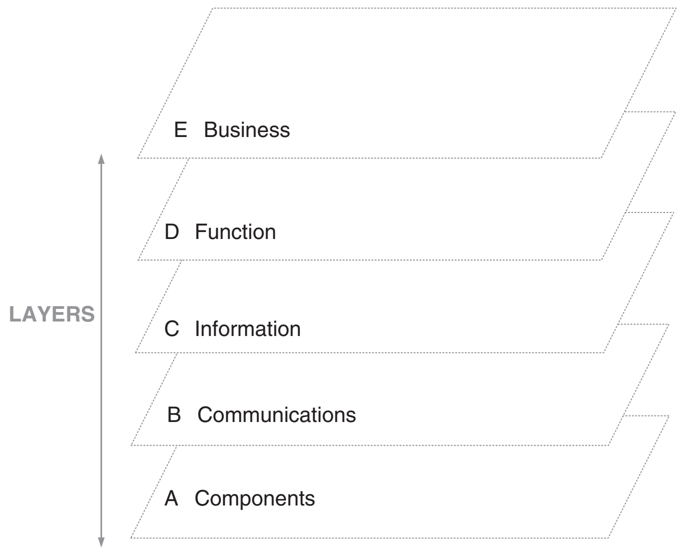

Figure 1.3 The layers of the Smart Grid.

B. **Communication**. This layer describes the communication protocols and mechanisms for exchange of information (connectivity). This layer is important to guarantee interoperatibility.
C. **Information**. This layer represents data that are used and exchanged between functions, services, and components: data concerning power quality, power flow, and protection, from DERs, customers, and meter readings, and so on.
D. **Function**. This layer contains the definition of the functions and services and their relationships from an architectural viewpoint. It describes how the functions or services are performed independently of actors and physical implementations, systems, or components.
E. **Business**. This layer represents the business view of the Smart Grid. It can be used to encompass the market, regulatory, and economic structures, as well as the policies, business models, products, and services of the market participants.

The SGAM is a very holistic view of the whole Smart Grid architecture, including widespread viewpoints on the power system. The classical approach to power engineering (i.e., all the domains of the process zone of the component layer) is enriched by the information management zones and all the other layers. The complementary zones and layers are defined in order to provide a clear description and to enable interoperability. This does not mean that they did not exist before; they were integrated in the power system engineering approach. In separating them, the clarity of the solution is enhanced.

