

DISTRIBUTED COOPERATIVE CONTROL FOR AUTONOMOUS MICROGRIDS

by Mahmuda Begum

Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy

under the supervision of A/Prof. Li Li (Principal Supervisor)
and Prof. Jianguo Zhu (Co-Supervisor)

University of Technology Sydney
Faculty of Engineering and IT

August 2021

Certificate of Original Authorship

I, *Mahmuda Begum* declare that this thesis, is submitted in fulfilment of the requirements for the award of *Doctor of Philosophy*, in the *Faculty of Engineering and IT* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Production Note:

Signature removed prior to publication.

Signature of Student:

Date: 15/08/2021

Keywords

Active Power Sharing, Autonomous Microgrid, Consensus Control, Cost Function, Distributed Control, Eigenvalue Analysis, Frequency Restoration, Fuzzy-Control, Hierarchical Control, Microgrid Control, Particle Swarm Optimisation, Reactive Power Sharing, Secondary Control, Small-Signal Model, Stability Analysis, Voltage Restoration, SoC Balancing, Power Sharing, Secondary Control.

Abstract

Distributed control for microgrids (MGs) is the current development due to its numerous benefits compared to traditional central control systems, such as system reliability, reducing its sensitivity to failures, and eliminating the requirement for central computing and communication structure. Although many research works have been accomplished on the design of MG control, distributed secondary control (DSC) needs more attention. There is still a lack of appropriate DSC design for islanded AC MGs which can restore the frequency and voltage along with precise power-sharing with detailed stability analysis. Another concern is the simplicity of DSC system design. Moreover, very little research addressed the DSC for distributed energy storage units (DESUs) for MGs considering state of charge (SoC) balancing along with frequency and voltage restoration with precise power-sharing.

This thesis proposes MG control that addresses frequency and voltage restoration with precise power-sharing, and optimises the control parameters by utilising intelligent controller and SoC balancing for DESUs in a single control strategy with detailed stability analysis. The significant contributions of this thesis are to: (1) design a DSC for MGs which covers all the control aspects in a single control strategy; (2) model the MGs for the proposed DSC in a systematic way and perform a detailed stability analysis; (3) verify the presented control with several case studies; (4) consider SoC balancing along with other control aspects in designing DSC for DESUs; (5) propose intelligent control methods to find the optimal control parameters for stability enhancement of MGs and verify their effectiveness with different case studies.

Firstly, a novel DSC with an incremental cost-based droop controller is proposed. The parameters of the proposed DSC are designed utilising the particle swarm optimization (PSO) method. A linearised small-signal state-space model considering DSC with stability studies of an islanded AC MG is also presented. The dynamic response of DSC initiates additional oscillatory modes, which affects the damping performance of the system. To enhance the system stability with DSC, a fuzzy logic based intelligent controller is also offered for tuning the secondary control parameters for the best functioning of the offered DSC. This research also introduces a new DSC system for DESUs in an islanded AC MG. By applying the suggested methodology, all the DESUs achieve exactly the same SoC with the power proportional to their capacity at the steady state, and hence the uneven degradation of DESUs is avoided.

Acknowledgement

Firstly, thanks to my Almighty lord Allah, for giving me his blessing to finish this thesis. I would like to express my sincere gratitude to my principal supervisor, A/Prof. Li Li, for giving me the opportunity to do the research. It would not have been possible to finish this thesis without his inspiration, direction and constant support throughout my entire research period. I am tremendously thankful to him for doing my PhD under his supervision and sharing his opinions and advice during my PhD study. His patience, understanding, experience and vision continuously encouraged me to follow the exact track. I would also like to thank my research co-supervisor, Prof. Jianguo Zhu, for his supervision, understanding, patience as well as support during my study.

I would also like to give my acknowledgement to the University of Technology Sydney (UTS) for the financial support by providing me the UTS FEIT Strategic Scholarship (PhD Scholarship for research study). I would also like to thank all the staff from IT, UTS, who have always been helpful in providing in installing or updating software and any other associated technical issues. I am thankful to all my colleagues at UTS for their support and discussion at times during my research.

