

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

Qing-Chang Zhong   Tomas Hornik

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IN RENEWABLE ENERGY  
AND SMART GRID INTEGRATION**



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



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# 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

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system and is designed for authors who want professional output with a minimum of effort and without becoming specialists in typesetting. L<sub>Y</sub>X 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.

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# List of Abbreviations

<i>abc</i> frame	Natural Frame
$\alpha\beta$ frame	Stationary Reference Frame
<i>dq</i> 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

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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
$\operatorname{Re} s$ and $\operatorname{Im} s$	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

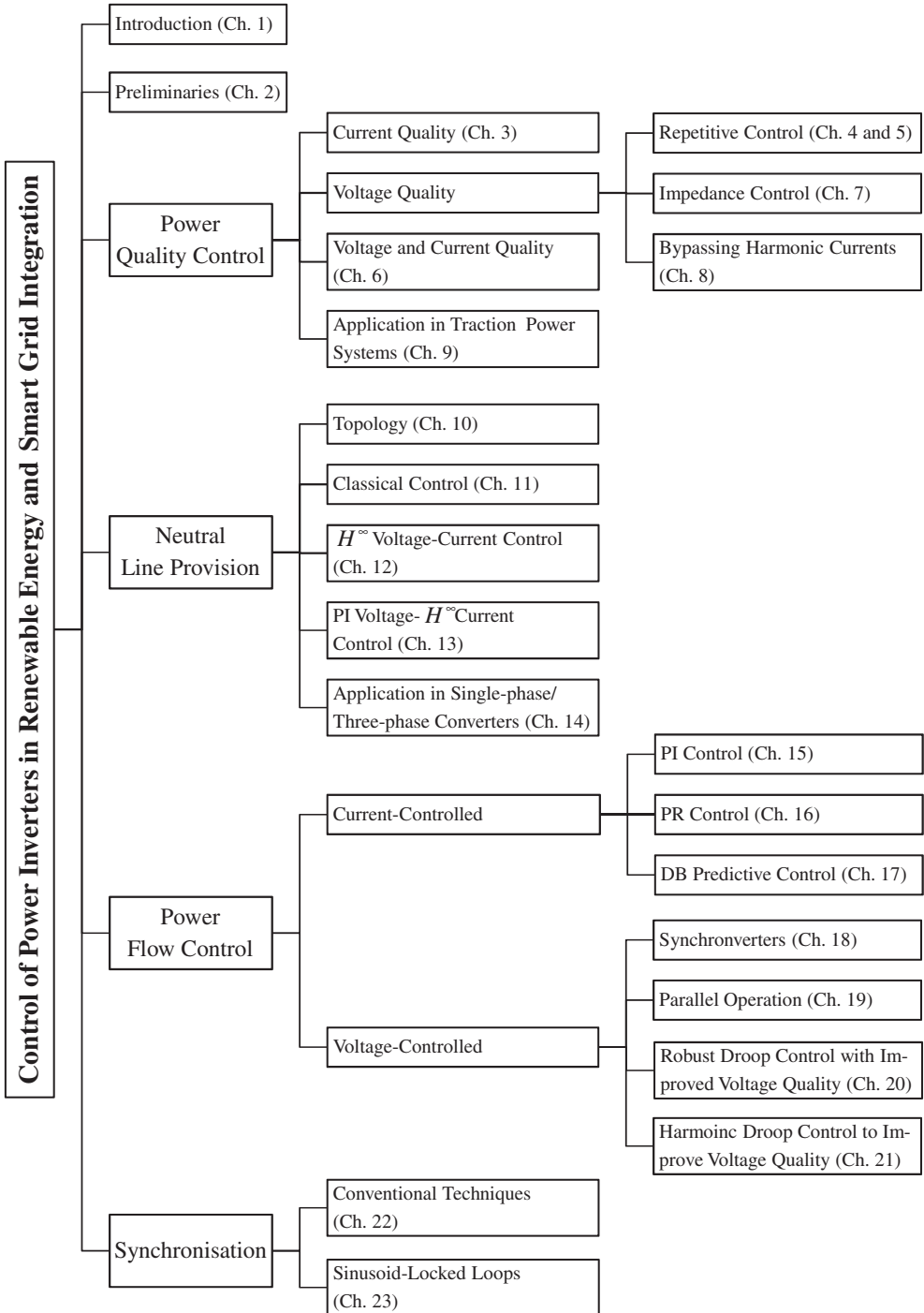
## Introduction

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.

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,



**Figure 1.1** Structure of the book