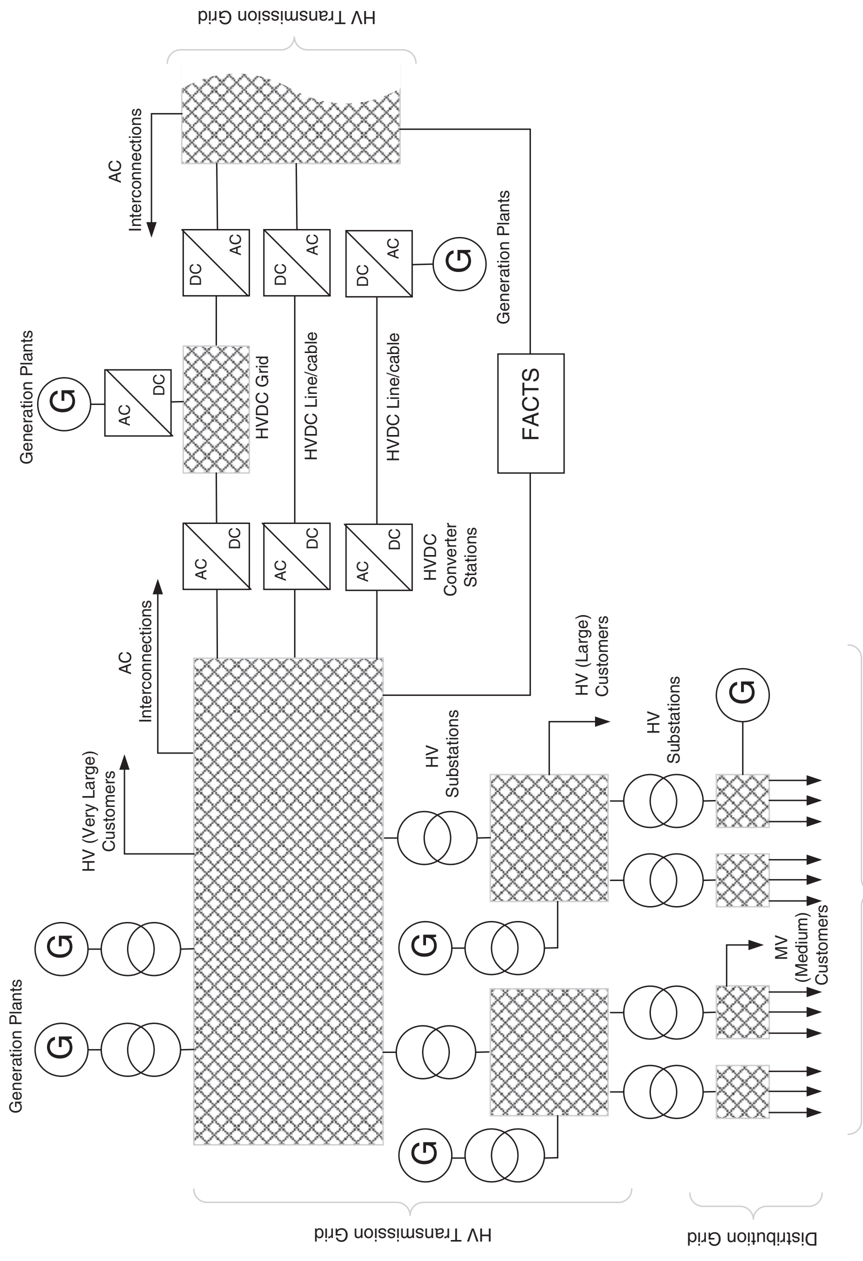

Figure 1.4 The basic structure of a power system.

JWST682-c01 JWST682-Diaz Printer: Yet to Come February 23, 2016 8:13 Trim: 244mm × 170mm

1.3 The Electric Power System

1.3.1 The Structure of the Power System

The way to organize the electricity system is shown in Figure 1.4. From the SGAM viewpoint, we will focus on all the domains of the process zone of the component layer. The system is divided into generating plants at 6–20 kV (the Bulk Generation domain); a high-voltage transmission grid using 66, 110, 132, 220, 400, 500, and 700 kV (the Transmission domain); the distribution grid, from 3 to 36 kV; the low-voltage grid (the Distribution domain); and consumption (the Customer Premises domain); with the associated protection and control systems. Substations in transmission grids are one of the fundamental components and they have mainly three functions: the first is interconnection of the lines; the second is the power transformation to feed the distribution networks that reach consumers; and, third, they are centers where measurement, protection, interruption, and dispatch operations take place. However, nowadays this structure is complemented by novel approaches to grid structures. Basically, this originated with the need to integrate renewable energy generators at different levels in the power grid. In this sense, there are two approaches that complement the rollout of renewable energy. On the one hand, there is massive connection of small-scale renewable generators at the distribution level (low and medium voltage), mainly photovoltaic installations in households or small-scale generation in light-industrial or commercial facilities (the DER domain). On the other hand, utilities and big investors are increasing their portfolio with renewable generation assets. These plants are at the scale of several megawatts up to hundreds of megawatts. They are considered to operate like traditional power plants and therefore TSOs are asking for compliance with grid codes. In order to intergrade remotely located renewables (in the most common case, offshore wind) in the system, high-voltage direct current (HVDC) technology is employed to connect such plants to the transmission grid (the Bulk Generation domain). HVDC has been employed in the past to perform long-distance transmission using thyristor-based line-commutated converter (LCC) technology. In recent years, voltage-source converter (VSC) technology has been available, which allows better controllability of the link. Nowadays, point-to-point HVDC links using both LCC and VSC technology are the state of the art, and are fixed parts of the power system structure. A logical step is to interconnect the DC lines and create a DC grid in order to increase the reliability of the system.

1.3.2 The Fundamentals of Power System Analysis

The analysis of power systems is fundamentally related to the time horizon with which a certain problem is analyzed. Figure 1.5 shows the relationship between the time horizon and the problem to be analyzed. Table 1.1 shows a small literature sample classified by the time horizon of the problem. We are aware that there are plenty of

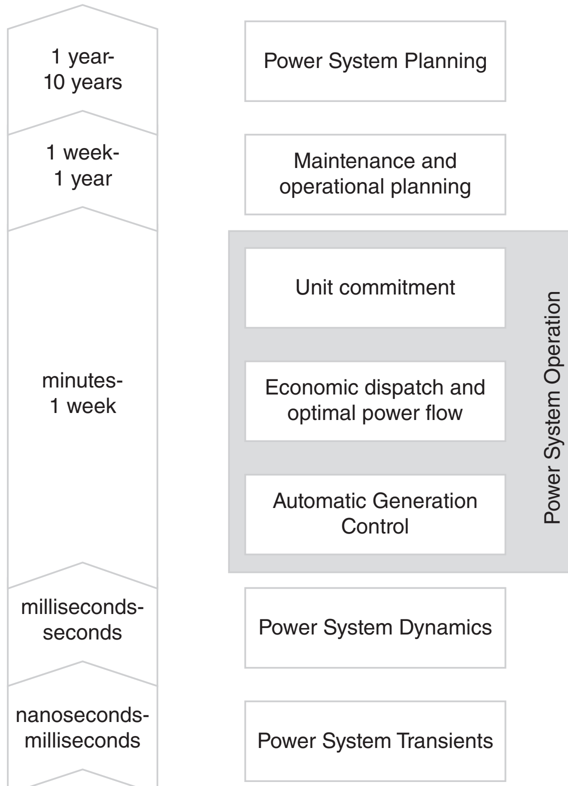

Figure 1.5 A time-horizon perspective of power system studies.

good references that we cannot cite in this book. Readers may take into account the fact that this book is focused on storage application in power systems. In this sense, this chapter aims to provide useful references to literature (see Table 1.1) if readers need to deepen their knowledge of some aspects of power systems.

