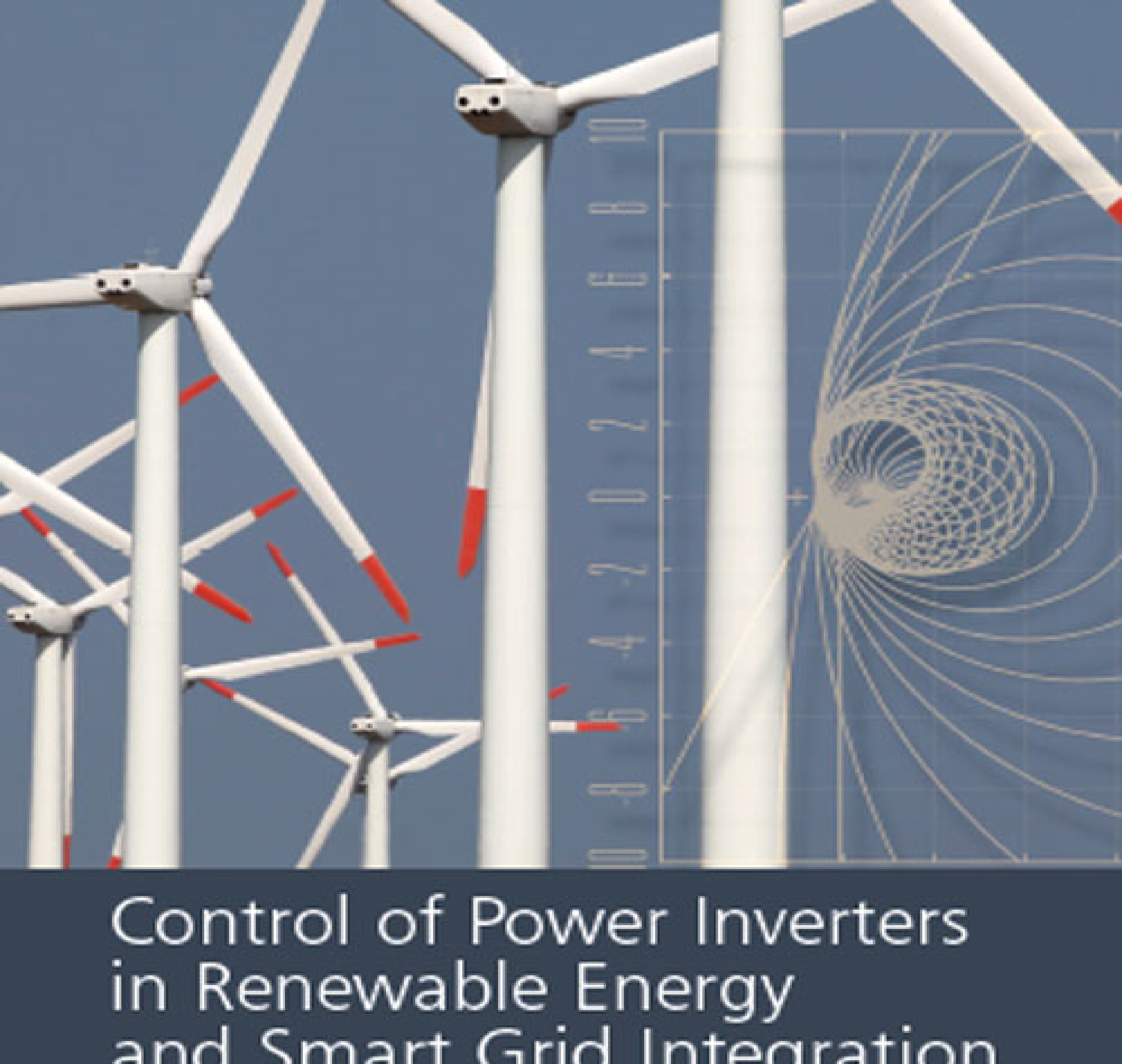

# Control of Power Inverters in Renewable Energy and Smart Grid Integration

Qing-Chang Zhong Tomas Hornik

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# Contents

# CONTROL OF POWER INVERTERS IN RENEWABLE ENERGY AND SMART GRID INTEGRATION

**Qing-Chang Zhong**
*The University of Sheffield, UK*

**Tomas Hornik**
*Turbo Power Systems Ltd., UK*

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*To those who have taught us in one way or another*

