Studies in Systems, Decision and Control

Volume 249

Series Editor

Janusz Kacprzyk, Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland

The series "Studies in Systems, Decision and Control" (SSDC) covers both new developments and advances, as well as the state of the art, in the various areas of broadly perceived systems, decision making and control–quickly, up to date and with a high quality. The intent is to cover the theory, applications, and perspectives on the state of the art and future developments relevant to systems, decision making, control, complex processes and related areas, as embedded in the fields of engineering, computer science, physics, economics, social and life sciences, as well as the paradigms and methodologies behind them. The series contains monographs, textbooks, lecture notes and edited volumes in systems, decision making and control spanning the areas of Cyber-Physical Systems, Autonomous Systems, Sensor Networks, Control Systems, Energy Systems, Automotive Systems, Biological Systems, Vehicular Networking and Connected Vehicles, Aerospace Systems, Automation, Manufacturing, Smart Grids, Nonlinear Systems, Power Systems, Robotics, Social Systems, Economic Systems and other. Of particular value to both the contributors and the readership are the short publication timeframe and the world-wide distribution and exposure which enable both a wide and rapid dissemination of research output.

** Indexing: The books of this series are submitted to ISI, SCOPUS, DBLP, Ulrichs, MathSciNet, Current Mathematical Publications, Mathematical Reviews, Zentralblatt Math: MetaPress and Springerlink.

More information about this series at http://www.springer.com/series/13304

Jianxing Liu · Yabin Gao · Yunfei Yin ·
Jiahui Wang · Wensheng Luo ·
Guanghui Sun

Sliding Mode Control Methodology in the Applications of Industrial Power Systems

Springer

Jianxing Liu
School of Astronautics
Harbin Institute of Technology
Harbin, China

Yunfei Yin
School of Astronautics
Harbin Institute of Technology
Harbin, China

Wensheng Luo
School of Astronautics
Harbin Institute of Technology
Harbin, China

Yabin Gao
School of Astronautics
Harbin Institute of Technology
Harbin, China

Jiahui Wang
College of Automation
Harbin Engineering University
Harbin, China

Guanghui Sun
School of Astronautics
Harbin Institute of Technology
Harbin, China

ISSN 2198-4182 ISSN 2198-4190 (electronic)
Studies in Systems, Decision and Control
ISBN 978-3-030-30654-0 ISBN 978-3-030-30655-7 (eBook)
https://doi.org/10.1007/978-3-030-30655-7

© Springer Nature Switzerland AG 2020
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To Yue, Jiahan and Jiaxuan
Jianxing Liu

To My Family
Yabin Gao

To My Family
Yunfei Yin

To My Family
Jiahui Wang

To My Family
Wensheng Luo

To My Family
Guanghui Sun

Preface

Sliding mode control (SMC) has been studied since the 1950s and widely used in practical applications, such as robot manipulators, aircraft, underwater vehicles, spacecraft, flexible space structures, electrical motors, automotive engines, power electronics systems, and fuel cell power systems, due to its insensitivity to parameter variations and robustness against external disturbances. Among these applications, many research endeavors have been focused during the past decades, on control and observation problems in fuel cell power systems and power electronics systems, using sliding mode technique. One of the most distinguished properties of SMC is that it utilizes a discontinuous control action, which switches between two distinctively different system structures such that a new type of system motion, called sliding mode, exists in a specified manifold. This particular characteristic of the motion in the manifold is its insensitivity to parameter variations, and complete rejection of external disturbances.

Polymer electrolyte membrane fuel cells (PEMFCs) have emerged as the most prominent technology for energizing future's automotive world. They are clean, quiet and efficient, and have been widely studied in automotive applications over the past two decades due to their relatively small size, lightweight and easy manufacture. While there are still major issues concerning cost, liability, and durability to be addressed before they become a widely used alternative to internal combustion engines (ICEs), fuel cells are expected to lead the world towards fossil-fuel-independent hydrogen economy in terms of energy and electro-mobility. One hindrance of fuel cells in general, as a kind of independent electrical power sources, is that their dynamic response is slow. Therefore, a fuel-cell-based power system requires additional storage elements with fast response time in order to handle rapid load variations.