Power system transients. This type of analysis deals principally with transient events such as switching, faults, and lightning, and covers response frequencies from DC to MHz. The nature of transients is that they have high-frequency components (with rapid attenuation) and also that large voltages and currents can occur. To analyze transients in power systems, it is important to understand their nature through the collection of good data, to form a detailed mathematical model of the system and to solve the resulting coupled differential equations.

Power system dynamics. This type of analysis treats the dynamic properties of electrical machines (synchronous machines), networks, loads, and

Table 1.1 A literature sample on power system modeling and analysis.

Time horizon	Author(s)	Source	Type of modeling or analysis	Reference
Power system transients	L. van der Sluis	*Transients in Power Systems*	Modeling components and analysis of power system transients	[8]
Power system dynamics	P. Kundur	*Power System Stability and Control*	Dynamic modeling and control of power systems	[7]
Power system operation	E. Handschin, A.F. Otero, and J. Cidrás	Steady-state single-phase models of power system components, Chapter 2 in *Electrical Energy Systems*	Modeling of the system components in steady state	[9]
Power system operation	A. Gómez-Expósito and F.L. Alvarado	Load flow, Chapter 3 in *Electrical Energy Systems*	Load flow analysis of power systems	[10]
Power system operation	A.J. Wood, B.F. Wollenberg, and G.B. Sheblé	*Power Generation, Operation and Control*, Chapters 3 and 4	Economic dispatching and unit commitment	[11]
Power system operation	D. Kirschen and G. Strbac	*Fundamentals of Power System Economics*	Electric markets	[12]
Maintenance and operational planning	P. Gill	*Electrical Power Equipment Maintenance and Testing*	Maintenance	[13]
Power system planning	H. Seifi and M.S. Sepasian	*Electric Power System Planning*	System planning	[14]
Power system operation and dynamics	D. Van Hertem, O. Gomis-Bellmunt, and J. Liang	*HVDC Grids for Transmission of Electrical Energy: Offshore Grids and a Future Supergrid*	HVDC transmission	[15]
-	ABB (formerly Westinghouse)	*Electrical Transmission and Distribution Reference Book*	Transmission and distribution manual	[16]
-	ABB (formerly BBC)	*Switchgear Manual*	Transmission and distribution manual	[17]

interconnected systems on a scale of milliseconds to seconds. It includes control of turbines, power exchange between networks, the behavior of machines in the event of disturbances, transient stability, the equal area criterion, models for small disturbances, voltage control, and the dynamic behavior and control of flexible AC transmission systems (FACTS) devices. The resulting differential equations are solved by analytical or numerical methods, including stability analysis, using approaches from control theory.

Power system operation. This type of analysis includes *steady state analysis*, *automatic generation control* (AGC), *economic dispatch and optimal power flow*, and *unit commitment*. In steady state analysis, basically a stable operation (no time frame is defined) of the power system is analyzed in order to determine voltage drops in the system, loading of the network components, and generator dispatching. AGC is a system for adjusting the power output of multiple generators at different power plants in response to changes in the load on a scale of seconds to minutes. Economic dispatch determines the best way to minimize the overall generator operating costs of a set of generators with differing respective cost functions, over periods ranging from hours to days. The objective of an optimal power flow to combine the power flow with economic dispatch in order to minimize the cost function of the overall system, such as the operating cost, taking into account realistic constraints such as line loads and generation limits. The unit commitment problem involves finding the least-cost dispatch of the available generation resources to meet the electrical load in a long-term perspective.

Maintenance and operational planning. In this type, strategies for the maintenance of electric power equipment are treated, and operational planning for normal and emergency situations is considered. Its time horizon is typically from weeks up to a year. It includes testing (such as of insulating materials and failure modes, and the impact of maintenance on arc-flash hazards) and various maintenance strategies (corrective, preventive, and reliability-centered maintenance).

Power system planning. This is typically carried out over a period of years. As for most planning situations, it is modeled as an optimization problem and the decision-making process is based on both technical and economic considerations. Both generation expansion planning and network expansion planning are treated. With regard to network analysis, steady state analysis techniques (AC or DC load flow, reactive power load flow, etc.) are employed and attention is also paid to security issues.

Security requires special attention in the analysis of power systems. It is defined as the degree of risk in its ability to overcome disturbances (contingencies) without interruption of customer supply [7]. Contingencies refer to outages such as the sudden and unscheduled loss of service of one or more of the main power system components [7]. Usually, power systems are operated according to the deterministic $N-1$ criterion. This means that the permanent loss of one power-system component should not affect the stable operation of the rest of the system. No time frame can be assigned to this kind of analysis.

