

Preface I

Power electronics and variable frequency drives are continuously developing multidisciplinary fields in electrical engineering, and it is practically not possible to write a book covering the entire area by one individual specialist. Especially, as recently we observe fast-development in neighboring fields like control theory, computational intelligence, and signal processing, which all strongly influence new solutions in control of power electronics and drives. Therefore, the book is written by key specialists working in the area of modern advanced control methods that penetrate current implementation of power converters and drives. Although some of the presented methods are still not adopted by the industry, they create new solutions with high further research and application potential.

The material of the book is presented in the following three parts:

Part I: Advanced Power Electronic Control in Renewable Energy Sources (Chaps. 1–4),

Part II: Predictive Control of Power Converters and Drives (Chaps. 5–7),

Part III: Neurocontrol and Nonlinear Control of Power Converters and Drives (Chaps. 8–11).

In Chap. 1 the state-of-the-arts of renewable energy are reviewed in respect to the installed power and market share, where wind power and photovoltaic power generation are the focus due to the fast growing speed and large share of installed capacity. Some basic principles of operation, mission profiles, as well as power electronics solutions and corresponding controls are discussed, respectively, in the case of wind power and photovoltaic power systems. Finally, a few development trends for renewable energy conversion systems are also given from a power electronics point of view. It is concluded that as the quick development of renewable energy, wind power and PV power both show great potential to be largely integrated into the power grid. Power electronics is playing an essential role in both systems to achieve more controllable, efficient, and reliable energy production—which is crucial for the cost reduction and spread use of renewable energies, because their fluctuated and unpredicted features are un-preferred for the operation of the power grid. Meanwhile, there are also some other emerging challenges and considerations in the renewable energy conversion systems, calling for more advanced controls as well as configurations of power electronics converters.

Chapter 2 presents advanced control of photovoltaic and wind turbine power systems, which can enable power conversion efficiently and reliably. For both PV and wind turbine power systems, advanced controls are addressed in order to enhance the integration of those technologies. Related grid demands have been presented first, where much more attention has been paid on specific requirements, like Low Voltage Ride-Through (LVRT) and reactive power injection capability. To perform the functions of such systems, advanced control strategies are presented with much more emphasis on the LVRT operation with reactive power injection for both single-phase and three-phase systems. Other advanced control strategies like constant power generation control for PV systems to further increase the penetration level, and the improvements in LVRT performance for a doubly fed induction generator-based wind turbine system by means of hardware protection solutions are also discussed in this chapter.

In **Chap. 3** operation of a reliable control method of a Grid Connected Converter (GCC) under grid voltage disturbances is presented. As GCC authors understand, power electronic AC-DC converter with AC side filter and DC-link capacitor operate as an interface between the electrical grid and Active Loads (AL). The chosen modeling approach of a GCC is discussed and the example of passive components calculation is provided. Next, a brief review of a basic GCC control method is described. A new reliable (robust to selected grid voltage disturbances such as dips, higher harmonics) control method is proposed—Robust Direct Power Control with Space Vector Modulation (RDPC-SVM). This new control method can assure sinusoidal like and balanced AC current in extremely distorted grid voltage. Moreover, the quality of current and power is considerably improved in comparison to classical methods. Hence, the negative impact of the GCC on the grid voltage is significantly reduced, i.e., lower Total Harmonics Distortion (THD) factor of the grid current, more accurate control of active and reactive power flow assure good quality of integration with the grid even, in case of increased impedance within operation limits.

At the end of Part I, **Chap. 4** discusses the faults and diagnosis systems in power converters used in renewable energy systems and drive systems. Increasing efforts have been put to improve these systems in terms of reliability in order to achieve high power, source availability, reduce the cost of energy, and also increase the reliability of overall systems. The chapter describes failures in power converters, like a power device and a capacitor faults, as well as their detection in order to do fault handling and still be able to run a power electronic system, increasing the reliability of power electronics. In this chapter, the diagnosis methods for power device faults are discussed by dividing them into open- and short-circuit faults. Then, the condition monitoring methods of DC-link electrolytic capacitor are also introduced. The chapter is supported with a number of examples including the three-level NPC converter.