This book is organized as follows. In Chap. 2, a brief review of sliding mode control for both linear and nonlinear systems are presented.

In Chap. 3, we focus on sliding mode observer (SMO) design for both linear uncertain systems and nonlinear systems. Two kinds of SMO design based on Utkin's and Lyapunov's methods for uncertain linear systems are recalled. Then, the SMO designs are extended to three forms of nonlinear systems (companion

form, triangular input form and algebraical observable form). The applications of SMO based fault detection and isolation (FDI) have been presented and fault reconstruction via traditional SMOs is discussed. Then, our theoretical contribution in Second-Order SMO-based FDI is introduced. A novel adaptive SOSM Observer is developed and its application in FDI is presented. In the end, two illustrative examples are shown to both SMO designs and their applications in FDI.

In Chap. 4, the model of a PEMFC system which includes a stack voltage model and an air feed system model is discussed. The air feed system is modeled as a four-state model which considers the dynamics of oxygen partial pressure, nitrogen partial pressure, compressor speed, and supply manifold pressure. Then, a real-time PEMFC emulator is designed using experimental data obtained from a 33 kW PEMFC unit containing 90 cells in series. Finally, the proposed air feed system model is validated experimentally through the hardware-in-loop (HIL) test bench which consists of a physical air-feed system, based on a commercial twin screw compressor and a real-time PEMFC emulator.

In Chap. 5, we focus on the problem of robust control in PEMFC system, in order to maximize the fuel cell net power and avoid the oxygen starvation by regulating the oxygen excess ratio to its desired value during fast load variations. The oxygen excess ratio is estimated via an extended state observer from the measurements of the compressor flow rate, the load current and supply manifold pressure. An HIL test bench which consists of a commercial twin screw air compressor and a real-time fuel cell emulation system, is used to validate the performance of the proposed extended state observer (ESO)-based second-order sliding mode (SOSM) controller. The experimental results show that the proposed controller is robust and has a good transient performance in the presence of load variations and parametric uncertainties.

In Chap. 6, the estimation problem of the PEMFC system is presented. First, the design of an SOSM observer is presented for the PEMFC air-feed system, in order to estimate the hydrogen partial pressure in the anode channel of the PEMFC, using the measurements of stack voltage, stack current, anode pressure and anode inlet pressure. The robustness of this observer against parametric uncertainties and load variations is studied, and the finite time convergence property is proved via Lyapunov analysis. Then, an algebraical observer is designed for the partial pressures of oxygen and nitrogen in the cathode of the PEMFC. The states of the PEMFC air-feed system are presented in terms of a static diffeomorphism involving the system outputs (compressor flow rate and supply manifold pressure) and their time derivatives, respectively. The implementation of the algebraical observer on the HIL test bench is described. The effectiveness and robustness of the observer are validated experimentally.

In Chap. 7, we focus on the fault diagnosis problem of the PEMFC system, considering a fault scenario of sudden air leak in the air supply manifold. The design of an SOSM observer is presented for the PEMFC air-feed system, considering state estimation, parameter identification and fault reconstruction problems simultaneously. An adaptive-gain SOSM observer is developed for observing the system states, where the adaptive law estimates the uncertain parameters. The

oxygen starvation phenomenon is monitored through an estimated performance variable (oxygen excess ratio). Satisfactory experimental results are obtained to show the effectiveness of the proposed observer. The effect of parameter variations and measurement noise are considered during the observer designs.

In Chap. 8, we concentrate on the control problem on the power side of the PEMFC system. Fuel cell power system requires power conditioning circuits with precise power control algorithms behind them such that the output power is compatible with the constraints of the power bus. These circuits include DC/DC converters which are used to control the voltages of the fuel cell and storage elements to the desired value. Furthermore, robust control design for DC/DC power converters is discussed, using sliding mode techniques. The main focus is on the necessary modification and improvement of conventional sliding mode methods for their applications to fuel cell power systems.