1.4 Energy Management Systems

An Energy Management System (EMS) is a system that uses computer-aided tools to monitor, control, and optimize the performance of the electric power system. Figure 1.6 shows a schematic of an EMS and its potential application. In utilities, they are used for the generation, transmission, and distribution systems, as well as for monitoring and control functions (where they are usually known as supervisory control and data acquisition, or SCADA, systems). A range of drivers are affecting this development: energy and climate policy, technology in general, and consumer needs. For an EMS, this means local renewable electricity generation such as PV and wind, infrastructure for measuring and managing electricity generation and usage, and new types of energy resources characterized by rapid pivoting and new output profiles. New consumption profiles are a consequence of electric vehicles, induction cookers, and the instant heating of tap water. These developments result in completely new challenges for an EMS in terms of increased dynamics and unpredictability in distribution. Novel needs also include balancing intermittent generation, the difficulty of predict its generation, and capacity problems in distribution systems due to the increased demand. The traditional approach to this type of challenge is to increase the capacity of the generation and power grids. In modern EMS approaches, the optimal operation of such systems can delay these investments.

An alternative approach is to leverage the flexibility of electricity systems by the end users; that is, households, commerce, and industry. The flexibility can come from relocation or reduction of electricity consumption, the use of energy storage, and active management of the generation and conversion of electricity. To achieve this, one must depend on effective decision models for the prediction of electricity consumption (e.g., charging requirements for electric vehicles), electricity generation in buildings and industrial facilities, the monitoring of available flexibility, and optimization models for the utilization of the available sources of flexibility. Furthermore, new technical possibilities are emerging due to the use of energy storage systems (ESSs). Various technologies, such as flywheels, supercapacitors, compressed gas, or battery banks are already being used in the electric power system to offer solutions for peak-load reduction, ancillary services transmission, system reliability, and support

JWST682-c01 JWST682-Diaz Printer: Yet to Come February 23, 2016 8:13 Trim: 244mm × 170mm

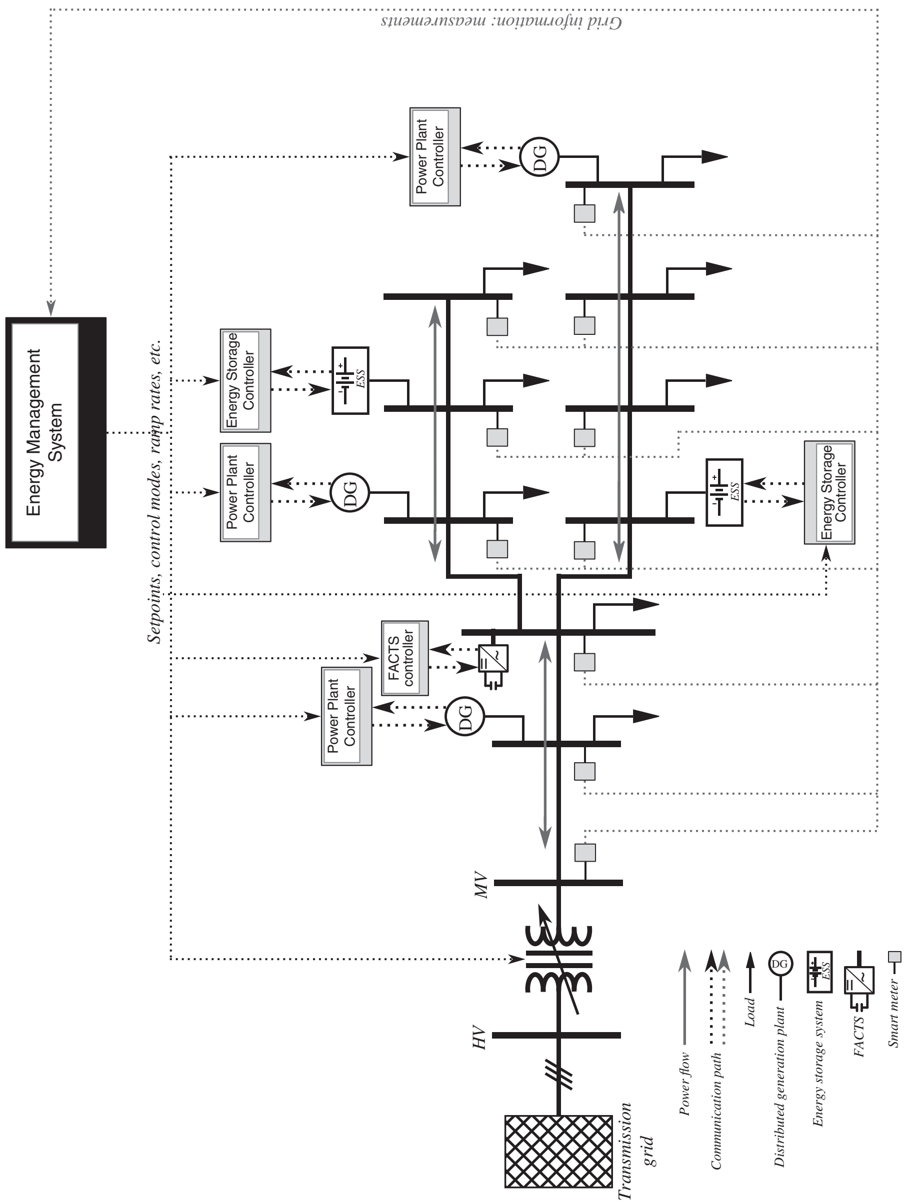

Figure 1.6 The operating principle of an EMS.

for renewables. Moreover, small-ESS technologies are also expected to grow in a distributed fashion along the electric power system, due to the falling price of storage technologies. Such small storage solutions would be mainly based on electric batteries, which would offer additional controllability to the EMS. A large amount and broad distribution of batteries would decouple generation from consumption, opening up new energy management scenarios and opportunities, and also offering new market rules and possibilities for grid operators.