# Preface

It has been a long journey since the lead author had the idea of writing a research monograph on the control of power inverters, which are the common key devices used to integrate renewable energy and distributed generation into smart grids. Soon after he was appointed at Imperial College London, UK, in 2001 to work on a project on the control of power inverters, he realised that there were many challenging problems in this area and that research activities on renewable energy and grid integration would become very important worldwide in the near future. Four kinds of problem were identified at that time, that is, power quality issues, the provision of a neutral line, power flow control, and synchronisation. Over the past 10 years, he has kept working on these problems, sometimes with his collaborators and PhD students, although he has experienced several job moves. The co-author joined his team as a PhD student in 2007 and soon built up a test rig, which facilitated the research and made the idea of writing the book more concrete. The award of a Senior Research Fellowship from the Royal Academy of Engineering, UK, and the Leverhulme Trust in 2009 has considerably accelerated the process of the book project. Finally, the award of a one-year International Collaboration Sabbatical from the Engineering and Physical Sciences Research Council (EPSRC), UK, in 2011 has made the book a reality.

Energy and sustainability are two major problems the world faces today. Renewable energy has been seen as a promising means to address these problems while smart grids are being developed to improve energy efficiency, security and resilience of power systems. Integrating renewable energy and other distributed energy sources into smart grids, often via inverters, is arguably the greatest "new frontier" for smart grid advancements. Inverters should be controlled properly so that their integration does not jeopardise the stability and performance of power systems and a solid technical backbone is formed for the other functions and services of smart grids.

There are several important control problems associated with inverters. For example, how to make sure that the quality of the power fed into the grid is high, even when there are nonlinear loads and/or the grid voltage is distorted; how to make sure that a balanced neutral line is provided for applications where a neutral line is needed, e.g. when three-phase loads are not balanced; how to make sure that inverters can be operated in the grid-connected mode or the stand-alone mode and how to minimise the transient dynamics when the operation mode is changed; how to synchronise inverters with the grid so that they can be connected to the grid when needed; how to make sure that parallel-operated inverters share power proportionally according to their power ratings to avoid damage; how to operate grid-connected inverters in a grid-friendly manner so that the impact on the grid is minimised, etc. Many original ideas and control strategies, which have been developed to address these problems over the past 10 years, are presented in this book. These include different strategies to improve the power quality in smart (and/or micro) grids, inverters with capacitive output impedances (C-inverters), the provision of a neutral line for inverters, grid-friendly integration using inverters that mimic synchronous generators (synchronverters), parallel operation of inverters with robust droop controllers to share power in proportion to their ratings, harmonic droop controllers to improve power quality, sinusoid-locked loops to lock the frequency and the amplitude, in addition to the phase, of the grid voltage, etc. These advanced control strategies are expected to considerably facilitate the large-scale utilisation of renewable energy and smart grid integration.

The book consists of one introductory chapter (Chapter 1), one preliminary chapter (Chapter 2) and four parts: Power Quality Control (Chapters 3–9), Neutral Line Provision (Chapters 10–14), Power Flow Control (Chapters 15–21) and Synchronisation (Chapters 22–23). In the introductory chapter, some basics about power processing, hardware issues about inverters, and brief descriptions of wind power, solar power and smart grid integration are presented. In the preliminary chapter, some common knowledge of power quality issues, repetitive control and reference frames is introduced. In Part I, several control strategies according to different mechanisms are presented to improve the quality of the inverter voltage, and the current exchanged with the grid. In Part II, the topologies to provide a neutral line are discussed and several control strategies are presented to maintain a balanced stable neutral line, which facilitates the independent operation of phases. In Part III, both current-controlled and voltage-controlled strategies are presented to control the power flow between an inverter and the grid. Innovative concepts such as synchronverters (inverters that mimic synchronous generators), robust droop controllers, harmonic droop controllers, etc., are presented. In Part IV, conventional synchronisation methods are presented at first, followed by a sinusoid-locked loop developed according to the principles of a synchronous generator that does not exchange power with the grid.