In Chap. 9, we consider the control and observation problems of three-phase AC/DC power converters. The controller design is based on the system model and has a cascaded structure which consists of two control loops. The outer loop regulates the DC-link capacitor voltage and the power factor providing the current references for the inner control loop. The current control loop tracks the actual currents to their desired values. To design the proposed controller, the load connected to the DC-link capacitor is considered as a disturbance, which directly affects the performance of the whole system. Theoretical analysis is given to show the closed-loop behavior of the proposed controller and experimental results are presented to validate the control algorithm under a real power converter prototype.

This book is a research monograph whose intended audience is graduate and postgraduate students, academics, scientists and engineers who are working in the field.

Harbin, China
June 2019

Jianxing Liu
Yabin Gao
Yunfei Yin
Jiahui Wang
Wensheng Luo
Guanghui Sun

Acknowledgements

There are numerous individuals without whose help this book will not have been completed. First, I would like to sincerely gratitude to Prof. Ligang Wu from Harbin Institute of Technology. It is really a great experience working with Prof. Wu's research group. With his abundant research experience, he shows me how to become an independent researcher. Our acknowledgments also go to our international collaborators, Prof. Leopoldo G. Franquelo, Dr. Sergio Vazquez, Dr. José I. Leon, Dr. Abraham Marquez, from Universidad de Sevilla, who have offered invaluable support and encouragement throughout this research effort. Thanks go to our students, Peng Chen, Chengwei Wu, Yongyang Xiong, Jiahui Wang, Tingting Yu, Huiyan Zhang, Xiaoning Shen, Tongyu Zhao, Hao Lin, Jinjiang Li, Tantan Dong.

Special thanks go to my supervisors Dr. Maxime Wack and Dr. Salah Laghrouche, for the continuous support of my Ph.D. study and research in Lab IRTES, for their patience, motivation, and immense knowledge, and for their inspiring guidance during my thesis. I would also like to thank all my colleagues in the laboratory for their help during my Ph.D. study. Especially, they are Fei Yan, Dongdong Zhao, Yishuai Lin, You Li, Jia Wu, You Zheng, Fayez Shakil Ahmed, Imad Matraji, Mohamed Harmouche, Adeel Mehmood.

Finally, I would like to express special thanks to my family. Without their endless love and understanding, I cannot finish this work.

Contents

1 General Introduction 1
1.1 Fuel-Cell-Based Industrial Power Systems 1
1.2 Motivation and Features of the Book 3
1.2.1 Sliding Mode Control, Observation and FDI 3
1.2.2 PEMFC Power System 5
1.2.3 Power Electronics System 6
1.3 Outline of the Book 6
References 9

2 Basic Theory of Sliding Mode Control 11
2.1 General Development of Sliding Mode Control 11
2.2 Fundamental Theory of SMC 12
2.2.1 SMC Design Methods 13
2.2.2 Chattering Problem 15
2.3 SOSM Control 17
2.3.1 Definitions 17
2.3.2 SOSM Dynamics 18
2.3.3 SOSM Controllers 20
2.4 Conclusion 23
References 24

3 Sliding Mode Observer and Its Applications 27
3.1 State of the Art 27
3.2 First-Order SMO 28
3.2.1 SMO Design Based on Utkin's Method 28
3.2.2 SMO Design Based on Lyapunov Method 31
3.2.3 SMO Design Based on Slotine's Method 32

3.3 SOSM Observer . . . 34
3.3.1 Super-Twisting Algorithm . . . 34
3.3.2 Modified Super-Twisting Algorithm . . . 37
3.3.3 Adaptive-Gain Super-Twisting Algorithm . . . 41
3.4 SMO-Based FDI . . . 44
3.4.1 First-Order SMO-Based FDI . . . 46
3.4.2 SOSM Observer-Based FDI . . . 49
3.5 Illustrative Examples . . . 56
3.5.1 Adaptive-Gain SOSM Observer Design . . . 57
3.5.2 SOSM Observer Based FDI . . . 58
3.6 Conclusion . . . 60
References . . . 60