1.5 Computational Techniques

The recent achievements in computational techniques and the scientific developments in rigorous methodologies for the solution of generic problems enable the power system research community to incorporate such technologies to solve specific problems.

1.5.1 Optimization Methods and Optimal Power Flow

Problems in power systems are complex and are usually associated with a large data set. The diversity and versatility of optimal power flow (OPF) formulations does not allow us to find a single optimization technique to solve all OPF problems. Therefore, the solution algorithms that are developed are specifically tailored for the specific problem that needs to be solved. The types of solution algorithm can be divided into deterministic and heuristic methods. Deterministic algorithms provide exact solutions and are designed to guarantee that they will find the optimal solution in an acceptable period of time. However, for very difficult optimization problems (e.g., the so-called "NP-hard" problems), the full resolution increases exponentially with the dimension of the problem. The heuristics do not guarantee an optimal solution; however, they usually find "good" solutions in a "reasonable" amount of time. Generally, heuristic algorithms are very specific and problem-dependent. In order to apply a heuristic algorithm in a problem-independent algorithmic framework, meta-heuristic algorithms have been developed. They provide a set of guidelines or strategies for the development of heuristic optimization algorithms. The deterministic solution techniques for OPF problems are continuous nonlinear programming (NLP), linear programming (LP), quadratic programming (QP), mixed integer linear programming (MILP), and mixed integer nonlinear programming (MINLP). The heuristic solution techniques applied to OPF problems are ant colony optimization (ACO), artificial neural networks (ANN), bacterial foraging algorithms (BFA), chaos optimization algorithms (COA), various evolutionary algorithms (EAs), particle swarm optimization (PSO), simulated annealing (SA), and tabu search (TS). Furthermore, storage elements imply large investments and high operational costs besides the operating constraints, which must be considered in attempts to find optimal solutions. The optimization tools chosen must be tailored to the nature of each case and each system. It is important to emphasize that once storage devices are included in a system, several variables, such as the location, cost, benefit, and charging scheduling, must be also considered in the optimization algorithm alongside the system requirements and constraints.

1.5.2 Security-Constrained Optimal Power Flow

Recent changes in power systems are influencing the way in which they are planned, operated, and controlled. A large penetration of renewable energy generation implies greater uncertainty in systems operation. For instance, in a system with a large penetration of offshore wind, the intermittency of this power generation can compromise its secure operation, as the wind power is not always available when needed to react to an outage, and therefore the accomplishment of the $N - 1$ contingency criterion in some cases (or, better, in some instances) is not guaranteed. The European transmission system is being extended by combining both AC and DC technologies. New devices installed in power grids, such as HVDC or FACTS, increase the controllability of situations but also their complexity. With the increased complexity, the reliability decreases. Therefore, novel methodologies are needed to extend the contingency operations with novel control functionality, taking security aspects into account. Some recent research has been done regarding a method called Security Constrained Optimal Power Flow (SCOPF), which takes the integration of intermittent generation into account. Aragüés *et al.* [18] analyse the secure and optimal operation of hybrid HVAC–HVDC connected systems with a large penetration of offshore wind, taking into consideration the system's spinning reserves. The operation and economic consequences of requiring higher or lower security are investigated. The SCOPF for hybrid AC–DC power systems allows us to optimize a specified objective function while guaranteeing all the equality and inequality constraints limiting the electrical variables. Security constraints are included, and both the preventive and corrective actions of the TSO can be used to ensure security. Additionally, the SCOPF algorithms must also deal with novel trends in electric power systems, such as the integration of ESSs. Combining renewables and storage could improve grid security and stability. As the penetration of renewables increases, TSOs are asking renewable plants for provide support to the electric power system. As a result, grid codes are starting to regulate generation, imposing technical challenges that could be surmounted through the integration of storage. In such a way, energy storage would allow us to provide voltage regulation, frequency regulation, fault support, ramp rate restrictions, and also power curtailments.

