CHAPTER 1

INTRODUCTION

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POWER SYSTEM RELIABILITY is a primary concern for power system engineers in planning and operation of the power grids to ensure adequate and secure electricity service to consumers. As an electrical network, a power system should be operated in such a way that the electrical quantities, for example, bus voltages and line currents, will be maintained within an acceptable range in an operating condition. Power system security is a criterion for planning and operation of a power grid. To meet the system security standards, various control devices and tools are needed.

As policies and technologies evolve, power systems have become more complex and difficult to plan and operate. These major changes include the creation of electricity markets, large-scale integration of renewable energy sources, and increasing demand response programs on the customer side. Due to the intermittency of wind and solar generation resources, large and sudden changes in power flow may be experienced, causing the power system to be operated closer to its capability limits. Under these conditions, voltage control becomes a significant challenge for power system operators.

Major progress in technology for control, automation, protection, sensing, and communication has been achieved. New facilities are being added to replace the aging power infrastructures. Further investment in new transmission lines is important to upgrade transmission capacities to meet new requirements. Recent major events affected large parts of the interconnected power systems of Europe (the Italian blackout in September 2003, the UCTE (Union for the Co-ordination of Transmission of Electricity) event in November 2006), and the Northeast United States in August 2003. A root cause of these blackouts is the insufficient transmission capacity to serve the increasing load demand while meeting the N-1 security requirement.

Reliable and secure operation of power systems is fundamental to support the continuing development of civilization and provide the social and economic foundations. Power system engineers must be innovative in order to ensure highly reliable and cost-effective electric energy supply to the end users. A power system is expected to operate efficiently by supporting a well-designed market and achieve sustainable use of natural resources.

Power system operators need efficient solutions and tools to operate the power systems in order to meet the economic and regulatory requirements. Due to the difficulties regarding construction of new transmission lines and need for fast and

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robust voltage and power flow control, the power electronic technology is a critical solution. Power electronics–based technology has shown excellent performance since its first use in direct current transmission in early 1960s and provide solutions for some limitations of the alternating current (AC) transmission systems. As technology advances, applications are also developed and deployed at the distribution system level.

Economic efficiency targets should be met from design to operation. Power system optimization is an important part of the literature. Optimal planning and operation as well as adaptation to constantly changing operating conditions can be achieved by well-designed tools for operation and decision support. Artificial intelligence (AI) techniques have been deployed in a range of applications due to the availability of powerful and versatile techniques. Application of power electronics and AI techniques help power systems to advance toward a "smart grid." Power electronic and AI techniques are among the critical tools available to modernize the power grids. As part of the vision for a smart grid, renewable energy sources and distributed generations have been integrated in large scale. Automation, protection, sensing, and other information and communication technologies have also advanced significantly.

Significant work has been done by authors to provide guidelines and techniques regarding the application of power electronics in power systems. We have benefited greatly from the prior work, including

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- Kimbark, E. W., *Direct Current Transmission*, 1971.
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- Hingorani, N. G., and Gyugyi, L., *Understanding FACTS. CONCEPTS and Technologies of Flexible AC Transmission Systems*, 2000.
- Mathur, R. M., and Varma, R. K., *Thyristor Based FACTS Controllers for Electrical Transmission Systems*, 2002.
- Sood, V. K., *HVDC and FACTS Controllers: Application of Static Converters in Power Systems*, 2004.
- Zhang, X. P., Rehtanz, C., and Pal, B., *Flexible AC Transmission Systems: Modelling and Control*, 2006.
- Sen, K. K., and Sen, M. L., *Introduction to FACTS Controllers. Theory, Modeling and Applications*, 2009.
- Yazdani, A., and Iravani, R., *Voltage Sourced Converters in Power Systems. Modeling, Control and Applications*, 2010.
- Jovcic, D., and Ahmed, K., *High-Voltage Direct-Current Transmission: Converters, Systems, and DC Grids*, 2015.

AI techniques were developed as complementary techniques to traditional methods that are based on rigorous mathematical foundations. AI techniques have been extensively applied to power system problems, such as genetic algorithms, artificial neural networks, expert systems, fuzzy logic, and decision trees. More recent applications are under development such as intelligent agents or particle swarm optimization. Genetic algorithms are good additions to the suite of tools including traditional optimization techniques. Expert systems can be used to support the power system operators in dispatching centers or substations in an online environment. Among the AI applications in power systems, rule- or logic-based technologies have been developed and deployed as decision support tools for distribution systems in an online environment. Artificial neural networks for load forecasting in power systems have been in practical use. Fuzzy logic is successfully applied in industrial controllers in power systems.