Finally, I would like to thank all my family members, especially my parents, for their love, endless motivation and support in every aspect. I am also grateful to my husband, Md Eusuf Iqbal for his care, understanding and constant support throughout my PhD tenure. Last but not least, thanks to my little daughter, Ishya Iqbal who has brought limitless joy and happiness to me.

Table of Contents

- Certificate of Original Authorship ii**
- Keywords iii
- Abstract iv
- Acknowledgement..... v
- Table of Contents vi
- List of Figures ix
- List of Tables xiv
- List of Abbreviations..... xv
- List of Publications xvii
- Chapter 1: Introduction 1**
- 1.1 Background..... 1
- 1.2 Research Motivation and Significance 7
- 1.3 Research Gaps..... 9
- 1.4 Research Aims and Objectives 10
- 1.5 Research Novelty and Contribution..... 11
- 1.6 Methodology 12
- 1.7 Thesis Structure 14
- Chapter 2: Literature Review 17**
- 2.1 Introduction..... 17
- 2.2 Hierarchical Control Structure..... 17
- 2.3 Decentralised/Distributed Control for MGs..... 19
- 2.4 Overview of Current Distributed Control Techniques for MGs..... 19
- 2.5 Distributed Control of Energy Storage Units..... 32
- 2.6 Summary..... 42

Chapter 3: Distributed Secondary Control for Frequency Restoration and Active Power Sharing	43
3.1 Introduction.....	43
3.2 Distributed Secondary Control.....	44
3.3 Proposed Control for Frequency Restoration and Optimal Active Power Sharing.....	45
3.4 Small-Signal State Space Model for Stability Analysis.....	46
3.5 Stability Analysis	48
3.6 PSO-based Optimal Active Power Sharing.....	51
3.7 Simulation and Results.....	53
3.8 Summary	56
Chapter 4: Distributed Secondary Control for Voltage Restoration and Reactive Power Sharing	57
4.1 Introduction.....	57
4.2 Proposed Control for Voltage Restoration and Reactive Power Sharing.....	58
4.3 Small-Signal State Space Model of Autonomous AC MG	59
4.4 Simulation and Result	61
4.5 Comparison of the proposed control with the one in [17]:.....	67
4.6 Summary.....	73
Chapter 5: Fuzzy-Based Distributed Cooperative Secondary Control with Stability Analysis for MGs.....	75
5.1 Introduction.....	75
5.2 The Proposed Distributed Secondary Controller.....	78
5.3 Small-Signal Modelling	80
5.4 Stability Analysis	83
5.5 Time-Domain Simulation Results.....	89
5.6 Summary	97
Chapter 6: Distributed Secondary Control of Energy Storage Units with SoC Balancing in AC MG	98

6.1	Introduction.....	98
6.2	Preliminaries	101
6.3	DSC for SoC Balancing and Power Sharing of DESUs	103
6.4	Time-Domain Simulations.....	111
6.5	Summary.....	123
Chapter 7: Conclusions and Future Works.....		125
7.1	Conclusions.....	125
7.2	Summary of Contributions.....	125
7.3	Recommendation for Future Works.....	127
Bibliography		129
Appendices.....		135
Appendix A.....		135

