Power Electronics in Smart Grid and Renewable Energy Systems

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Guest Editor

I am proudly presenting this special issue to the professional communities of the world. Power electronics is an extremely important element in modern smart grid and renewable energy systems. Basically, it uses high-efficiency switching power semiconductor devices to convert and control electrical power with the help of dc-to-dc, dc-to-ac, ac-to-dc, and ac-to-ac converters that are applied extensively in industrial, commercial, residential, transportation, aerospace, military, and utility systems. Power electronics plays significant role in modern industrial automation and high-efficiency energy systems that include renewable energy systems (such as wind and photovoltaic), bulk energy storage, electric and hybrid vehicles, and energy-efficiency improvement of electrical equipment. In modern electric power grid, power electronics is indispensable in high-voltage dc (HVDC) system, static VAR compensators (SVCs), flexible ac transmission system (FACTS)-based active and reactive power flow control, uninterruptible power system (UPS), fuel-cell-based energy system, etc. After a dynamic technology evolution for nearly five decades, power electronics has now grown possibly as the most important technology in the 21st century. Currently, most of our energy comes from fossil fuels and nuclear power plants. Fossil fuels cause environmental pollution that causes global warming or climate change problems. Nuclear energy is clean in that respect, but it has safety and radioactive waste disposal problems. For these reasons, the whole world is now turning toward renewable energy, where power electronics is an indispensable ingredient.

Currently, in the United States and some other countries, there is a tremendous stimulus of R&D activities in smart grid. Unfortunately, our present power grids are too old, obsolete, inefficient, unreliable, fault-intolerant and prone to cyber attacks. A smart grid is basically an advanced power grid of tomorrow that will integrate state-of-the-art power electronics, computers, information, communication, and cyber technologies. The broad objectives of smart grid are optimum resource utilization, high energy efficiency of the system, high system reliability, high system security, and economical electricity distribution to consumers. The smart grid will increasingly integrate renewable energy systems with the ultimate goal of carbon-free and nuclear-free generations. Power electronics is possibly the most important element in a smart grid.

> The special issue presents the state of the art and offers perspectives on future developments in the area of power electronics through applications-oriented reviews and tutorials.

This special issue contains 14 papers from the leading technology experts of the world which were invited by me. All the papers were reviewed rigorously by the experts in the field before acceptance for publication. Basically, these are application-oriented state-of-the-art technology review-type tutorials. The topics covered in the issue are power semiconductor devices; multilevel converters; HVDC; FACTS; wind generation system; solar energy system; ocean and geothermal energy; fuel cell system; energy storage system; and smart grid simulation, control, and application of AI techniques. Although variable-frequency motor drive is an extremely important topic, no separate paper is included in this area.

The first paper "Power Electronics, Smart Grid, and Renewable Energy Systems" is contributed by me. It is an introductory paper that gives basics of power electronics and its applications

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with emphasis on renewable energy systems and smart grid. The discussion includes modern power semiconductor devices and power electronics applications in energy saving, electric vehicles, wind and photovoltaic systems, and grid energy storage.

The paper "Power Semiconductor Devices for Smart Grid and Renewable Energy Systems" by Huang reviews the modern power semiconductor devices for applications in smart grid and renewable energy systems. The traditional Si-based devices, such as thyristor, GTO, IGCT, IGBT, and power MOSFET are discussed in the beginning highlighting the comparison of their characteristics. Then, the emerging wide bandgap devices based on SiC and GaN are discussed comparing their performances with Si-based devices. This latter class of devices is extremely important in future smart grid applications in terms of higher power rating, higher switching frequency, lower conduction drop, and higher temperature operation. The recent innovation of Si-based power devices is also discussed in the paper. The key applications of today's devices and the future technology for electric vehicle, energy storage, PV, wind, HVDC, FACTS, and solid-state transformer in smart grid are also summarized in the paper.

The paper "Multilevel Converters: Fundamental Circuits and Systems" by Akagi provides an extensive discussion on both high-voltage and medium-voltage multilevel converters (MLCs) based on modern power electronics technology. It introduces different topologies of MLCs which are extremely important not only for power grid applications, but also for high power motor drives. The topologies which are discussed are neutral-point- clamped (NPC), neutral-point-piloted (NPP), flying-capacitor (FLC), and modular multilevel cascaded H-bridge and half-bridge (also called chopper cell) converters. Traditionally, the cascaded half-bridge version with floating capacitors is now called a modular multilevel converter (MMC), and this topology is emerging as the most important among all types of MLCs. Various configurations of MMC, such as single-stage bridge-cell (SSBC), double-star bridge-cell (DSBC), triple-cell bridge-cell (TSBC), single-delta bridge-cell (SDBC), double-delta bridge-cell (DDBC), and double-star chopper-cell (DSCC) are described. The paper includes experimental systems with back-to-back DSCC configuration for 50-Hz utility system and variable frequency motor drives with DSCC and TSBC topologies. The capacitor voltage fluctuation remains a problem for variable frequency drives with DSCC converter. However, the problem is less severe for pump-, fan-, and blower-type drives where torque is low at low speed.