A significant amount of work has been done for development of AI applications in power systems, and further work is needed as the technology is continuously advancing. We acknowledge the following contributions:

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- Goldberg, D. E., Genetic algorithms in search, optimization and machine learning, 1989.
- Dillon, T. S., and Laughton, M.A., Expert systems applications in power systems, 1990.
- Zimmerman, H.J., Fuzzy set theory, 1990.
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- Tsoukalas, L. H., Uhrig, R. E., and Zadeh, L. A., Fuzzy and neural approaches in engineering, 1997.
- El-Hawary, M.E., Electric power applications of fuzzy systems, 1998.
- Jennings, N., and Wooldridge, M. (Eds.), Agent technology: Foundations, applications, and markets, 1998.
- Wehenkel, L., Automatic learning techniques in power systems, 1998.
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The idea of this project was conceived as a comprehensive handbook on high voltage direct current (HVDC)/flexible alternating current transmission systems (FACTS) and AI applications for power engineering professionals and students. These subjects are already embedded in the academic curricula around the world. This is the case of the master program in electrical power systems at the University "Politehnica" of Bucharest (UPB), which includes courses on "high voltage direct current transmission" and "advanced technologies in power systems: FACTS and AI." Several international courses have been organized at UPB under the title "Advanced technologies in power systems: FACTS and AI," with participants from European countries. The support from various European programs (e.g., Erasmus, Tempus), the activities organized under Institute of Electrical and Electronics Engineers (IEEE) and International Council on Large Electric Systems / Conseil International des Grands Réseaux Électriques (CIGRE), and other opportunities have allowed the development of linkages among universities and industry from many countries, including Brazil, Canada, China, Denmark, France, Greece, Korea, India, Iran, Ireland, Romania, Slovenia, Spain and United States to carry out the project of this book. Topics related to the application of power electronics and AI techniques in power systems have been integrated in the academic curricula and extensively studied in PhD research in many universities around the world, for example, North America, South America, Europe, and Asia.

This book on "Advanced solutions in power systems: HVDC, FACTS and AI" is complementary to the book on "Electrical Power System Dynamics: Modeling, Stability and Control." The previous book was focused on providing dynamic models for the classical components of a power system, methods for stability assessment, strategies for voltage and frequency control, and analysis of power system blackouts. This book, on the other hand, presents advanced technologies and tools that are solutions to improve the performance of the power systems by enhancing the stability reserves and the transmission capacity, by improving the voltage control, by providing decision support tools for power system control, by improving the flexibility in operation and so on.

This book is organized into three parts, each dealing with one of the three main topics, that is, HVDC, FACTS, and AI. Each chapter is founded on the valuable knowledge and experience of its contributor(s).

The power electronic systems deployed in power systems include two types of installation: HVDC transmission links and FACTS devices. In both cases, two classes of converters exist, the *current source converters* (CSC) that are based on the conventional thyristors (with no intrinsic turn-off ability) and the *voltage source converters* (VSC) that are based on self-commutated devices. The advent of power electronic technology has removed several barriers in power transmission as regards the voltage level, power, and distance.

The first two parts are devoted to applications of power electronics. Each chapter is intended to guide the reader through the state-of-the art, principles of operation, modeling for steady-state and dynamic simulations, case studies, and installations in operation around the world.

The first part of the book is concerned with the theory of HVDC transmission. This part begins with a comprehensive description of the semiconductor devices and power electronic converters in Chapter 2 with a focus on their architectures and functionalities. The power electronic–based technologies are rapidly progressing as new power semiconductors are developed, reaching higher rated voltages, currents, or commutation frequencies. However, challenges remain in developing models and algorithms for both static and dynamic operation.

The next two chapters of the first part present the theory of CSC–HVDC and VSC–HVDC technologies. The CSC–HVDC technology employed for overhead transmission lines is mature today, reaching ultra high voltage levels and very high transmission capacities. However, in the absence of a commercial breaker, multi-terminal systems are limited in practice to three terminals only. CSC–HVDC links provide good power flow control under normal operating conditions, whereas severe events occurring in the AC system may affect it significantly. It is worth noticing that the CSC–HVDC links have reached the distance of 2400 km and transmission capacity of 8000 MW; these goals are difficult to achieve with AC lines. There are high expectations for the VSC–HVDC technology, which is fast developing due to the ability to eliminate problems associated with CSC–HVDC. Relative to the CSC–HVDC links, the VSC–HVDC technology is expensive as it is more suited for cable lines. In order to allow integration of renewable energy sources, mainly offshore, and face the unexpected critical events that may damage the power system, the vision for developing the transmission grids, *supergrid/highway*, is to adopt a hybrid AC–DC power system. The reader may find an extended presentation of both types of HVDC transmission links and be able to understand how power system performances can be improved.

Another class of power electronic applications, presented in the second part of the book, is FACTS devices. They can be series, shunt, or series–shunt connected and are designed to control various parameters of the AC power system in a wide range of operating conditions. For this reason, FACTS devices are also called controllers. These sophisticated controls are the modern version of the breaker-switched connected capacitors and reactors and conventional (mechanical) tap-changing transformers with a much faster response. Similar to the HVDC links, FACTS devices may be categorized into two classes depending on the type of converters.