This book is written for control engineers who are moving into the area of power electronics, renewable energy and distributed generation, smart grids, flexible AC transmission systems, power systems for more-electric aircraft and all-electric ships, etc, and researchers and practitioners working in these areas who are eager to see what benefits advanced control algorithms can bring. It systematically explores the fundamental and challenging problems with respect to control of power inverters and fully demonstrates the beauty of the integration of control and power electronics. Most of the artful control strategies presented in this book are accompanied by extensive experimental results and, hence, this book is also very useful for practitioners in this area to see how advanced control strategies could improve system performance and work in practice. This book also provides an excellent opportunity for graduate students and researchers who work in the area to become familiar with the latest developments. It can be adopted as a textbook for graduate programmes on advanced control engineering, power electronics, microgrids, renewable energy and smart grid integration.

# Acknowledgments

This research monograph systematically summarises the research I, together with my collaborators and PhD students, have carried out over the past 10 years in the area of control of power inverters in renewable energy and smart grid integration. It is impossible to list everyone who has made contributions to this book as co-authors but their contributions are greatly appreciated. George Weiss, my advisor and collaborator, currently at Tel Aviv University, is the one who started this all. He opened this whole new world for me, which has paved the way for my career. Tomas Hornik, my past PhD student, has made significant direct contributions to this book and deserves to be a co-author, not just for himself but also on behalf of others. I am grateful to Long Nguyen, Zhenyu Ma, Shamsul A. Zulkifli, Wen-Long Ming, Yu Zeng, Zhi Hou, Xiaolin Wang and Xin Cao for their contributions. I am also grateful to Frede Blaabjerg, Chunmei Feng, Tim Green, Joseph M. Guerrero, Leslie Hobson, Marcel G. Jayne, Miroslav Krstic, Jun Liang and George Weiss for the collaborative work we have done.

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I also wish to thank the Royal Academy of Engineering, UK, and and the Leverhulme Trust for the award of a Senior

Research Fellowship during 2009–2010. This offered me valuable time to concentrate on my research and many of the results are included in this book.

The links with, and support from, industrial partners have always facilitated our research. I am particularly grateful to Phill Cartwright and Kevin Daffey (Rolls-Royce Plc), Roger Critchley and Fainan Hassan (ALSTOM Grid), Damien Culley (National Grid, UK), Brett Dowen (add2 Ltd), Nordine Haddjeri (Nheolis, France), Tony Lakin (Turbo Power Systems), Robert Owen (Texas Instruments), Graham Chapman (Power Systems Warehouse) and David Doherty (Yokogawa Measurement Technologies Ltd) for their valuable direct support to our research.

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Last but not least, I would like to formally thank the LyX team for having developed the LyX document processor, which has made my writing experience in the past 12 years so enjoyable and has saved me a lot of time. LyX functions as a front-end to the LaTeX typesetting system and is designed for authors who want professional output with a minimum of effort and without becoming specialists in typesetting. LyX is available in multiple languages for various operating systems, including Windows, Mac OS X, Linux, UNIX, OS/2 and Haiku, and can be downloaded, redistributed and modified for free from http://www.lyx.org under the terms of the GNU General Public License.

Qing-Chang Zhong
*Chair in Control and Systems Engineering*
*Department of Automatic Control and Systems Engineering*

*The University of Sheffield, UK*

*Q.Zhong@Sheffield.ac.uk*
*http://zhongqc.staff.shef.ac.uk*

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# About the Authors

**Qing-Chang Zhong** received his Diploma in electrical engineering from Hunan Institute of Engineering, Xiangtan, China, in 1990, his MSc degree in electrical engineering from Hunan University, Changsha, China, in 1997, his PhD degree in control theory and engineering from Shanghai Jiao Tong University, Shanghai, China, in 1999, and his PhD degree in control and power engineering (awarded the Best Doctoral Thesis Prize) from Imperial College London, London, UK, in 2004, respectively. He holds the Chair in Control and Systems Engineering at the Department of Automatic Control and Systems Engineering, The University of Sheffield, UK. He has worked at Hunan Institute of Engineering, Xiangtan, China; Technion–Israel Institute of Technology, Haifa, Israel; Imperial College London, London, UK; University of Glamorgan, Cardiff, UK; The University of Liverpool, Liverpool, UK; and Loughborough University, Leicestershire, UK. He has been on sabbatical at the Cymer Center for Control Systems and Dynamics (CCSD), University of California, San Diego, USA; and the Center for Power Electronics Systems (CPES), Virginia Tech, Blacksburg, USA. He is the author or co-author of *Robust Control of Time-Delay Systems* (Springer-Verlag, 2006), *Control of Integral Processes with Dead Time* (Springer-Verlag, 2010) and *Control of Power Inverters in Renewable Energy and Smart Grid Integration* (Wiley-IEEE Press, 2013). His research focuses on advanced control theory and applications, including power electronics, renewable energy and smart grid integration, electric drives and electric vehicles, robust and $H^\infty$ control, time-delay systems and process control. He is a Specialist recognised by the State Grid Corporation of China (SGCC), a Fellow of the Institution of Engineering and Technology (IET), a Senior Member of