List of Figures

Fig. 1.1 Renewable generation capacity by energy source [2]	1
Fig. 1.2 Renewable power capacity growth [2]	2
Fig. 1.3 Renewable share of annual power capacity expansion [2].....	2
Fig. 1.4 A simple form of AC MG structure.....	4
Fig. 1.5 Flow chart of research methodology	14
Fig. 2.1 Hierarchical control arrangement of an MG.....	18
Fig. 2.2 (a) Centralised, (b) Decentralised and (c) Distributed control structure of an MG	19
Fig. 2.3 Block diagram of an individual DG	21
Fig. 2.4. The relationship between f - P and v - Q droop controllers.....	21
Fig. 2.5 Block diagram of an individual DG with virtual impedance.....	22
Fig. 2.6 MPC based droop control algorithm proposed in [86].....	25
Fig. 2.7 Schematic of general distributed architecture for MAS control.....	26
Fig. 2.8 Block diagram of the proposed distributed control for reactive power sharing [91].....	27
Fig. 2.9 Centralized event-triggered time generator [106]	29
Fig. 2.10 Distributed event-triggered time generator [106].....	29
Fig. 2.11 Tertiary control level structure [89].....	30
Fig. 2.12 A simple MG structure with battery energy storage units (BESUs)	32
Fig. 2.13 Classification of ESSs	33
Fig. 2.14 Block diagram representation of SoC balancing [124]	36
Fig. 2.15 The diagram of distributed finite-time control scheme of DESUs [79]	40
Fig. 3.1 Simplified structure of an inverter-based DG (primary and DSFC)	45
Fig. 3.2 MG test model for simulation and the communication diagraph	50

Fig. 3.3 Eigenvalues of system matrix considering DSFC for stable operation	50
Fig. 3.4 Traces of low frequency modes (a) & (b) Modes 1-6.....	52
Fig. 3.5 Convergence curve of the objective function	52
Fig. 3.6 Dominant eigenvalues (a) before and (b) after optimisation in S plane	53
Fig. 3.7 Output of DGs under only primary control (Droop control) (a) Frequencies (b) Active powers.....	54
Fig. 3.8 Output of DGs with DSFC before PSO optimization (a) Frequencies (b) Optimal values for active powers for 10s (c) Optimal values for active powers for 2.5s	55
Fig. 3.9 Output of DGs with DSFC after PSO optimization (a) Frequencies (b) Optimal values for active powers for 10s (c) Optimal values for active powers for 2.5s	56
Fig. 4.1 Block diagram for a DG unit with droop controller	58
Fig. 4.2 Simulation diagram of the MG test model and the communication diagram..	61
Fig. 4.3 Steps of the stability analysis process in MATLAB.....	62
Fig. 4.4 Eigenvalues of system matrix considering DSVC for stable operation.....	63
Fig. 4.5 Dominant modes for both primary and considering DSVC for stable operation	63
Fig. 4.6 Traces of low-frequency modes.....	64
Fig. 4.7 Outputs of three DGs for Case 1, voltage outputs (a) without and (b) with DSVC and reactive power sharing (c) without and (d) with DSVC.....	66
Fig. 4.8 Outputs of three DGs for Case 2, (a) voltage outputs (b) reactive power sharing with DSVC	67
Fig. 4.9 Simulation diagram of the MG test model and the communication diagram...	68
Fig. 4.10 Outputs of 4 DGs for Case 1, (a) frequency (b) voltage and (c) reactive power	70

Fig. 4.11 Outputs of 4 DGs for Case 2, (a) frequency (b) voltage and (c) active power and (d) reactive power	71
Fig. 4.12 Outputs of 4 DGs for Case 3, (a) frequency (b) voltages (c) active power and (d) reactive power	73
Fig. 5.1. Simplified block diagram for the distributed generation (DG) unit with primary and secondary controllers	79
Fig. 5.2. Single line diagram of the MG test model with the communication link.....	82
Fig. 5.3. Eigenvalues of system matrix with distributed secondary control (DSC) for stable operation	84
Fig. 5.4. Participation factors of modes 6–9 (a) Mode 6; (b) Modes 7 and 8 and (c) Mode 9	85
Fig. 5.5. Traces of dominant modes 6–9. (a) Traces of dominant mode 9 when K_P varies from 0.0001 to 0.1 and K_I varies from 5 to 40; (b) traces of dominant modes 7 and 8 when X_{viri} varies from 0.01 to 0.5 Ω and D_{Qi} varies from 10 to 40 and (c) traces of dominant mode 6 when D_{fi} varies from 100 to 400 and D_{Pi} varies from 100 to 400	86
Fig 5.6. Input–output relations of the proposed fuzzy logic tuner.....	88
Fig 5.7. Membership functions for (a) input1, frequency stability region; (b) input2, voltage stability region; (c) output1, active power gain, D_{Pi} and (d) output2, reactive power gain, D_{Qi}	88
Fig. 5.8. Output surface for stability. (a) D_{fi} and (b) X_{vir}	89
Fig. 5.9. Comparison of dominant modes with before and after tuning of DSC for stable operation	89
Fig. 5.10. Outputs of 4 DGs: (a) frequency and (b) voltage restoration for group 1 ..	90
Fig 5.11. Outputs of 4 DGs: (a) frequency restoration; (b) voltage restoration and (c) point of common coupling (PCC) bus voltage restoration as in case 1	91
Fig. 5.12. Output power of 4 DGs for random load change: (a) active power and (b) reactive power as in case 2.....	92