4 Introduction of Proton Exchange Membrane Fuel Cell Systems . . . 63
4.1 Introduction of PEMFCs . . . 63
4.2 PEMFC Stack Voltage . . . 65
4.3 PEMFC Air-Feed System Model . . . 67
4.3.1 Supply Manifold Model . . . 68
4.3.2 Compressor Model . . . 69
4.3.3 Cathode Flow Model . . . 70
4.3.4 Dynamic Model with Four States . . . 72
4.4 Experimental Validation . . . 74
4.4.1 PEMFC Emulator . . . 75
4.4.2 Validation of 4th Order Model with PEMFC Emulator . . . 77
4.5 Conclusion . . . 78
References . . . 82

5 Sliding Mode Control of PEMFC Systems . . . 83
5.1 Introduction . . . 83
5.2 Problem Formulation . . . 85
5.2.1 The Vapor Partial Pressures Dynamics . . . 86
5.2.2 State Space Representation of PEMFC System . . . 87
5.2.3 Control Objectives . . . 87
5.3 Control Design . . . 89
5.3.1 Oxygen Excess Ratio Control . . . 89
5.3.2 Closed-Loop Stability Analysis . . . 94
5.4 Experimental Results . . . 94
5.5 Conclusion . . . 100
References . . . 100

6 Sliding Mode Observer of PEMFC Systems . . . 103
6.1 Introduction . . . 103
6.2 SMO Design for PEMFC Systems . . . 106
6.2.1 Nonlinear Dynamic Model of PEMFC . . . 106

6.2.2 Gas Dynamics of Hydrogen Partial Pressure 107
6.2.3 SOSM Observer Design 108
6.3 Algebraical Observer Design of PEMFC Systems 112
6.3.1 Algebraic Observer Design Using Sliding Mode Differentiators 113
6.4 Simulation Results of SMO for PEMFC Systems 119
6.5 Conclusions 124
References 126

7 Sliding-Mode-Observer-Based Fault Diagnosis of PEMFC Systems 129
7.1 Introduction 129
7.2 Dynamic Modeling of PEMFC Systems 133
7.2.1 State-Space Representation of PEMFC Modeling 134
7.3 Nonlinear Observer Design for PEMFC System 136
7.3.1 Problem Formulation 136
7.3.2 Adaptive SOSM Observer Design 137
7.4 Fault Reconstruction 143
7.5 FDI of PEMFC System 144
7.6 Experimental Results 146
7.7 Conclusion 154
References 154

8 Sliding Mode Control of DC/DC Power Converters 157
8.1 Introduction 157
8.2 Modeling of Boost Type DC/DC Converters 159
8.2.1 Representation of the Tracking Error System with Uncertain Parameters 160
8.2.2 A Simplified Ellipsoidal-Type IT2FNN 162
8.2.3 Control Objective 163
8.3 Control Design and Stability Analysis 164
8.3.1 Dynamic SMC Design 164
8.3.2 Ellipsoidal-Type IT2FNN-Based Dynamic SMC Design 167
8.3.3 Design of the Parameter Updating Rules of the Ellipsoidal-Type IT2FNN 169
8.4 Simulation Results 171
8.4.1 Set Up 171
8.4.2 Case 1: Control Against the Input Voltage Variation 171
8.4.3 Case 2: Control Against the Load Resistance Variation . . . 176
8.4.4 Case 3: Control Against the Variations of the Load Resistance and Input Voltage 180
8.5 Conclusion 183
References 183

9 Sliding Mode Control of Three-Phase Power Converters 185
9.1 Introduction 185
9.2 Problem Formulation 187
9.2.1 Dynamic System Model 187
9.2.2 Modeling Uncertainties 188
9.2.3 Control Objectives 189
9.3 Disturbance Observer Based SMC Design 189
9.3.1 Recalling of Super-Twisting Algorithm 190
9.3.2 Extended State Observer Design 191
9.3.3 Capacitor Voltage Regulation Loop 193
9.3.4 Current Tracking Loop 194
9.4 Experimental Results 197
9.4.1 Load Step at DC-Link 199
9.4.2 Reactive Power Command Step 200
9.5 Conclusions 203
References 203

