University of Technology, Sydney

Advanced Control in Smart Microgrids

Jiefeng HU

M.E. (Electrical Engineering), B.E. (Electrical Engineering)

School of Electrical, Mechanical and Mechatronic Systems
University of Technology, Sydney, Australia

A thesis submitted to the University of Technology, Sydney
for the Degree of Doctor of Philosophy

June 2013

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

Production Note:
Signature removed prior to publication.

Acknowledgements

First of all, I would like to express sincere gratitude and appreciation to my supervisor, Professor Jianguo Zhu, for his invaluable guidance, enthusiastic help, and consistent encouragement throughout the entire research project. I am also thankful to Associate Professor David G. Dorrell, the co-supervisor, for his fruitful discussions and useful suggestion.

Also, I would like to thank Dr. Glenn Platt, the external co-supervisor, from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for his kind support and encouragement. His rich industrial experience and advices broadened my mind of microgrids, which had a very positive impact on this work.

Thanks also go to my laboratory colleagues, in particular Dr. Greg Hunter and Dr. Gang Lei, of the Centre for Electrical Machines and Power Electronics, University of Technology, Sydney (UTS), for their helpful advices, technical support and friendship.

I appreciate the support provided by Professor Qishuang Ma from Beijing University of Aeronautics & Astronautics and Dr. Xiaoying Kong from UTS. I am also thankful to Professor Josep M. Guerrero from Aalborg University, Denmark, for his valuable discussions on smart microgrid technologies.

I would also like to express my deepest gratitude to my parents for their support and encouragement. Their inspiring suggestions and practical experience sharing are very important and helpful when I made my own decisions on various occasions.

Finally, I want to express my deepest love to Jenny Mok, for her encouragement and understanding throughout the thesis project.

TABLE OF CONTENTS

CERTIFICATE OF AUTHORSHIP/ORIGINALITY I

ACKNOWLEDGEMENTS II

TABLE OF CONTENTS... III

LIST OF SYMBOLS VI

LIST OF ABBREVIATIONS VIII

LIST OF FIGURES XI

LIST OF TABLES.. XVI

ABSTRACT XVII

1. INTRODUCTION 1

1.1 Distributed Generation 1

1.2 Control of Power Converters for Distributed Generation 3
   1.2.1 Control Strategies of A Single Converter 3
   1.2.2 Control Strategies of Parallel-Connected Converters 13

1.3 The Concept of Microgrids 21

1.4 Research Objectives 26

1.5 Outline of the thesis 26

References 28

2. WIND POWER GENERATION... 36

2.1 Introduction 36
   2.1.1 Wind Power Generation System.. 36
   2.1.2 State of Art of Wind Power Generation Techniques 44

2.2 Grid Synchronization and Flexible Power Regulation................................. 47
   2.2.1 DFIG Modeling 47
   2.2.2 Virtual Torque 49
   2.2.3 An Improved Predictive Direct Control Strategy 50

2.2.4 A New Strategy for Grid Synchronization and Flexible Power Regulation Strategy 55

2.3 Numerical Simulation and Experimental Verification 59
  2.3.1 Numerical Simulation 59
  2.3.2 Experimental Verification 63

2.4 Summary of the Chapter 71

References 73

3. SOLAR PHOTOVOLTAIC (PV) POWER GENERATION 79

3.1 Introduction 79
  3.1.1 Principle and Configuration of PV systems 79
  3.1.2 Power Converters and Controllers for PV systems 82

3.2 Islanded Operation 91
  3.2.1 System model 91
  3.2.2 Voltage control in islanded mode 93

3.3 Grid-connected Operation 96
  3.3.1 Flexible Power Regulation 96
  3.3.2 Switching Frequency Reduction 99

3.4 Numerical Simulation and Experimental Verification 100
  3.4.1 Numerical Simulation 100
  3.4.2 Experimental Verification 103

3.5 Summary of The Chapter 106

References 107

4. MULTI-OBJECTIVE MODEL-PREDICTIVE CONTROL FOR HIGH POWER CONVERTERS 112

4.1 Introduction 112

4.2 Multi-Objective Model-Predictive Control 114
  4.2.1 Concept of Multi-Objective Model-Predictive Control 115
  4.2.2 Discrete-time Digital Implementation 119
  4.2.3 Switching Frequency Reduction 120
  4.2.4 System Stability Improvement 121
  4.2.5 Computational Time Reduction 122