1.6 Microgrids

Microgrids are conceived as self-contained electricity systems with the ability to operate independently of the grid. They could be stand-alone systems; or if tied to the grid, they could be operated by islanding from the grid. Microgrids are also characterized as the “building blocks of Smart Grids.” The organization of microgrids is based on the control capabilities over the network operation offered by the increasing penetration of distributed generators. In general, microgrids are an integration platform for supply-side (microgeneration) storage units and demand resources (controllable loads) located in local distribution grids. In the microgrid concept, there is a focus on the local supply of electricity to nearby loads. A microgrid is typically located at the LV level, with a total installed microgeneration capacity below the MW range (with some exceptions). The improvement in storage technologies is also enhancing the horizon regarding microgrid performance. Energy storage is a very important requirement in microgrids, as it allows us to manage energy efficiently but also incorporates new technological possibilities. With the integration of small storage systems in a distributed fashion, close to the point of consumption, new grid structures and topologies can be glimpsed. In this way, these new configurations will lead to new grid concepts, such as prosumers, and also to small grid segments incorporating the storage capacity of electric vehicles into the grid facilities (V2G). Microgrids are normally capable of operating in both grid-connected and emergency (islanded) states. The majority of the future microgrids will be operated mostly in grid-connected mode because of the advantages of bidirectional power interchange. Long-term islanded operation requires large storage sizes and capacity ratings of microgenerators to guarantee the load supply. Demand flexibility and demand response also enable such operation conditions. The difference between microgrids and passive grids penetrated by microsources lies mainly in the management and coordination of the available resources. Operation in islanded mode presents an important challenge, and further research is needed in order to coordinate the power electronic interfaces between resources to guarantee voltage and frequency stability. Usually, hierarchical control at four levels is proposed, based on their bandwidth. The upper level is also called tertiary control or EMS: it is responsible for power flow management and can determine both the active and reactive power, the voltage levels, and the power exchanges with the main grid. The EMS and lower-level controls of the microgrid are responsible for guaranteeing the voltages and power transfer limits inside the microgrid, and therefore the EMS must take the electrical constraints into consideration when it comes to generating power references for the local control units.

1.7 The Regulation of the Electricity System and the Electrical Markets

The electricity markets are described as a very important zone in the Smart Grid plane. Markets are a way of organizing the distribution of commodities in an efficient manner such that the conditions can enhance perfect competition between the actors. However, electricity is not a simple commodity. In order to ensure the reliable and continuous delivery of significant amounts of electricity, the system needs bulk generation plants, transmission and distribution grids, and various control and monitoring functions to maintain the system in a technically feasible state. The simple fact that there is a limited amount of storage capability in the grids (for technical and economic reasons) makes the electricity market unique. The technical differences of the "electricity" commodity have a profound effect on the organization and rules of the electricity markets. Several models of competition have been discussed [12] and are listed below:

Monopoly. This model describes the traditional monopoly utility. In some cases, the utility integrates the generation, transmission, and distribution of electricity; while in other cases, the generation and transmission are integrated in one utility, which provides the electricity to distribution companies that operate within a local monopoly.

Purchasing agency. In this model, independent power producers are integrated into the system, competing between each other and with utility-owned generators. The utility acts as a purchasing agent, buying the best generator offers, and distributes the energy to the customers in a monopoly transmission and distribution system.

Wholesale competition. This model is a hybrid, because there is competition at the generation level but not at the retail level. In this model, distribution companies purchase the electricity directly from generating companies on a wholesale electricity market that takes place mainly at the transmission level. The distribution companies retain a monopoly at the retail level. Large consumers are the exception to this system, because they can purchase electricity directly on the market.

Retail competition. This model allows all consumers to choose their supplier freely. In practice, only large consumers will participate in the wholesale market directly. To enhance the complex participation in the electricity market of small and medium consumers, those consumers purchase their electricity via retailers that are operating in the wholesale market. In this model, the distribution activity is separated from the energy sales to create competition on the retail side, with the objective of reducing electricity prices for consumers. For physical reasons, the transmission and distribution remain as monopolies, regulated by the governmental agencies, and their costs are charged to the consumers.

The introduction of competition in electricity supply has been accompanied by the privatization of utilities. However, privatization is not a condition for the introduction of competition – all of the models described above can also run with public ownership. A market is a mechanism for matching the supply and the demand for a commodity by finding an equilibrium price. Markets can be organized in different ways; each type is complementary to the others and therefore they can be combined. The various types are described as follows:

Spot market. In a spot market, the seller delivers the goods immediately, with no conditions regarding delivery. The buyer also pays for the goods immediately and no party can withdraw once the deal has beendone.

Forward contracts. Forward contracts fix the price and quantity for a future delivery of a commodity, in order to share the price risk.

Future contracts and futures markets. This type is a secondary market, in which the producers and consumers buy or sell forward contracts.

Options. In this type of contract, the contract holder can decide whether or not to make use of the contract. The "call option" gives the holder the right to buy a given amount of a commodity at a price, and the "put option" gives its holder the right to sell a given amount at a specified price.

Given these elementary ways to regulate the electricity system and the available market structures, they can be applied to the electricity system. Due to the particular technical implications of the commodity, the operation of the electricity market is basically organized using the following models:

Bilateral trading. In this type of trading, two partners (a buyer and a seller) agree on a transaction of electricity at a certain price.

Electricity pools. In this type of trading, a centralized pool is created, in which all producers and consumers act. There, all participants are buying and selling electricity, regardless of who might be the final supplier or consumer. This type of trading is well established in power systems, as the transactions and the physical commodity exchange (power flow) are decoupled from each other.

The managed spot market. Electricity systems need to handle imbalances between generation and loads. Therefore, an organized spot market has to be established in order to adjust the daily schedule by means of short-term trading. Since the spot market is the last resort for electrical energy, it strongly affects the other markets.