The first class of controllers includes the static VAr controller (SVC), thyristor-controlled series capacitor (TCSC), and thyristor-controlled phase shifter, which employ conventional thyristors with no intrinsic turn-off capability. Depending on the connection type, these controllers may act on one of the three parameters that influence the power flow, that is, voltage (SVC), line impedance (TCSC), and phase angle (phase-shifter). While TCSC and the phase-shifter are designed to control the power flow on transmission lines, the main purpose of an SVC is to control the bus voltage.

The TCSC is inserted as variable capacitive impedance in series with the line inductive impedance at a distance calculated to achieve maximum efficiency. The device acts by developing a compensating voltage based on line voltage and thus affects the line current. The SVC is the most important FACTS device used in power systems, with at least one thousand installations in operation in the world in various configurations. An SVC is inserted into the electrical network as a variable shunt admittance and thus it acts by exchanging reactive power, which depends on the bus voltage. When operating in the normal domain, the thyristor-controlled devices demonstrate an outstanding performance. However, when large disturbances occur which significantly affect the line current or voltage, the SVC and TCSC are forced to operate outside their normal control range and are seen as fixed elements. Under these circumstances, the thyristor-controlled devices are no longer efficient and the power system cannot count on them. It is important for the reader to understand not only the operating principles of a specific device but also its importance and performance limits when the device is integrated in the power system as explained in Chapters from 5 to 7. This is important for engineers in order to select the best solutions to strengthen the power system.

The drawbacks of thyristor-controlled devices can be overcome by the second type of FACTS devices, based on self-commutated voltage-source switching converters, including the static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), unified power flow controller (UPFC), interline power flow controller (ILPF), and the convertible static compensator (CSC). The VSC-based FACTS devices are similar to the synchronous machine as they are able to exchange active and reactive power while providing an almost instantaneous speed of response and control characteristics. A DC capacitor is used as the voltage source for the VSC, which may be able to generate or absorb reactive power with the AC system as the VSC voltage is greater or smaller than the voltage at the AC bus. The VSC technology has advanced considerably to reduce the active power losses in the converters and handle greater powers at higher voltages.

The VSC-based FACTS devices can perform significantly better than the thyristor-based FACTS devices, enhancing system stability, voltage control, and power flow control. However, due to the high cost of the VSC converters, a large number of STATCOM units have been implemented, whereas the UPFCs are primarily pilot projects. So far, the SSSC can be found only in the UPFC structure. A guide through the architecture, operation principles, modeling, and example installations is provided in Chapters 8–11.

A special class of flexible devices is the Sen transformer, presented in Chapter 12, that can be used to perform independent power flow control similar to FACTS devices.

Initially FACTS devices were intended to be installed in the transmission system to achieve various objectives. As the power electronics technology advances, FACTS applications have also been deployed in distribution networks, called D-FACTS, which is discussed in Chapter 13. They are designed for power quality improvement to mitigate voltage dips, flickers, and phase unbalance.

The third part of the book, consisting of Chapters 17–22, is devoted to applications of AI and computational intelligence (CI) techniques to power systems. The chapters provide a comprehensive overview of the AI and CI techniques that help realize the vision of a smart grid. These techniques include expert systems, artificial neural networks, fuzzy systems, decision trees, genetic algorithms, multiagent systems, heuristic optimization, and unsupervised learning.

Although AI and CI techniques emerged in mid-1950s as a computer science field, power engineers have been conducting research and development in practical applications to power systems since early 1980s. At that time, computers became more accessible for researchers around the world and the computing power has increased significantly, enabling conventional mathematical approaches to be utilized, such as linear programming, nonlinear programming, dynamic programming, and Pontryagin maximum principle, etc. However, these mathematical approaches have shortcomings in their applications as the power systems are becoming increasingly complex, large-scale, nonlinear, and stochastic. AI and CI techniques are complementary to the more rigorous mathematical techniques in many fields, such as operations research, control theory, and numerical analysis.

Electric power systems are constantly adapted to meet the technical and economic objectives. With the advent of computer and communication technologies, power systems are provided with more intelligence at all levels of operation, control, forecasting, and scheduling activities. The range of solutions to the increasingly complex problems in power system engineering is expanded to incorporate logic reasoning, heuristic search, perception, and the abilities to handle uncertainties. AI and CI open new opportunities for developing the intelligence of the future smart grid.

AI and CI techniques are applicable in a wide range of power system problems, including stability assessment/enhancement, power system control, security assessment, load forecasting, reactive power planning and control, state estimation, fault diagnosis, and behavior classification.

Successful applications of AI and CI techniques are also found in problems that involve HVDC and FACTS devices. Genetic algorithms are extensively used in optimization problems, such as placement of shunt or series FACTS devices, and voltage–VAr planning involving FACTS compensators. Decision threes and artificial neural networks are applied with good results for stability studies, in which increased attention is paid to power electronic applications. The number of AI and CI applications in power systems that include power electronic–based devices is increasing at the same time the computation power enables complex simulations.

The book is intended to provide insights into promising technologies and tools for application in power system operation and planning in such a way that the gap between theory and application can be bridged. This book is suitable for readers working in the fields of power systems, power electronics, computer applications, and industry applications. The content is addressed to students, faculty, researchers, engineers, consultants, utilities, and others.