Notations and Acronyms

$\triangleq$	Is defined as
$\simeq$	Approximately equals to
$\ll$	Is much less than
$\gg$	Is much greater than
$\in$	Belongs to
$\forall$	For all
$\mathbf{\Sigma}$	Sum
$\lvert\cdot\rvert$	Euclidean vector norm
$\lVert\cdot\rVert$	Euclidean matrix norm (spectral norm)
$\lVert\cdot\rVert_2$	$\mathcal{L}_2$-norm: $\sqrt{\int_0^\infty \lvert\cdot\rvert^2 dt}$ (continuous case)
	ℓ_2-norm: $\sqrt{\sum_0^\infty \lvert\cdot\rvert^2}$ (discrete case)
$\mathcal{L}_2\{[0,\infty),[0,\infty)\}$	Space of square summable sequences on $\{[0,\infty),[0,\infty)\}$ (continuous case)
$\ell_2\{[0,\infty),[0,\infty)\}$	Space of square summable sequences on $\{[0,\infty),[0,\infty)\}$ (discrete case)
$\dot{s}$	The first-order derivative of function s
$\ddot{s}$	The second-order derivative of function s
$\frac{\partial f}{\partial x}$ or $\frac{\partial}{\partial x}f$	The derivative of the function f with respect to x
$\mathbf{R}$	Field of real numbers
$\mathbf{R}^n$	Space of n-dimensional real vectors
$\mathbf{R}^{n\times m}$	Space of $n \times m$ real matrices
X^{T}	Transpose of matrix X
X^{-1}	Inverse of matrix X
$X > (<) 0$	X is real symmetric positive (negative) definite
$X \geq (\leq) 0$	X is real symmetric positive (negative) semi-definite
$*$	Symmetric terms in a symmetric matrix
0	Zero matrix
$0_{n\times m}$	Zero matrix of dimension $n \times m$
I	Identity matrix

I_n	$n \times n$ identity matrix
$\mathrm{col}\{x_1,\ldots, x_n\}$	Column vector $[x_1, \ldots, x_n]^{\mathrm{T}}$ with n elements
$\det(\cdot)$	The determinant computed from the elements of a square matrix
$\mathrm{diag}\{X_1,\ldots, X_{\mathrm{m}}\}$	Block diagonal matrix with blocks $X_1, \ldots, X_m$
inf	Infimum, the greatest lower bound
lim	Limit
$\mathrm{In}(\cdot)$	The natural logarithm of a number
max	Maximum
min	Minimum
$\mathrm{rank}(\cdot)$	Rank of a matrix
$\mathrm{sing}(\cdot)$	The signum function of a real number
sup	Supremum, the least upper bound
$\lambda_{\min}(\cdot)$	Minimum eigenvalue of a real symmetric matrix
$\lambda_{\max}(\cdot)$	Maximum eigenvalue of a real symmetric matrix
AC	Alternating current
AFC	Aqueous alkaline fuel cell
AFE	Active front end
ARE	Algebraic Riccati equation
bar	A metric unit of pressure
DC	Direct current
DSP	Digital signal processor
Eq. or Eqs.	Equation or Equations
ESO	Eextended state observer
FC	Fuel cell
FDI	Fault detection and isolation
Fig. or Figs.	Figure or Figures
FNN	Fuzzy neural network
FOU	Footprint of uncertainty
FPGA	Field-programmable gate array
FTC	Fault tolerant control
GDM	Gradient descent method
HGO	High-gain observer
HIL	Hardware-in-loop
HOSM	High-order sliding mode
ICE	Internal combustion engine
IGBT	Insulated gate bipolar transistor
IT2	Interval type-2
IT2FNN	Interval type-2 fuzzy neural network
KF	Kalman filter
kVAr	Kilovolt-amperes reactive, thousand Volt-ampere reactive, a unit of reactive power
LMF	Lower membership function
LMI	Linear matrix inequality