Part II of this book is focused on predictive control methods applied in power electronics and drive systems.

Chapter 5 introduces the reader to basic principles and methods of model predictive control with a view toward applications in power electronics and drives.

The simplest predictive control formulations use horizon-one cost functions, which can be related to well-established dead-beat controllers. Model predictive control using larger horizons has the potential to give significant performance benefits, but requires more computations at each sampling instant to solve the associated optimization problems. For particular classes of system models, practical algorithms are discussed, which make long-horizon predictive control suitable for power electronics.

Chapter 6 presents a general application of predictive control in power electronics. The analyzed application is an energy conversion system from alternate current to direct current and to alternate current again. This example has been carefully selected because a number of predictive control principles can be clearly explained using this topology and later expanded to a wide variety of converter topologies. The chapter includes mathematical models and a clear presentation of the advanced control strategies. The results show that the use of predictive control introduces a conceptually different solution which allows for the control of electrical energy without using pulse-width modulation and linear controllers.

In **Chap. 7** a long-horizon Model Predictive Control strategy for speed regulation of a drive system with an elastic transmission is applied. Torsional vibrations caused by elastic connection of the driven motor and loading machine are evident in many industrial drive systems: starting from traditional rolling-mill drives, conveyer belt drives, machines for paper and textile industry, deep space antenna drives, the windmill generators, modern servo drives, and robotic applications. The flexible modes affect the performances of the drive, and in some situations can even lead to the failure of the entire drive system. The mathematical model and short characteristic of the control problems of such drive system are given in the chapter. Next, the advanced methodology for robust control strategy design is presented, based on suitable selection of the explicit form of MPC, which enables the drive's safety and physical limitations to be directly incorporated into control algorithm synthesis. The simulation and experimental results show that the long-horizon MPC is very effective in torsional vibration damping and controlling the load speed of the drive system with elastic coupling for a wide-range of the changes of the load side inertia, ensuring a suitable dynamics and constraints fulfillment.

Part III of this book consists of four chapters which concern the application of artificial intelligence and nonlinear control methods for power converters and drive systems.

In **Chap. 8** basic principles of neurocontrol are revised and discussed from the point of view of application in converter-fed drive systems. The neural network structures used as neural controllers are classified into two groups: off-line and on-line trained controllers. From the point of view of drive system uncertainties, caused by simplifying assumptions under mathematical model formulation, errors in drive parameters identification, and changes in the models and their parameters under different operation conditions, on-line adaptive neural controllers are recommended for practical applications. Different neural structures and their on-line training methods are discussed. The chosen neurocontrollers are verified in

simulation and experimental tests for converter-fed drives with rigid and resilient mechanical connections between the driving motor and loading machine.

Chapter 9 presents the application of a particle swarm optimization (PSO) to a controller tuning in selected power electronic and drive systems. An example of PSO used for optimization of selected learning parameters in the adaptive neural network-based online trained speed controller for urban vehicle (3D problem) is presented. Next, this algorithm is applied to selecting penalty factors in the LQR with augmented state for a three-phase four-leg sine wave inverter (15D problem). It is demonstrated for these case studies why and where the PSO, or any other similar population-based stochastic search algorithm can be beneficial. This chapter illustrates that in some cases it is relatively easy to reduce the non-straightforward controller tuning tasks into the objective function selection problem and automatically determine the relevant controller parameters by the PSO.

Chapter 10 is devoted to the Space Vector Modulation (SVM) in three-phase three-level flying capacitor converter-fed adjustable speed drive. First the classical and adaptive SVM, which minimizes number of switching and thus reduces the switching losses in FCC are described. Next, elimination of DC sources unbalance in full range of operation of the Voltage Source Converters and minimization of the flying capacitor voltage pulsation is presented. Taking into account the requirements of the demanding drive application, like low speed operation without phase current distortion and high speed operation over the linear range of the converter with reference output voltage amplitude, the additional features for both modulation techniques: the dead-time effect and semiconductor devices voltage drop compensation as well as the overmodulation algorithm are shown.