The paper "Multilevel Converters: Control and Modulation Techniques for Their Operation and Industrial Applications" by Leon *et al.* reviews the topologies that are mostly used in industrial applications. The modulation and control methods to achieve a high-performance operation of multilevel converters are addressed, with control targets such as balancing the dc voltages, reducing common-mode voltages, and minimizing power losses. The use of multilevel converters for different applications such as motor drives, power quality applications, high-voltage dc transmission systems, and renewable energy integration is presented. The future perspective of multilevel converters is also addressed.

The paper "HVDC Systems in Smart Grids" by Barnes *et al.* reviews both classical thyristor-based line-commutated converter (LCC) systems and modern IGBT-based voltage–source converter (VSC) systems illustrating their application examples around the world. The main motivating factors of HVDC systems are economical and efficient long-distance power transmission, coupling of asynchronous interties, and fault-level controls. The VSC-based system provides the additional advantages of independent active and reactive power control, multiterminal connection, and system stability improvement. The MMC with cascaded half-bridges (invented by Marquardt) is being increasingly popular because of a reduced number of devices, fault-tolerant operation, and simple staircase ac voltage synthesis.

The paper "Flexible AC Transmission Systems (FACTS) and Resilient AC Distribution Systems (RACDS) in Smart Grid" by Peng provides a comprehensive review of the modernization efforts in FACTS technology leading up to its usage in smart grids. Extension of FACTS technology to the ac distribution system (RACDS) to facilitate the transition to "smart distribution" is also discussed in detail. The key benefits of the modern FACTS technology lie in its ability to achieve fast, efficient, dynamic voltage/VAR control, optimized power routing, and independent real and reactive power control using fractionally rated inverters. A key benefit of the RACDS technology is its ability to provide the first line of defence, improve grid resiliency, and impart "self-healing" qualities to the power grid. Additionally, RACDS has the ability to integrate distributed energy sources into the power grid and enables bidirectional, interconnected distribution systems that are essential to a smart grid. Detailed analysis of different configurations of these technologies, a review of existing and ongoing commercial installations, and an overview of current and future research in this area form the crux of this paper.

The paper "Wind Energy Systems" by Blaabjerg and Ma reviews power electronics technologies used for wind generation systems. The main driving factors are the final cost of energy, as well as the compatibility with the grid operation. For individual wind turbines, the power electronics converters, including their associated controls, have significantly improved the power controllability of generator, speed variability of turbine, and also the power quality of grid. On the wind farms levels, introduction of power electronics can improve the efficiency of power transmission and capability of active/reactive power control. These benefits enable the wind generation system to behave like conventional power plant based on synchronous generators. Future challenges are discussed including the complex mission profile of a wind turbine, even more strict grid codes, and growing reliability requirements, which are calling for more efficient, scalable, and reliable power semiconductor devices and circuit configurations in this field.

The paper "Solar Photovoltaic and Thermal Energy Systems: Current Technology and Future Trends" by Malinowski *et al.* essentially reviews solar photovoltaic systems with solar cells and different topologies of power conversion systems. Concentrated solar power (CSP) has been briefly described, but because of high installation cost, high running cost, and complexity of operation its application is being deemphasized recently. Different types of solar cells, such as CdTe, monocrystalline and amorphous Si, CIGS and multicrystalline Si properties, have been summarized. A general PV system consisting of a PV cell array, a capacitor filter, a dc–dc boost converter, a filter, an inverter, and an output filter can be either for standalone application or interconnected to grid with a stepup transformer. The dc-dc converter not only boosts the input voltage but also controls the output power of the MPPT algorithm. Because of fluctuating nature of solar power, several battery storage techniques used commercially around the world have been summarized. For a grid-connected operation, various grid codes, such as harmonic distortion, behavior with grid faults, etc., have been developed because of recent higher penetration of PV power in the grids.