For secure and reliable operation of the power system, certain "ancillary services" have to provided. These services maintain the quality of the supply in an acceptable range by regulating the frequency, or providing a spinning reserve or power to compensate for imbalances. Typically, these tasks are performed by very flexible generation plants. Also, the TSO could ask for generator schedules to be modified for security reasons, in order to handle the overloading of power lines or transformers. All these commercial transactions have to be settled between all participants and market types as well as with the ancillary services. This process is very complex for the electricity system, and for this reason the settlement system for electricity markets is typically centrally organized.

1.8 Exercise: A Load-Flow Algorithm with Gauss–Seidel

The load-flow study is the most important numerical analysis to determine the flow of electric power at steady state in meshed power systems. This study aims to obtain the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line for a given load and generation scenario. There are several numerical algorithms that solve such problems [19]; for example, Gauss–Seidel, Newton–Raphson, and the fast decoupled method. In this exercise, a given hypothetical grid (Figure 1.7) should be solved by means of computer programming, applying the simplest load-flow method, namely Gauss–Seidel. A simple case will be treated: a six-bus system with only one slack generator, with the rest of the buses being PQ nodes. The following solution has been written in MATLAB® and is presented in a number of steps:

1. For given bus data, a function is created that shows the data in "per unit" (pu) related to the buses of the system, specifying the bus number, the bus active power generation, the bus reactive power generation, the bus active power load, and the bus reactive power load, respectively:

```
function data = busdata()
%               | Bus |  PGi | QGi | PLi   | QLi  |
data =     [        1    0.0    0       0       0;
                    2    0.8    0.4     0       0;
                    3    0.7    0.3     0       0;
                    4    0.0    0       0.6     0.3;
                    5    0.0    0       0.5     0.2;
                    6    0.0    0       0.9     0.5];
```

2. Next, the power lines or transformers are identified by the following function containing the line data matrix. First, the bus numbers from where the line is coming and to where the line is going are identified. Then, the resistance, reactance, and susceptance of the line, in pu, are introduced:

```
function data = linedata()

%          |  From |  To   |    R    |    X    |    B/2 |
%          |  Bus  | Bus   |         |         |        |
data       = [ 1      2        0.10     0.20      0.02;
               1      4        0.06     0.20      0.02;
```

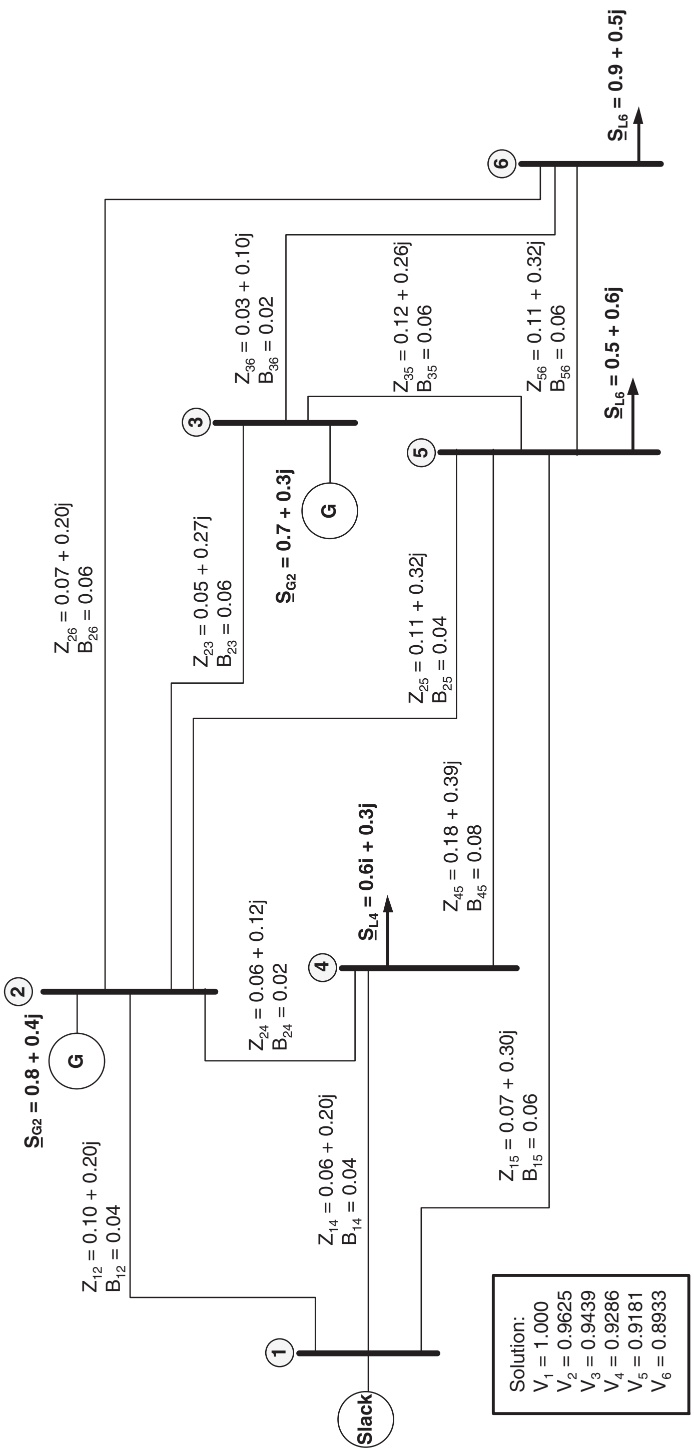

Figure 1.7 The six-bus system for the load-flow study.

```
1     5     0.07    0.30    0.03;
2     3     0.05    0.27    0.03;
2     4     0.06    0.12    0.01;
2     5     0.11    0.32    0.02;
2     6     0.07    0.20    0.03;
3     5     0.12    0.26    0.03;
3     6     0.03    0.10    0.01;
4     5     0.18    0.39    0.04;
5     6     0.11    0.32    0.03;];
```