Fig. 5.13 Output results of 4 DGs for voltage restoration with time delays (a) 0.1 s; (b) 0.5 s; (c) 1 s and (d) 2 s as in case 3.....	93
Fig. 5.14. Output results of 4 DGs for (a) frequency and (b) voltage restoration with communication link failure when $t > 2.6$ s in case 4.....	94
Fig. 5.15. Various communication topologies for the test MG system: (a) mesh (b) ring and (c) line for case 5	94
Fig. 5.16. Output results of 4 DGs: (a) frequencies (b) voltages and (c) active power and (d) reactive power for case 6	96
Fig 5.17. Output results of 4 DGs: (a) frequencies, (b) voltages and (c) active power and (d) reactive power for case 7	96
Fig. 6.1. Simple configuration of test MG model	101
Fig. 6.2. Block diagram of inverter interfacing individual energy storage unit.....	102
Fig. 6.3 Input-Output relation of the proposed fuzzy logic tuner	109
Fig. 6.4 Block diagram of fuzzy-logic control system for active power.....	109
Fig. 6.5 Membership functions for (a) input1, error (b) input2, derivative of error (c) output1 and (d) output2.....	110
Fig. 6.6. Output of DESUs under only primary control (Droop control) (a) Frequency (b) Voltage (c) Active power and (d) SoC (e) Reactive power.....	113
Fig. 6.7 Output of DESUs after applying proposed DSC in DESUs (a) Frequency (b) Voltage (c) Active power and (d) SoC (e) Reactive power.....	115
Fig. 6.8 Output of DESUs after applying proposed DSC in DESUs with step load change (a) SoC (b) Active power and (c) Reactive power	116
Fig. 6.9 Output of DESUs after applying proposed DSC in DESUs with plug-n-play (a) Frequency (b) Voltage (c) Active power and (d) SoC and (e) Reactive power	117
Fig. 6.10 Output of DESUs after applying proposed DSC in DESUs with measurement noise (a) Frequency and (b) Voltage.....	118

Fig. 6.11 Output of DESUs after applying proposed DSC in DESUs with different communication topologies (a) Communication topology 1 (b) Communication topology 2 (c) SoC for (b) and (d) Active power for (b).....119

Fig. 6.12 Output of DESUs after applying proposed DSC in DESUs with different capacities of storage units (a) SoC (b) Active power and (c) Reactive power120

Fig. 6.13. Output of DESUs after applying different values of $\alpha\omega$ in DSC (a) $\alpha\omega = 1.3$ (b) $\alpha\omega = 5.2$ (c) $\alpha\omega = 10.5$121

Fig. 6.14 Output of DESUs with real-data from PV (a) SoC (b) PV power (c) Active power and (d) Reactive power and (e) V-I and V-P graph based on MPPT for PV123