4.3 Numerical Simulation and Experimental Verification 123
  4.3.1 Numerical Simulation 123
  4.3.2 Experimental Verification 126

4.4 Summary of The Chapter 133

References 134

5. SMART MICROGRID SYSTEM CONTROL 138

5.1 Introduction 138

5.2 Smart Microgrid Topology 140

5.3 Control of Parallel Connected Inverters in Microgrids 145
  5.3.1 Voltage Droop Method 146
  5.3.2 Flux Droop Method 155

5.4 Coordinated Control of a microgrid with PVs and Gas Microturbine 167
  5.4.1 Microgrid Configuration and Problems Identification 167
  5.4.2 Coordinated Control Strategy 171
  5.4.3 Cases Study 172

5.5 Model Predictive Control of Microgrids 180
  5.5.1 Microgrid Modeling 180
  5.5.2 Problem Description 189
  5.5.3 Proposed Concept of Model Predictive Control for Microgrids 191
  5.5.4 Results and Discussions 195

5.6 Summary of The Chapter 199

References 200

6. CONCLUSIONS AND FUTURE WORK 206

6.1 Conclusions 206

6.2 Future Work 206

PUBLICATIONS 208

List of Symbols

C	Filter capacitance [μF]
D_i	Switching state of phase i ($i = a$, b, c) leg of the IGBT bridges
f_1, f_2, f_{11}, f_{22}	Slopes or derivatives
f_g	Grid frequency [Hz]
$\boldsymbol{i}_f$, $\boldsymbol{i}_L$, $\boldsymbol{i}_g$	Filter current, load current, and grid current [A]
$\boldsymbol{I}_\mathrm{d}$	Current through the diode [A]
$\boldsymbol{I}_\mathrm{PV}$	Photocurrent of the PV cell [A]
$\boldsymbol{I}_\mathrm{s}$, $\boldsymbol{I}_\mathrm{r}$	Stator and rotor phase current vectors [A]
K_p, K_i	Gain constant of the Proportional-Integral (PI) controller
L	Line inductance [mH]
L_m, R_m	Magnetizing inductance and resistance per phase [Ω]
$L_{\sigma\mathrm{s}}$, $L_{\sigma\mathrm{r}}$	Stator and rotor phase winding leakage inductance [Ω]
L_s, L_r	Stator and rotor phase winding self-inductance [Ω]
L_t	Tie-line inductance [mH]
m, n	Droop coefficients [rad/W, Wb/Var]
N	Coincidence point
P_1, P_2	Active power injected by DGs to microgrid [W]
P_L	Active load power [W]
P_g	Active power injected by utility to microgrid [W]
P_rated, Q_rated	Active and reactive power rating of the DGs [W]
P_s, Q_s	Stator active and reactive power [W]
p	Number of pole pairs
Q_1, Q_2	Reactive power injected by DGs to microgrid [Var]
Q_L	Reactive load power [Var]
Q_g	Reactive power injected by utility to microgrid [Var]
R	Line resistance [Ω]
R_L	Load resistance [Ω]
R_{PVs}, R_{PVsh}	Intrinsic series and shunt resistances of the PV cell [Ω]
R_s, R_r	Stator and rotor phase winding resistance [Ω]
R_t	Tie-line resistance [Ω]