The paper "Ocean and Geothermal Energy Systems" by von Jouanne and Brekken reviews several forms of ocean energy—wave, tidal, current, and ocean thermal—along with land-based geothermal energy. The paper presents a broad technology overview of each type, along with summaries of cost of energy studies, and an overview of grid interface systems. Geothermal energy and ocean thermal energy track closely with traditional dispatchable synchronous generator-based generation systems, while wave, tidal, and current bear greater similarities to wind power in terms of technology, cost trends, and grid interface.

The paper "Fuel Cell Power Systems and Applications" by Lai and Ellis reviews basic characteristics of fuel cell system, different types of fuel cells, their electrical characteristics, and discusses their applications in transportation and stationary distributed generation systems in a power grid. Hydrogen is the basic fuel in a fuel cell which can be stored locally, or it can be generated from hydrocarbon fuel. Low-temperature-type fuel cells, such as polymer electrolyte membrane (PEM) with hydrogen fuel, have high power density, rapid startup, and simple assembly, and are particularly popular for transportation applications. Direct methanol fuel cells (DMFCs) take dilute methanol solution as fuel and have higher energy density than the PEM type. High-temperature-type fuel cells, such as solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs), have higher cost and slower startup, but have the advantages of cogeneration in addition to electricity generation which are normally used in stationary applications. Fuel cells generate low dc voltage and should be used in stacks, and their dynamic operation is poor. Normally, a fuel cell energy system requires a dc–dc boost converter followed by an inverter for transportation and grid-interface applications. Various converter topologies are also discussed in the paper.

The paper "Energy Storage and Power Electronics Technologies: A Strong Combination to Empower the Transformation to the Smart Grid" by Molina makes comprehensive analysis of major technologies in electrical energy storage systems and their power electronic interface for smart grid applications. There are various emerging technologies of energy storage available in the market for applications with high potential to provide key services for supporting the smart grid development. The value of all these services changes significantly depending on where the storage is deployed on the power grid and the stakeholders involved. These energy storage devices require advance power conditioning systems to meet the performance requirements of different grid applications, which include decrease of energy consumption as well as the volume, weight, and ultimately the cost. The combination of these innovative energy storage technologies and cutting-edge power electronics systems has created an opportunity for storage systems to provide unique services to the upcoming smart grid. This article puts a spotlight on the issues derived from this vital integration for the development of the smart grid and discusses technology maturity, current challenges, and future perspectives. The study is extended with a description of major practical storage installations around the world.

The paper "Smart Grid Simulations and Their Supporting Implementation Methods" by Chakrabortty and Bose reviews both state-of-the-art and future implementation strategies for modeling and simulation of power systems. A comprehensive list of existing simulation packages is provided, followed by a detailed discussion on how they need to be upgraded as grid models continue to grow in size and complexity with more renewables, FACTS, HVDC, storage, and smart loads. Special attention is drawn toward the cyber–physical aspect of simulations, where conventional continuous-time models of the grid must merge with stochastic discrete-event models of communication networks. The discussion is extended to several other upcoming challenges including model aggregation, hybrid simulation, faster-than-real-time simulations, the use of remote testbeds, and the associated interoperability standards required to make all of these futuristic aspects of smart grid simulation a reality.

The paper "Controls for Smart Grids: Architectures and Applications" by Samad and Annaswamy focuses on the role of control systems in the power grids of today and tomorrow. Control has always been a critical technology for power systems and its importance has increased with the drive for increased generation from intermittent renewable sources (and the challenges associated with this goal). Due in part to advances in power electronics, control concepts are being pursued and deployed across the smart grid space. The paper presents system-architectural patterns or templates for a number of application scenarios that cover customers, transmission and distribution networks, markets, and other actors. Human-in-the-loop control and cyber–physical security and resilience are noted as important topics for future research in smart grid control.

The final paper "Artificial Intelligence Techniques in Smart Grid and Renewable Energy Systems—Some Example Applications" is also contributed by me. It summarizes some novel application examples of AI in smart grid and renewable energy systems.