List of Tables

Table 2.1 Comparison of Different Distributed Control Schemes at the Primary and Secondary Control Level.....	31
Table 3.1 Inverters Parameters Used in the Test MG	49
Table 3.2 Parameters Used for PSO.....	52
Table 3.3 Secondary Controller Parameters.....	53
Table 4.1 Parameters for the Inverters Used in the MG Test Model System	62
Table 4.2 Line and Load Data Used in the Test System	62
Table 4.3 Secondary Controller Parameters.....	63
Table 4.4 Secondary Controller Most Dominant Modes with and without Secondary Control	63
Table 4.5 Parameters for the Inverters Used in the MG Test Model System	69
Table 4.6 Load and Line Data Used in the MG Test Model System.....	69
Table 4.7 Parameters of the Power Controller Used in the MG Test Model System	70
Table 4.8 Comparison of the Performance of Two Methods.....	73
Table 5.1 System Dynamics and Stability Analysis Result.	87
Table 5.2 Distributed Secondary Control (DSC) Parameters with and without the Fuzzy Logic Controller.....	89
Table 5.3 Convergence Time for Various Communication Topologies	94
Table 6.1 Fuzzy Rule Set for Inputs and Outputs	110
Table 6.2 Specifications of Test MG	111
Table 6.3 Secondary Controller Parameters.....	112

List of Abbreviations

AC-Alternating Current
ADM-Active Demand Management
DC-Direct Current
DER-Distributed Energy Resources
DG-Distributed Generation
DQ-Direct Quadrature
DSC-Distributed Secondary Controller
DSFC-Distributed Secondary Frequency Controller
DSM-Demand Side Management
DSVC-Distributed Secondary Voltage Controller
ED-Economic Dispatch
EES-Electrical Energy Storage
GPS-Global Positioning Control
ILC-Interlinking Converter
LC-Inductor-Capacitor
LCL-Inductor-Capacitor-Inductor
(P - f) Droop-(Active Power-Frequency) Droop
PI-Proportional-Integral
PV- Photovoltaic
PCC-Point of Common Coupling
PSO-Particle Swarm Optimisation
PWM-Pulse Width Modulation
RL-Resistor-Inductor
RC-Resistor-Capacitor
RLC-Resistor-Inductor-Capacitor
MAS-Multi-Agent System
MATLAB-Matrix Laboratory

MG-Microgrid

MCC-Microgrid Central Controller

MPC-Model Predictive Control

SoC- State of Charge

($Q-v$) Droop- (Reactive Power-Voltage) Droop

VSI-Voltage Source Inverter

List of Publications

Journal Papers:

1. **Begum, M.**, Li, L. & Zhu, J. 2021, 'Fuzzy-Based Distributed Cooperative Secondary Control with Stability Analysis for Microgrids', *Electronics*, vol 10, issue 4.

Conference Papers:

2. **Begum, M.**, Li, L. & Zhu, J. 2020, 'Distributed Secondary Control of Energy Storage Units for SoC balancing in AC Microgrid', *IEEE Innovative Smart Grid Technologies (ISGT-North America)*, Washington DC, USA.
3. **Begum, M.**, Li, L. & Zhu, J. 2019, 'PSO-based Secondary Frequency Control and Active Power Sharing', *IEEE Innovative Smart Grid Technologies (ISGT-Asia)*, Chengdu, China.
4. **Begum, M.**, Li, L. & Zhu, J. 2018, 'State-Space Modelling and Stability Analysis for Microgrids with Distributed Secondary Control', *The 27th IEEE International Symposium on Industrial Electronics (ISIE)*, Cairns, Australia.
5. **Begum, M.**, Li, L. & Zhu, J. 2017, 'Distributed Control Techniques for Autonomous AC Microgrids-A brief Review', *The 5th International Conference on IEEE Region 10 Humanitarian Technology Conference (R10HTC)*, Dhaka, Bangladesh.
6. **Begum, M.**, Li, L. & Zhu, J. 2017, 'Distributed Secondary Voltage Regulation for Autonomous Microgrid', *20th IEEE International Conference on Electrical Machines and Systems (ICEMS)*, Sydney, Australia.
7. Abuhilaleh, M., Li, L. & Zhu, J., **Begum, M.** 2017, 'Power Management and Control Strategy for Hybrid AC/DC Microgrids in Autonomous Operation Mode', *20th IEEE International Conference on Electrical Machines and Systems (ICEMS)*, Sydney, Australia.