Sk	Sector division
T_c	Computing time [μs]
T_e	Electromagnetic torque [Nm]
T_s	Sampling period [μs]
T_V	Virtual torque [Nm]
V_dc1, V_dc2	DC source voltage of the Distributed Generation [V]
$\boldsymbol{V}_\mathrm{i}$, $\boldsymbol{V}_\mathrm{c}$, $\boldsymbol{E}$	Inverter voltage, capacitor voltage, and load-side voltage [V]
V_g	Magnitude of the grid voltage [V]
$\boldsymbol{V}_\mathrm{s}$, $\boldsymbol{V}_\mathrm{r}$	Stator and rotor phase voltage vectors [V]
ω_1, ω_r, ω_s	Synchronous, rotor, and slip angular frequency [rad/s]
ω_c	Cut-off angular frequency [rad/s]
ω_g	Grid angular frequency [rad/s]
$\boldsymbol{\psi_s}$, $\boldsymbol{\psi_r}$	Stator and rotor flux vectors [Wb]
$\boldsymbol{\psi}_V$, $\boldsymbol{\psi}_E$	Inverter flux vector and load-side flux vector [Wb]
φ_{fV}, φ_{fE}	Phase angles of the inverter flux and load-side flux [rad]
φ_V, φ_E	Phase angles of the inverter voltage and load-side voltage [rad]
φ_Z	Phase angles of the line impedance [rad]
δ	Phase angle difference between inverter flux and load-side flux [rad]
λ	Leakage coefficient
λ_2, λ_3	Weighting factors

List of Abbreviations

ADC	Analog to Digital Conversion
ALS	Average Load Sharing
AMI	Advanced Metering Infrastructure
BDFTSIG	Brushless Doubly Fed Twin Stator Induction Generator
CHP	Combined Heat and Power Stations
3C	Circular Chain Control
CSCF	Constant Speed Constant Frequency
CSI	Current Source Inverter
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAC	Digital to Analog Conversion
DFC	Direct Flux Control
DFIG	Doubly-Fed Induction Generator
DG	Distributed Generation
DPC	Direct Power Control
DSP	Digital Signal Processor
DTC	Direct Torque Control
ESS	Energy Storage System
FACTS	Flexible Alternating Current Transmission Systems
FRT	Fault Ride Through
HVDC	High Voltage Direct Current Transmission Systems
ICT	Information Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IGCT	Insulated Gate Commutated Transistor
IPM	Intelligent Power Module
ISR	Interrupt Service Routine
LB	Load Bank
LPF	Low Pass Filter
MOMPC	Multi-Objective Model-Predictive Control
MPC	Model Predictive Control
MPDFC	Model Predictive Direct Flux Control
MPPT	Maximum Power Tracking Point

MS	Master-Slave
MT	Micro-turbine
NIST	National Institute of Standard and Technology
NPC	Neutral-point-clamped
PC	Personal Computer
PCC	Point of Common Coupling
PDPC	Predictive Direct Power Control
PDVTC	Predictive Direct Virtual Torque Control
PEMFC	Proton Exchange Membrane Fuel Cell
PI	Proportional-Integral
PMSG	Permanent Magnet Synchronous Generator
PV	Photovoltaic
PWM	Pulse Width Modulation
RTDX	Real Time Data Exchange
SCADA	Supervisory Control and Data Acquisition
SCIG	Squirrel Gage Induction Generator
SDFC	Switching Table Based Direct Flux Control
SDPC	Switching Table Based Direct Power Control
SGA	Smart Grid Australia
SOC	State of Charge
SPI	Serial Peripheral Interface
SPWM	Sinusoidal Pulse Width Modulation
STATCOM	Static Synchronous Compensator
STS	Static Transfer Switch
SVM	Space Vector Modulation
REIF	Renewable Energy Integration Facility
RF	Radio Frequency
THD	Total Harmonic Distortion
TSR	Tip Speed Ratio
UART	Universal Asynchronous Receiver Transmitter
UPS	Uninterruptible Power Supply
UTS	University of Technology, Sydney
VC	Vector Control
VOC	Voltage-Oriented Control

VSCF	Variable Speed Constant Frequency
VSI	Voltage Source Inverter
WFSG	Wound Field Synchronization Generator