IEEE, the Vice-Chair of IFAC TC 6.3 (Power and Energy Systems) responsible for the Working Group on Power Electronics and was a Senior Research Fellow of the Royal Academy of Engineering/Leverhulme Trust, UK (2009–2010). He serves as an Associate Editor for *IEEE Transactions on Power Electronics* and the Conference Editorial Board of the IEEE Control Systems Society.

**Tomas Hornik** received a Diploma in Electrical Engineering in 1991 from the Technical College V Uzlabine, Prague, the BEng and PhD degree in electrical engineering and electronics from The University of Liverpool, UK, in 2007 and 2010, respectively. He was a postdoctoral researcher at the same university from 2010 to 2011. He joined Turbo Power Systems as a Control Engineer in 2011. His research interests cover power electronics, advanced control theory and DSP-based control applications. He had more than ten years working experience in industry as a system engineer responsible for commissioning and software design in power generation and distribution, control systems for central heating and building management. He is a member of the IEEE and the IET.

# List of Abbreviations

| | |
|---|---|
| *abc* frame | Natural Frame |
| $\alpha\beta$ frame | Stationary Reference Frame |
| *dq* frame | Synchronously Rotating Reference Frame |
| AC | Alternating Current |
| ADC | Analog-to-Digital Converter |
| APC | Active Power Compensator |
| APF | Active Power Filter |
| APFM | Amplitude Phase Frequency Model |
| APM | Amplitude Phase Model |
| C-inverters | Inverters with Capacitive Output Impedances |
| CHP | Combined Heat and Power |
| CPU | Central Processing Unit |
| CSI | Current Source Inverter |
| CSP | Concentrated Solar Power |
| CVCF | Constant-Voltage Constant-Frequency |
| DAC | Digital-to-Analog Converter |
| DB | Dead-Beat |
| DC | Direct Current |
| DDSRF-PLL | Decoupled Double SRF-PLL |
| DFIG | Doubly-Fed Induction Generator |
| DSC | Digital Signal Controller |
| DSP | Digital Signal Processor |
| EKF | Extended Kalman Filter |
| EMI | Electromagnetic Interference |
| EPLL | Enhanced PLL |
| ESR | Equivalent Series Resistance |
| FRF-PLL | Fixed-Reference Frame PLL |
| GTO | Gate-Turn Off |
| HAPF | Hybrid Active Power Filter |
| HB | Hysteresis Band |
| HC | Harmonics Compensator |
| HCS | Hill-Climb Search |

| | |
|---|---|
| IGBT | Insulated Gate Bipolar Transistor |
| IPM | Intelligent Power Module |
| KCL | Kirchhoff's Current Law |
| KVL | Kirchhoff's Voltage Law |
| L-inverters | Inverters with Inductive Output Impedances |
| LF | Loop Filter |
| LPF | Low-Pass Filter |
| MIMO | Multiple-Input Multiple-Output |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| MPP | Maximum Power Point |
| MPPT | Maximum Power Point Tracking |
| P controller | Proportional controller |
| PD unit | Phase-error Detection unit |
| PI controller | Proportional–Integral controller |
| PLL | Phase-Locked Loops |
| PMSG | Permanent Magnet Synchronous Generators |
| PPF | Passive Power Filter |
| PR controller | Proportional–Resonant controller |
| PSF | Power Signal Feedback |
| PV | Photovoltaic |
| PWM | Pulse-Width Modulation |
| R-inverters | Inverters with Resistive Output Impedances |
| RMS | Root Mean Square |
| RPC | Railway Static Power Conditioner |
| SCIG | Squirrel-Cage Induction Generator |
| SISO | Single-Input Single-Output |
| SLL | Sinusoid-Locked Loops |
| SOA | Safe Operating Area |
| SOGI-PLL | Second-Order Generalised Integrator-based PLL |
| SOGI-QSG | SOGI-based Quadrature-Signal Generator |
| SPC | Static Power Conditioner |
| SPWM | Sinusoidal Pulse-Width Modulation |
| SRF-PLL | PLL in the Synchronously Rotating Reference Frame |
| SSM | Single-phase Synchronous Machine |
| STA | Sinusoidal Tracking Algorithm |
| SVC | Static Var Compensators |