LPV	Linear parameter varying
LTI	Linear time-invariant
MCFC	Molten carbonate fuel cell
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PI	Proportional integral
PLL	Phase locked loop
PMSM	Permanent magnet synchronous
PR	Proportional plus resonant
PWM	Pulse-width modulation
THD	Total harmonic distortion
T-S	Takagi-Sugeno
SMC	Sliding mode control
SMO	Sliding mode observer
SOFC	Solid oxide fuel cell
SOSM	Second-order sliding mode
SOSML	The addition of linear term to the nonlinear SOSM term
SPD	Symmetrical positive definite
SRF	Synchronous reference frame
ST	Super-twisting
STA	Super-twisting algorithm
UIO	Unknown input observers
UKF	Unscented Kalman filter
VSC	Variable structure control

List of Figures

Fig. 1.1 PEMFC power system 2
Fig. 1.2 Observer as the heart of control systems [2]. 3
Fig. 1.3 Basic configuration of observer-based FDI [14] 5
Fig. 1.4 Main contents of this publication 7
Fig. 2.1 SOSM trajectory 18
Fig. 2.2 STA phase trajectory 21
Fig. 2.3 Twisting algorithm phase trajectory 22
Fig. 2.4 Sub-optimal algorithm phase trajectory 23
Fig. 3.1 Frequency characteristics of STA 36
Fig. 3.2 Frequency characteristics of SOSML 38
Fig. 3.3 Estimates of state and disturbance 57
Fig. 3.4 Adaptive law $L(t)$ of the SOSM algorithm (3.63). 58
Fig. 3.5 The performance of observer (3.145) 59
Fig. 3.6 Fault reconstruction and its error for the pendulum system. 59
Fig. 4.1 Fuel cell reaction 64
Fig. 4.2 Typical fuel cell voltage 65
Fig. 4.3 Voltage drops due to different types of losses in FC. **a** Activation losses; **b** Ohmic losses; **c** Concentration losses; **d** Total losses 66
Fig. 4.4 Fuel cell system scheme 67
Fig. 4.5 Test bench [8]. 74
Fig. 4.6 Scheme of HIL system used in the experiments 75
Fig. 4.7 Stack voltage response 77
Fig. 4.8 Stack current under load variation 78
Fig. 4.9 Experimental validation of P_{net} and λ_{O_2} 79
Fig. 4.10 Experimental validation of p_{O_2} and p_{N_2} 80
Fig. 4.11 Experimental validation of ω_{cp} and p_{sm}. 81
Fig. 5.1 Fuel cell system scheme 86
Fig. 5.2 Block diagram of the oxygen excess ratio control system. 89
Fig. 5.3 Block diagram of the HIL test bench 95

Fig. 5.4 Stack current under load variation 96
Fig. 5.5 Measurement of compressor flow rate under load variation 97
Fig. 5.6 Performance of oxygen excess ratio (**a**) and its regulation error (**b**) 97
Fig. 5.7 Performance of the differentiator (5.22) 98
Fig. 5.8 Performance of the compressor flow rate 98
Fig. 5.9 Stack voltage performance 99
Fig. 5.10 Fuel cell net power 99
Fig. 6.1 Fuel cell system scheme 106
Fig. 6.2 Schematic diagram of the proposed SOSM observer 120
Fig. 6.3 Stack current under load variation 120
Fig. 6.4 Stack voltage response under load variations 121
Fig. 6.5 Voltage measurement noise 122
Fig. 6.6 Net power under load variations 123
Fig. 6.7 Performance of oxygen excess ratio 124
Fig. 6.8 Estimation of p_{H_2} under load variations and measurement noise 125
Fig. 6.9 Estimation error of hydrogen partial pressure 125
Fig. 7.1 Typical fuel cell voltage 134
Fig. 7.2 Schematic diagram of the observer based fault reconstruction 147
Fig. 7.3 System output measurement noise 147
Fig. 7.4 Estimate of nitrogen partial pressure and its error 148
Fig. 7.5 Estimate of compressor speed and its error 149
Fig. 7.6 Performance of the adaptive differentiator 150
Fig. 7.7 Estimate of stack current and its error 151
Fig. 7.8 Fault reconstruction and its error 152
Fig. 7.9 Estimate of λ_{O_2} and gain $L_o(t)$ versus time (s) 153
Fig. 8.1 Topology of the DC/DC boost converter: **a** Switching OFF state, and **b** Switching ON state 160
Fig. 8.2 Structure of the designed adaptive IT2FNN-based DSMC 169
Fig. 8.3 Variation of the input inductor V_i 172
Fig. 8.4 MFs of IT2FNN for inputs z_1, z_2 and z_3 173
Fig. 8.5 Duty cycle and sliding surface under Case 1 by the three controls 174
Fig. 8.6 Capacitor voltage under Case 1 by the three controls 174
Fig. 8.7 Capacitor voltage tracking error under Case 1 by the three controls 175
Fig. 8.8 Inductor current under Case 1 by the three controls 175
Fig. 8.9 Inductor current tracking error under Case 1 by the three controls 176
Fig. 8.10 Variation of the load resistance R 177
Fig. 8.11 Duty cycle and sliding surface under Case 2 by the three controls 177