LIST OF FIGURES

Fig. 1.1 Typical configurations of DG systems. (a) wind turbine system, and (b) PV system. 2
Fig. 1.2 Control methods of power converters 4
Fig. 1.3 Block diagram of VOC 5
Fig. 1.4 Block diagram of DPC 6
Fig. 1.5 Block diagram of SVM-DPC 7
Fig. 1.6 Block diagram of fuzzy logic control 8
Fig. 1.7 Block diagram of sliding mode control 9
Fig. 1.8 Block diagram of deadbeat based predictive control 10
Fig. 1.9 Block diagram of model predictive control 11
Fig. 1.10 Block diagram of vector-sequence-based predictive control 12
Fig. 1.11 Block diagram of the centralized control 14
Fig. 1.12 Block diagram of the current chain control (3C) 15
Fig. 1.13 Block diagram of MS control 16
Fig. 1.14 Block diagram of ALS control, (a) average current sharing, (b) average power sharing 18
Fig. 1.15 Block diagram of the conventional droop control 20
Fig. 1.16 Microgrid system 22
Fig. 1.17. Smart city 23
Fig. 1.18. Existing microgrid installations around the world 24
Fig. 2.1 Wind power generation system 36
Fig. 2.2 Cost share of a variable speed wind system 37
Fig. 2.3 Turbine output power characteristics for different wind speeds. 38
Fig. 2.4 CSCF system with squirrel-cage induction generator 39
Fig. 2.5 Wound field synchronous generator system 40
Fig. 2.6 Permanent magnet synchronous generator system 41
Fig. 2.7 Doubly fed wound induction generator system 42
Fig. 2.8 Prototype of a 30 kW CBDFIG at UTS 42
Fig. 2.9 Squirrel cage induction generator system 43
Fig. 2.10 MPPT strategies: (a) Wind speed measurement, (b) Power versus rotor speed characteristic. 45
Fig. 2.11 Torque, rotor flux, active power, and reactive power derivatives against rotor flux position at sub-synchronism. (a) torque and flux derivatives, (b) active and reactive power derivatives 52
Fig. 2.12 Possible voltage vectors generated by the inverter and sector division 52
Fig. 2.13 Waveforms for three vectors based predictive direct control 53
Fig. 2.14 Control diagram of DFIG 55
Fig. 2.15 One step delay in digital implementation 58
Fig. 2.16 Responses of virtual torque and rotor flux when system starts to operate in Mode 1. (a) CDVTC, (b) PDVTC. 60

Fig. 2.17 Responses of stator induced voltage and rotor currents when system starts to operate in Mode 1. (a) CDVTC, (b) PDVTC. 61
Fig. 2.18 Stator voltage and rotor current spectrum analysis. (a) CDVTC (stator voltage THD = 6.22%, rotor current THD = 2.54%), (b) PDVTC (stator voltage THD = 2.06%, rotor current THD = 0.69%). 61
Fig. 2.19 Responses of virtual torque, rotor flux, rotor currents and stator currents at grid connection instant. (a) CDVTC, (b) PDVTC. 62
Fig. 2.20 Responses of transition from Mode 1 to Mode 2 and power regulation in Mode 2. 63
Fig. 2.21 Laboratory setup. (a) DFIG and its control centre, (b) part of the control panel of ControlDesk from dSPACE. 64
Fig. 2.22 Experimental results of stator induced voltage and rotor currents when system starts to operate in Mode 1. (a) CDVTC, (b) PDVTC, (c) PDVTC at 800 rpm............ 66
Fig. 2.23 Experimental results of one-step delay compensation using model based prediction. (a) CDVTC with and without compensation, left: without compensation, right: with compensation, (b) PDVTC with and without compensation, left: without compensation, right: with compensation. 67
Fig. 2.24 Experimental results of grid connection. (a) CDVTC, (b) PDVTC. 68
Fig. 2.25 Experimental results of power regulation. (a) constant reactive power, (b) constant active power. 69
Fig. 2.26 Experimental performances with and without rotor position sensor. (a) with rotor position sensor, (b) without rotor position sensor. 70
Fig. 2.27 Sensorless scheme validation. (a) active power error, (b) estimated sector, (c) reactive power derivative for the first active vector, (d) reactive power derivative for the second active vector. 71
Fig. 3.1 PV output power measured in two different days. 79
Fig. 3.2 Centralized PV configuration 80
Fig. 3.3(a) PV panels in strings with individual inverters, (b) PV panels in a multi-string configuration. 81
Fig. 3.4 AC-Module power electronics configuration 82
Fig. 3.5 Single-phase single-stage PV power electronics 83
Fig. 3.6 Single-phase multiple-stage PV power electronics 84
Fig. 3.7 Three-phase PV topology with line-frequency transformer 84
Fig. 3.8 Example of the control scheme for PV systems 85
Fig. 3.9 Equivalent circuit of a PV cell 86
Fig. 3.10 Current versus voltage characteristic of a PV cell. [3.5] 87
Fig. 3.11 Inverter possible output voltage vectors 92
Fig. 3.12 One-phase model of inverter-based PV system 92
Fig. 3.13 Basic principle of MPC 93
Fig. 3.14 Block diagram of voltage control 94
Fig. 3.15 Block diagram of MPC-based power regulation 98
Fig. 3.16 Simulation results of PCC voltage and load current. 101
Fig. 3.17 Simulation results of grid synchronization and connection 101