3. After that, a function to generate the admittance matrix is created by applying the following equations:
   - Diagonal elements:

$$\underline{Y}_{ii} = \sum_{i=1}^{n} \text{admittances: connected to bus } i$$

   where n is the number of buses in the grid.
   - Off-diagonal elements:

$$\underline{Y}_{ij} = -\sum \text{admittances connected between bus } i \text{ and bus } j.$$

   where $i \neq j$.

```
function ybus=ybusfct();
lines= linedata(); %Read the line data
fb=lines(:,1); %Read the from bus data
tb=lines(:,2); %Read the to bus data
r=lines(:,3); %Read the resistance data in pu
x=lines(:,4); %Read the reactance data in pu
b=lines(:,5); %Read the susceptance data in pu
zl=r+i*x; % Calculate the line impedance
yl=1./zl; %Calculate the admittance
bl=i*b; %Calculate the susceptance
nbus=max(max(tb), max(fb)); %Read the max. number of buses
nlines=length(fb); %Read the max. number of lines
Y=zeros(nbus,nbus); %Create an empty admittance matrix
for k=1:nlines %Admittance matrix creation algorithm for
off-diagonal elements
    Y(fb(k),tb(k))=Y(fb(k),tb(k))-yl(k);
    Y(tb(k),fb(k))=Y(fb(k),tb(k));
end
for m=1:nbus %Admittance matrix creation algorithm for diagonal
elements
    for n=1:nlines
        if fb(n)== m
```

```
            Y(m,m)=Y(m,m)+yl(n)+b(n);
        elseif tb(n)== m
            Y(m,m)=Y(m,m)+yl(n)+b(n);
        end
    end
end
ybus=Y;
```

4. Calculation of the voltages from the given data, using the Gauss–Seidel method. The voltage of each bus for iteration $m + 1$ can be calculated from the active power P_i and the reactive power Q_i, the admittance matrix values, and the voltages from the iteration m by

$$\underline{V}_{i(m+1)} = \frac{P_i - jQ_i}{\underline{Y}_{ii}\underline{V}^*_{i(m)}} - \sum_{k\neq i}^{n} \frac{\underline{Y}_{ik}}{\underline{Y}_{ii}} \underline{V}_{k(m)}, \qquad (1.1)$$

$$i = 2 \ldots n.$$

The value of the starting voltages for buses 2–6 is assumed to be 1 pu (flat start). For simplification of the algorithm, the voltage calculation can be performed by

$$\underline{YV} = \sum_{k\neq i}^{n} \underline{Y}_{ik}\underline{V}_{k(m)}$$

$$\underline{V}_{i(m+1)} = \frac{\dfrac{P_i - jQ_i}{\underline{V}^*_{i(m)}} - \underline{YV}}{\underline{Y}_{ii}}, \qquad (1.2)$$

$$i = 2 \ldots n.$$

The following code is the main program that has to be executed in the same folder where all the other functions are saved:

```
ybus=ybusfct();
bdata = busdata(); %Read the bus data
bus=bdata(:,1); %Read the buses
GenP=bdata(:,2); %Read the generation active power
GenQ=bdata(:,3); %Read the generation reactive power
LoadP=bdata(:,4); %Read the load active power
LoadQ=bdata(:,5); %Read the load reactive power
nbus=max(bus); %Read the number of buses
P=GenP-LoadP; %Calculate the active power injection
Q=GenQ-LoadQ; %Calculate the reactive power injection
```

```
V=ones(nbus,1); %Initialvoltages. Flat start at 1\,pu
Viter=V; %Storing the voltage of the current iteration
tol=1; %initial value of the tolerance
iter=1; %number of iterations
while ((tol> 0.00001)& (iter<100))
    for i=2:nbus;
        YV=0;
        for k=1:nbus %Calculation of the sum of YV
           if i ~ =k
                YV=YV+ybus(i,k)*V(k);
           end
        end
        V(i)=((P(i)-j*Q(i))/conj(V(i))-YV)/(ybus(i,i)); %Gauss Seidel
        algorithm
    end
    iter=iter+1; %Iteration counter
    tol= max (abs(V-Viter)); %Tolerance calculation
    Viter=V; %Storing the result of the current iteration
end
display(iter);
display(abs(V));
```

An additional function is provided to convert the polar coordinates of the complex number into rectangular coordinates:

```
function rect = pol2rect(mag,angle)
rect = mag*cos(angle) + j*r*sin(angle);
```

The resulting voltages are obtained after 38 iterations and are displayed in Figure 1.7 (from bus 1 to bus 6, in pu).