Fig. 8.12 Capacitor voltage under Case 2 by the three controls 178
Fig. 8.13 Capacitor voltage tracking error under Case 2 by the three controls 178
Fig. 8.14 Inductor current under Case 2 by the three controls 179
Fig. 8.15 Inductor current tracking error under Case 2 by the three controls 179
Fig. 8.16 Duty cycle and sliding surface under Case 3 by the three controls 180
Fig. 8.17 Capacitor voltage under Case 3 by the three controls 181
Fig. 8.18 Capacitor voltage tracking error under Case 3 by the three controls 181
Fig. 8.19 Inductor current under Case 3 by the three controls 182
Fig. 8.20 Inductor current tracking error under Case 3 by the three controls 182
Fig. 9.1 Circuit of the three-phase two-level grid-connected power converter 188
Fig. 9.2 Block diagram of the STA + ESO controller for the voltage loop 194
Fig. 9.3 Block diagram of the current tracking regulation loop 196
Fig. 9.4 Power converter prototype: **a** Power converter, **b** DC load 198
Fig. 9.5 Transient response of DC-link capacitor voltage under a load step: **a** PI-SRF algorithm, **b** ESO-SOSM strategy, **c** PI-SRF algorithm with increased bandwidth 199
Fig. 9.6 Transient response of grid currents in the dq frame under a load step. Top: PI-SRF algorithm. Bottom: ESO-SOSM strategy 200
Fig. 9.7 Transient response of grid currents in the dq frame under a load step for the PI-SRF algorithm. Top: Grid currents in the SRF. Bottom: Instantaneous active and reactive power 201
Fig. 9.8 Transient response of grid currents in the dq frame under a load step for the ESO-SOSM strategy. Top: Grid currents in the SRF. Bottom: Instantaneous active and reactive power 201
Fig. 9.9 Steady state currents for a instantaneous reactive power command of 3 kVAr: **a** Current waveforms for PI-SRF algorithm, **b** Current spectrum for PI-SRF algorithm, **c** Power factor for PI-SRF algorithm, **d** Current waveforms for ESO-SOSM strategy, **e** Current spectrum for ESO-SOSM algorithm, **f** Power factor for ESO-SOSM strategy 202

List of Tables

Table 2.1 Main approaches to alleviate or limit the chattering problems . . . 16
Table 3.1 Parameters for the numerical simulation . . . 56
Table 4.1 Summary of typical fuel cell characteristics (Table 16, [5]) . . . 64
Table 4.2 Parameters used in compressor model . . . 69
Table 4.3 Parameter definition . . . 74
Table 4.4 Emulated PEMFC system parameters [8] . . . 76
Table 5.1 Parameters defined in system (5.3)–(5.7) . . . 88
Table 5.2 Variations of system parameters . . . 96
Table 6.1 PEMFC system parameters . . . 122
Table 6.2 Parameter variations of the PEMFC system . . . 123
Table 8.1 $\frac{\partial \underline{g}_{ij}}{\partial \xi}$ and $\frac{\partial \bar{g}_{ij}}{\partial \xi}$ of the ellipsoidal-type IT2 membership functions . . . 170
Table 8.2 Nominal values of the parameters of the DC/DC boost converter . . . 171
Table 9.1 Electrical system parameters . . . 197
Table 9.2 Controller design parameters . . . 197
Table 9.3 Grid current THD for the load step experiment . . . 199