Fig. 3.18 Simulation results of flexible power regulation. (a) SDPC, (b) proposed MPC strategy. 102

Fig. 3.19 Laboratory test bench. 103

Fig. 3.20 Experimental results of islanded mode. 104

Fig. 3.21 Experimental results of grid synchronization. 104

Fig. 3.22 Experimental results of flexible power regulation. (a) active power steps of SDPC, (b) reactive power steps of SDPC, (c) active power steps of proposed MPC strategy, (d) reactive power steps of proposed MPC strategy. 105

Fig. 4.1 AC/DC converter structure 114

Fig. 4.2 Possible voltage vectors. 114

Fig. 4.3 Control block of SDPC 116

Fig. 4.4 Basic principle of MPC 117

Fig. 4.5 Schematic illustration of MOMPC concept 118

Fig. 4.6 Switching paths of vectors: the green dashed lines standing for no switching, the black solid lines one-state change, the red dashed lines two-state change, the red solid lines three-state change. 120

Fig. 4.7 Active power trajectories and switching position with N-step prediction. 121

Fig. 4.8 Simulated steady-state performance. (a) SDPC.I, and (b) SDPC.II. 124

Fig. 4.9 Simulated steady-state performance. (a) MOMPC.I, and (b) MOMPC.II. 125

Fig. 4.10 Simulated steady state performance. (a) MOMPC.III, λ_2=70, and (b) MOMPC.IV, λ_2=70, λ_3=0.12. 126

Fig. 4.11 Laboratory test bench: (1) Semikron intelligent power module based AC/DC converter, (2) control unit, (3) inductors, (4) DC resistive load, (5) three-phase auto-transformer, (6) three-phase isolated transformer, (7) Tektronix current probe, and (8) voltage probe. 127

Fig. 4.12 Experimental results. Left: CH1-grid phase A voltage, CH3 and CH4-converter input currents; Right: CH2-DC-link voltage, CH3-active power, CH4-reactive power. (a) SDPC.I, THD = 16.68%, f_{sw} = 1562 Hz, (b) SDPC.II, THD = 11.04%, f_{sw} = 5017 Hz, (c) MOMPC.I, THD = 11.72%, f_{sw} = 2439 Hz, (d) MOMPC.II, THD = 7.16%, f_{sw} = 4482 Hz. 128

Fig. 4.13 Experimental results of frequency reduction scheme and system stability improvement. Left: CH1-grid phase A voltage, CH3 and CH4-converter input currents; Right: CH1-PWM signals of upper leg of phase A, CH3-phase A current, (a) MOMPC.III, λ_2=70, THD = 14.38%, f_{sw} = 1953 Hz, (b) MOMPC.IV, λ_2=70, λ_3=0.12, THD = 7.75%, f_{sw} = 2638 Hz. 129

Fig. 4.14 Experimental results of computing time reduction algorithm MOMPC.V, CH1: grid phase A voltage, CH3 and CH4: converter input currents; CH2: DC-link voltage, CH3: and active, CH4: reactive power,λ_2=70, λ_3=0.12, THD = 7.89%, f_{sw} = 2623 Hz. 130

Fig. 4.15 Line current spectrum, 60 mA/div, 1 kHz/div, Sa=20 kSa, (a) SDPC.I, (b) SDPC.II, (c) MOMPC.I, (d) MOMPC.II, (e) MOMPC.III, (f) MOMPC.IV. 131

Fig. 4.16 Experimental results of dynamic response of SDPC.II, (a) active and reactive power, (b) three-phase input currents. 132