In the last **Chap. 11** several applications of nonlinear control methods for induction motor drive are described, such as feedback linearization (FLC) and sliding mode control (SMC). The FLC guarantees the exact decoupling of the motor speed and rotor flux control. Thus this control method gives a possibility to get very good behavior in both dynamic and steady states. The SMC approach assures direct control of inverter legs and allows using a simple table instead of performing complicated PWM calculation. Moreover, the SMC is robust to drive uncertainties. Thus the SMC and FLC, both together and separately, offer an interesting perspective in the converter-fed drive applications, and these approaches are also a good alternative to other solutions, such as predictive and adaptive systems, and soft computing-based methods.

The book has strong monograph attributes and is intended for engineers, researchers, and students in the field of power electronics and drives who are interested in the use of advanced control methods and also for specialists from the control theory area who like to explore new areas of applications. Some parts of the content can be considered as part of graduate and undergraduate studies in electrical engineering, robotics, and mechatronics faculties.

We would like to express our sincere thanks to the chapter contributors for their enthusiastic response, cooperation, and timeliness. Special thanks is directed to Prof. Janusz Kacprzyk, the Editor of Springer Book Series “Studies in Computational Intelligence” for his interest and motivation to write this book. Thanks

also to Dr. Thomas Ditzinger and Dr. Leontina Di Cecco, both from Springer Applied Sciences and Engineering, for support during implementation of this project. Finally, we are very thankful to our families for their cooperation.

Wrocław, Poland

Aalborg East, Denmark

Valparaíso, Chile

Teresa Orłowska-Kowalska

Frede Blaabjerg

José Rodríguez

Preface II



It is our great honor and pleasure to dedicate this book to Prof. Marian P. Kaźmierkowski on the occasion of his 70th anniversary. He is one of the most prominent and world-recognized researchers in the area of industrial electronics, power electronics, and electrical drives. His professional and scientific career has been associated with the Institute of Control and Industrial Electronics of the Warsaw University of Technology. There, having completed his Ph.D. studies (1969–1972), he continued research as assistant professor (since 1973), associated professor (since 1988), and next full professor (since 1995). In 1987–1990 and in 1996–2008 he was

Director of the Institute of Control and Industrial Electronics and now he still holds the position of full professor there. He has also cooperated with the Electrotechnical Institute in Warsaw-Miedzylesie, as a researcher in 1967–1969, and since 1996—as professor-consultant and member of the Scientific Board.

In the years 1980–1982 he was granted the Humboldt Foundation scholarship at the RTWH Aachen (Germany) and later completed there a 2-year DFG scientific research project. Later, he was often invited as visiting professor to various universities: NTH Trondheim (Norway), University of Minnesota, Minneapolis (USA), University of Padova (Italy), University of Aalborg (Denmark), University of Bologna (Italy), ENSEEIHT/LEEI Toulouse (France), University of Sevilla, LSE/ENIT Tunis, Texas A&M University at Qatar, Doha.

The main areas of his interest include problems of vector control of the converter-fed induction motor and permanent magnet synchronous motor drives, including real-time sensorless control, new topologies of multilevel converters, modulation techniques focused on current control, active rectifiers with unity power factor, artificial intelligence and predictive control applications in power electronics, advanced control methods of power electronics devices for renewable energy systems, and recently also contactless energy transfer systems. To all these topics Prof. Kaźmierkowski has contributed with important publications (more than 400 papers in peer review journals and conference proceedings) and 11 books. Among the most popular books are: *Automatic Control of Converter fed Drives*,

ELSEVIER-PWN, 1994, and *Control in Power Electronics*, Academic Press, USA, 2002.