Organizing a special issue like this is an enormous task. I must express my gratitude to the participating authors for their enthusiasm, cooperation, and timeliness without which this special issue could not be possible. I also express sincere thanks to my professional colleagues for their help in bringing out this issue. They are: Dr. Iqbal Hussain, Dr. Akshoy Rathore, Dr. Edson Watanabe, Dr. Mario Pacas, Dr. Peter Palensky, Dr. Debaprasad Kastha, Dr. Hirofumi Akagi, Dr. Fred Wang, Dr. Jose Rodriguez, Dr. K. Gopakumar, Dr. Sudip Mazumder, Dr. Dimosthenis Peftisis, Dr. Bin Wu, Dr. Brandon Grainger, Dr. Arman Kiani, Dr. Vivek Agarwal, Dr. Ron Hui, Dr. Mahesh Kumar, Dr. Alex Huang, Dr. Tariq Samad, Dr. Aniruddha Gole, Dr. Thomas Strasser, Dr. June Liang, Dr. Keyue Smedley, and Dr. Bhim Singh. Finally, I am thankful to Vaishali Damle and Jo Sun, the Proceedings of the IEEE production team, and my family members for their help and cooperation. ■

ABOUT THE GUEST EDITOR

Bimal K. Bose (Life Fellow, IEEE) received the B.E. degree from Indian Institute of Engineering Science and Technology (IIEST) (formerly Bengal Engineering College), India, in 1956, the M.S. degree from the University of Wisconsin, Madison, WI, USA, in 1960, and the Ph.D. degree from Calcutta University, India, in 1966. Currently, he is an Emeritus Professor of the University of Tennessee, Knoxville, TN, USA. Early in the career, he was a faculty member of IIEST from 1960 to 1971. From 1971 to 1976, he was an Associate Professor of Electrical Engineering at the Rensselaer Polytechnic Institute, Troy, NY, USA. From 1976 to 1987, he was a Research Engineer in General Electric Corporate Research and Development (GE-CRD) (now GE Global Research Center), Schenectady, NY, USA. From 1987 until 2003, he was Endowed Chair Professor (Condra Chair of Excellence in Power Electronics) in the University of Tennessee. Concurrently, he was the Distinguished Scientist (1990–1992) and the Chief Scientist (1987–1989) of EPRI Power Electronics Applications Center (PEAC) in Knoxville, TN, USA. He specialized in power electronics and motor drives that include AI applications, renewable energy systems, DSP-based digital control systems, and power electronics applications for solving climate change problems. He has authored/edited seven books in power electronics: *Power Electronics and Motor Drives—Advances and Trends* (New York, NY, USA: Academic Press, 2006), *Modern Power Electronics and AC Drives* (Englewood Cliffs, NJ, USA: Prentice-Hall, 2001), *Power Electronics and Variable Frequency Drives* (Piscataway, NJ, USA: IEEE Press, 1997), *Modern Power Electronics* (Piscataway, NJ, USA: IEEE Press, 1992), *Microcomputer Control of Power Electronics and Drives* (Piscataway, NJ, USA: IEEE Press, 1987), *Power Electronics and AC Drives* (Englewood Cliffs, NJ, USA: Prentice Hall, 1986), *Adjustable Speed AC Drive Systems* (Piscataway, NJ, USA: IEEE Press, 1982). He holds 21 U.S. patents and published more than 250 papers.

Dr. Bose served the IEEE in various capacities, including Member of the IEEE Awards Board, Chairman of the IEEE Medal in Power Engineering Committee, Chairman of the IEEE IES Power Electronics Council, Associate Editor of the IEEE Transactions of Industrial Electronics, Member of the IEEE Fellow Committee, Vice-Chair of the IEEE Medals Council, and Member of the Proceedings of the IEEE Editorial Board (1995–2006). He was the Guest Editor of the Proceedings of the IEEE "Special Issue on Power Electronics and Motion Control" (August 1994). He received the IEEE Power Electronics Society Newell Award (2005), the IEEE Millennium Medal (2000), the IEEE Meritorious Achievement Award in Continuing Education (1997), the IEEE Lamme Gold Medal (1996), the IEEE Industrial Electronics Society (IES) Eugene Mittellmann Award (for lifetime achievement) (1994), the IEEE Region 3 Outstanding Engineer Award (2004), the IEEE Industry Applications Society Outstanding Achievement Award (1993), the General Electric Silver Patent Medal (1986), the GE Publication Award (1985), and the Calcutta University Mouat Gold Medal (1970). He also received the IIEST Distinguished Alumnus Award (2006), the D.Sc. degree (*Honoris Causa*) from IIEST (2013), Distinguished Lecturership of IAS and IES, and a number of prize paper awards. He is a member of the National Academy of Engineering. The IEEE Industrial Electronics Magazine published a special issue (June 2009) "Honoring Dr. Bimal Bose and Celebrating His Contributions in Power Electronics" with a cover photo. The IES Dr. Bimal Bose Energy Systems Award was established in 2014, which is funded by the IEEE Foundation and the IEEE IE Society.