Fig. 4.17 Experimental results of dynamic response of MOMPC.V, (a) active and reactive power, (b) three-phase input currents. 133
Fig. 5.1 Smart grid topology 139
Fig. 5.2 Schematic diagram of a simplified microgrid system................................. 141
Fig. 5.3 Microgrid configuration in energy centre of CSIRO 143
Fig. 5.4 Smart microgrid, (a) laboratory setup, (b) schematic topology.................... 144
Fig. 5.5 Equivalent circuit of parallel-inverters-based microgrid 147
Fig. 5.6 Droop characteristics, (a) P - ω droop characteristics, (b) Q - E droop characteristics. 148
Fig. 5.7 Control block of voltage and current feedback control................................ 149
Fig. 5.8 Control diagram of the whole microgrid control based on voltage droop method.. 150
Fig. 5.9 Power flows within microgrid. 153
Fig. 5.10 Per phase current within the microgrid. 153
Fig. 5.11 Response of voltage and AC common bus and current through STS 154
Fig. 5.12 Synchronization of micro- and utility-grids. 154
Fig. 5.13 Equivalent circuit of a DG unit connected to a common AC bus............... 156
Fig. 5.14 Possible voltage vectors generated by the inverter 156
Fig. 5.15 P – δ characteristic 159
Fig. 5.16 Equivalent circuit of small signal model of the P – δ droop controller 159
Fig. 5.17 Equivalent circuit of small signal model of the Q – $|\psi_V|$ droop controller... 160
Fig. 5.18 Block diagram of the proposed flux droop control strategy of micrigrods .. 163
Fig. 5.19 Microgrid structure under study... 164
Fig. 5.20 Dynamic performance of power sharing 166
Fig. 5.21 Voltage across capacitor C_1 166
Fig. 5.22 Microgrid under study.. 168
Fig. 5.23 Total PV output power measured in two different days............................ 169
Fig. 5.24 PV characteristics. (a) dynamic response to the loss of external grid voltage, (b) dynamic response to the voltage variation... 170
Fig. 5.25 A simplified diagram of a microturbine generation system in a microgrid. 171
Fig. 5.26 The renewable energy integration facility (REIF) 173
Fig. 5.27 Power flow in grid-connected mode 174
Fig. 5.28 Voltage and frequency response in grid-connected mode.......................... 174
Fig. 5.29 Active and reactive power sharing in islanded mode................................. 175
Fig. 5.30 Voltage and frequency response islanded mode....................................... 175
Fig. 5.31 Microturbine output current... 176
Fig. 5.32 Simplified diagram of test system under faults 177
Fig. 5.33 Response of current and voltage during a fault in grid-connected mode (a) Currents, (b) PCC Voltage. 178
Fig. 5.34 Voltage and current response to grid fault in islanded mode (a) current at CB2, (c) PCC Voltage... 179
Fig. 5.35 Smart microgrid topology... 181
Fig. 5.36 PV system, (a) PV array, (b) Equivalent circuit of the PV cell 181

Fig. 5.37 Total PV output power measured in two different days. 183
Fig. 5.38 DFIG based wind power system in the University of Technology, Sydney, (a) experimental platform, (b) equivalent circuit of a DFIG in the synchronous reference frame 184
Fig. 5.39 Wind speed. 184
Fig. 5.40 Power output of the wind power system. 185
Fig. 5.41 300W PEMFC stack. 186
Fig. 5.42 Current-voltage and power characteristics of a 300W PEMFC. 186
Fig. 5.43 Battery Bank model, (a) Pb-acid type battery, (b) Equivalent circuit of battery bank. 187
Fig. 5.44 Load profile of an office during a day [5.44]. 188
Fig. 5.45 Control objectives of microgrids. 191
Fig. 5.46 Powers generated and consumed during a day. 196
Fig. 5.47 The gap between the power generated and consumed during a day. 196
Fig. 5.48 SOC of the battery bank. 197
Fig. 5.49 The power generated by the fuel cell and the power exchanged between the micro and utility grid. 198
Fig. 5.50 Performance of the reactive power compensation under grid voltage sag of 0.1 pu. 198