| | |
|---|---|
| SVF | Space Vector Filter |
| SVPWM | Space Vector Pulse-Width Modulation |
| THD | Total Harmonic Distortion |
| TSR | Tip Speed Ratio |
| UPS | Uninterruptible Power Supply |
| VCO | Voltage Controlled Oscillator |
| VSI | Voltage Source Inverter |
| ZOH | Zero Order Hold |

# Conventions

| | |
|---|---|
| $A^T$ and $A^*$ | transpose and complex conjugate transpose of $A$ |
| $A^{-1}$ and $A^{-*}$ | inverse of $A$ and shorthand for $(A^{-1})^*$ |
| det($A$) | determinant of $A$ |
| $G(s) = \left[\begin{array}{c\|c} A & B \\ \hline C & D \end{array}\right]$ | shorthand for $G(s) = D + C(sI - A)^{-1}B$ |
| $j\mathbb{R}$ | imaginary axis |
| Re $s$ and Im $s$ | real and imaginary parts of $s \in \mathbb{C}$ |
| $\mathbb{Z}$, $\mathbb{R}$ and $\mathbb{C}$ | fields of integral, real and complex numbers |
| $\in$ | belong to |
| $\cap$ | intersection |
| $\subset$ | subset |

# 1

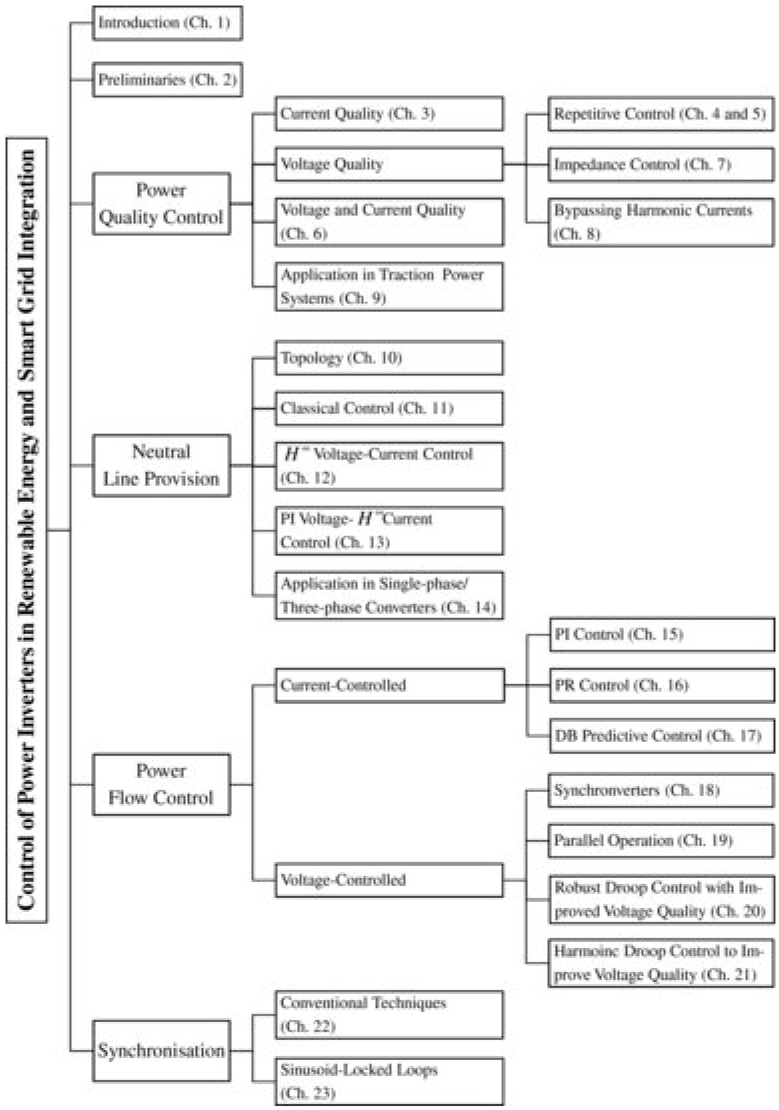
# Introduction

In this chapter, an overview of the book is given at first, followed by some basics about power processing and some hardware issues relevant to the design of power inverters. Moreover, wind power systems, solar power systems and smart grid integration are briefly described to set the scene for the rest of the book.