Professor Kaźmierkowski has been active in cooperation with the industry (*ABB Research Centre*, Krakow; *APATOR*, Torun; *Huettinger Electronics*, Warsaw; *TWERD*, Torun) and has been granted 16 patents. He has also conducted many research projects, international (5): Maria Skłodowska-Curie Found II, NSF-PAN Phare-SCI-TECH II; the V and VI European Union Framework, and national (15) founded by: the Committee of Scientific Research (KBN), Ministry of Science and Higher Education, Foundation of Polish Science, National Centre for Research and Development.

The activities of Prof. Kaźmierkowski in research and education have been appreciated by the highest scientific committees in Poland. He was elected a Member of the T-10 Council for Research Projects Evaluation in Electrical Energy and Measurements, the Ministry of Science and Technology (KBN), Warsaw, (1996–2004). In 1993 he became a member of the Electrical Engineering Committee of the Polish Academy of Sciences, and in 1999–2011 he was the chairman of the Power Electronics and Electrical Drives Section of this Committee. In 2007 he was elected a *corresponding member* of the Polish Academy of Sciences and since 2011 he has been the Dean of the *Division IV Engineering Sciences* of this Academy.

In his international activities he served as Vice-President for Publications of the *IEEE Industrial Electronics Society* 1999–2001 Editor-in-Chief (2004–2006) and the Past Editor-in-Chief (2006–2009) of the *IEEE Transactions on Industrial Electronics*. Currently, he is member of the editorial boards of international journals: *IEEE Transactions on Industrial Electronics*, *IEEE Transactions on Industrial Informatics*, *IEEE Industrial Electronics Magazine*, *Bulletin of the Polish Academy of Science, Technical Science* (Warsaw, Poland), *Journal of Power Electronics* (JPE—Seoul, Korea), *Acta Electrotechnica et Informatica* (Technical University of Košice, Slovak Republic). Since 1996 he is an active member of *Power Electronics and Motion Control Council (EPE-PEMC)* organizing series of PEMC conferences in East and Middle Europe.

For outstanding papers in international journals and activity in the IEEE Prof. Kaźmierkowski has received a number of international awards and distinctions, just to mention: *IEE F.C. Williams Premium*—for the best paper 1989 (UK); *Best Paper Award* at the Conf. IEEE-IECON'2000 in Nagoya (Japan); 2013 *Best Paper Award* in the IEEE Industrial Electronics Magazine (USA); *Dr. Eugene Mittelmann Achievements Award*—IEEE Industrial Electronics Society 2005; IEEE Industrial Electronics Society *Anthony J. Hornfeck Service Award*, 2007. Also, in Poland he was honored with prestigious awards, including *Research Award of Siemens* (2007) and the *Technical Science Subsidies* by the Polish Science Foundation (FNP) in 2001–2004. In 1998, he received the *Fellow Member Grade* of the IEEE, USA; in 2001 he was elected the member of the *International Academy of Electrotechnical Sciences—Moscow, Russia*, and in 2010—Honorary Member of *Hungarian Academy of Science*. He has been granted honorary doctorates of European universities, like: University of Aalborg, Denmark (2004),

Institute National Polytechnique Toulouse (INPT), France (2010), and the University of Zielona Gora, Poland (2012).

Professor Kaźmierkowski is undoubtedly one of the greatest scientists specializing in power electronics and electrical drives. He is an outstanding lecturer, warmly remembered by many generations of students and conference participants. On his 70th birthday, we wish him all the best—many happy years to come, with continuous scientific success and satisfaction of his and his students' achievements in the field of power electronics and electrical drives.

Wrocław, Poland
Aalborg East, Denmark
Valparaíso, Chile

Teresa Orłowska-Kowalska
Frede Blaabjerg
José Rodríguez

Advanced and Intelligent Control in Power Electronics
and Drives

Orłowska-Kowalska, T.; Blaabjerg, F.; Rodríguez, J. (Eds.)

2014, XX, 410 p. 284 illus., 161 illus. in color.,

Hardcover

ISBN: 978-3-319-03400-3