LIST OF TABLES

TABLE 2.1 Advantages and Disadvantages Compared with Generators..................... 43
TABLE 2.2 Vector Selection Strategy of Predictive Control 53
TABLE 2.3 Direction of Change of Sector... 57
TABLE 2.4 Parameters of wind power system 59
TABLE 2.5 Quantitative comparison of steady state at 1200 rpm before grid connection 68
TABLE 3.1 System Parameters of the PV system 100
TABLE 3.2 Quantitative Comparison of Steady-state Performance of PV system ... 106
TABLE 4.1 Switching Table of Conventional SDPC 116
TABLE 4.2 Parameters of the MOMPC System in Simulation 124
TABLE 4.3 Parameters of the MOMPC System in Experiment 127
TABLE 5.1 System Parameters of Microgrid Using Voltage Droop Method 152
TABLE 5.2 Vector Selection Strategy of DFC 162
TABLE 5.3 System Parameters of Microgrid Using Flux Droop Method 164
TABLE 5.4 Voltage Deviations for $\triangle P = 0.1$ MW and $\triangle Q = 0.1$ MVar................... 167

ABSTRACT

This thesis presents various advanced control strategies in smart microgrid applications.

In recent years, due to the rapid depletion of fossil fuels, increasing demand of electricity, and more strict compulsory government policies on reduction of greenhouse gas emissions, renewable energy technologies are attracting more and more attentions and various types of distributed generation (DG) sources, such as wind turbine generators and solar photovoltaic (PV) panels, are being connected to low-voltage distribution networks. Because of the intermittent nature of the renewable energy sources, it would be a good idea to connect these DG units together with energy storage units and loads to form a local micro power system, known as microgrid. This PhD thesis project aims to develop new and competitive control methods for microgrid applications.

Based on a review of the state of the art of the wind power techniques, a new predictive direct control strategy of doubly fed induction generator is proposed. This method can achieve fast and smooth grid synchronization, and after grid connection, the active and reactive power can be regulated flexibly, which enables the wind power systems contributing to the grid voltage support and power quality improvement. The proposed strategy is simple and reliable, and presents excellent steady-state and dynamic performance.

A new control approach using the model predictive scheme is developed for a PV system in microgrid applications. In the islanded operation, the inverter output voltage is controlled stably for the local loads. A simple synchronization scheme is introduced to achieve seamless transfer, and after being connected to the utility grid, the PV system can inject both active and reactive power into the grid flexibly within its capacity.

As the capacity of DGs getting larger, the power conversion efficiency becomes more important. In order to reduce the switching loss, a multi-objective model-predictive control strategy is proposed for the control of high power converters. By revising the cost function properly, the switching frequency can be reduced considerably without deteriorating the system performance. The control strategy is simplified using a graphical algorithm to reduce the computational burden, which is very useful in practical digital implementation where high sampling frequency is required. The proposed method is very flexible and can be employed in both AC/DC and DC/AC energy conversions in microgrids.

For a microgrid consisting of several DG units, various system level control methods are studied. A novel flux droop control approach is developed for parallel-connected DGs by drooping the inverter flux instead of drooping the inverter output voltage. The proposed method can achieve autonomous active and reactive power sharing with much lower frequency deviation and better transient performance than the conventional voltage droop method. Besides, it includes a direct flux control (DFC) algorithm, which avoids the use of proportional-integral (PI) controllers and PWM modulators.

For a microgrid system consisting of a 20 kW PV array and a 30 kW gas microturbine, a coordinated control scheme is developed for both islanded and grid-connected operations. The experimental results from a renewable energy integration facility (REIF) laboratory confirmed the feasibility of the control strategy. The response of this microgrid under the condition of grid faults is investigated and the relevant protection mechanism is proposed.

Given the intermittent nature of the renewable energy sources, and the fluctuated load profile, an appropriate solution is to use energy storage systems (ESS) to absorb the surplus energy in the periods when the power production is higher than the consumption and deliver it back in the opposite situation. In order to optimize the power flow, a model predictive control (MPC) strategy for microgrids is proposed. This method can flexibly include different constraints in the cost function, so as to smooth the gap between the power generation and consumption, and provide voltage support by compensating reactive power during grid faults.