## 1.1 Outline of the Book

After making an introduction in this chapter and presenting preliminaries in Chapter 2, the book is divided into four Parts: Power Quality Control (Chapters 3–9), Neutral Line Provision (Chapters 10–14), Power Flow Control (Chapters 15–21) and Synchronisation (Chapters 22–23). The overall structure of the book is shown in Figure 1.1. Some chapters are related to more than one part, which is not shown in Figure 1.1 but will be mentioned below.

Figure 1.1 Structure of the book




Part I is devoted to the power quality issues of the current fed into the grid and the output voltage of an inverter. A current controller is designed in Chapter 3 with the $H^\infty$ repetitive control strategy so that the current injected into the grid is clean. This chapter is also directly linked to Part III under the category of current-controlled strategies. Several control strategies are presented in Chapters 4–8 to address voltage quality issues based on different mechanisms. In Chapters 4 and 5, the controllers are designed based on the $H^\infty$ repetitive control strategy, with different sets of feedback signals and different models. Both the voltage quality and the current quality are addressed in Chapter 6 with a cascaded current–voltage controller, according to the $H^\infty$ repetitive control strategy. In Chapters 4–6, the voltage quality issues are addressed essentially from the control point of view as a tracking problem. The voltage quality issue can also be addressed involving fundamental understanding about the degradation mechanisms of voltage quality. In Chapter 7, it is shown that the output impedance of an inverter can be changed to obtain inverters with inductive, resistive and capacitive output impedances, which are called L-inverters, R-inverters and C-inverters, respectively. C-inverters are able to offer much better voltage quality than L-inverters and R-inverters with the same hardware. In Chapter 8, a strategy that is the same as bypassing the harmonic components in the load current is presented to improve the voltage quality. Another strategy that falls into this category is to inject the right amount of voltage harmonics into the reference voltage of an inverter so that it cancels the harmonic voltage dropped on the output impedance, which improves the quality of the output voltage. This is presented in Chapter 21, in Part III, after presenting the robust droop control in Chapter 19. As an application example, the power quality issues in traction power systems, including current harmonics, negative-sequence currents and low power factor, are addressed in Chapter 9.

Part II is devoted to the provision of an independently-controlled neutral line, which facilitates the implementation of other functions in a power electronic system. The topologies to provide a neutral line are presented in Chapter 10. In Chapter 11, a controller is designed to maintain a stable neutral point with classical control strategies, from which the parameters of the neutral leg are determined. In Chapter 12, a controller is designed with the $H^\infty$ control strategy, taking the voltage shift of the neutral point and the current flowing into the DC-link capacitors as feedback.

In Chapter 13, an $H^\infty$ current controller is designed to minimise the current flowing into the DC-link capacitor and a PI controller is designed to bring the DC voltage shift back to the mid-point of the DC link. These two controllers are decoupled in the frequency domain and, hence, can be arranged in a parallel control structure. The provision of an independently-controlled neutral line is applied in Chapter 14, as an application example, to the generation of an independent three-phase power supply from a single-phase source.

Part III is devoted to power flow control. The control strategies can be classified into two categories: current-controlled strategies to directly control the current exchanged with the grid and voltage-controlled strategies to control the voltage of the inverter so that the power flow is indirectly controlled. Current-controlled strategies are easy to implement but the inverters equipped with current-controlled strategies cannot directly take part in the regulation of power system frequency and voltage and, hence, they may cause problems for system stability when the share of power fed into the grid is significant. The PI control, PR control and DB predictive control presented in Chapters 15–17 belong to this category. The repetitive controller presented in Chapter 3, in Part I, also belongs to this category. Voltage-controlled strategies have attracted a lot of attention from academia and industry in recent years because they are able to take part in the regulation of system frequency and voltage. In Chapter 18, a control strategy is presented to make inverters mathematically equivalent to conventional synchronous generators. Such inverters are called synchronverters. As a result, all the technologies developed for synchronous generators can be applied to inverters, which considerably facilitates the grid connection of renewable energy and smart grid integration. A highly compact controller is presented to implement the