

Contents

List of Abbreviations	xvi
List of Symbols	xix
1 Introduction	1
1.1 Project Hypotheses	4
1.2 Project Objectives	5
1.3 Contributions	6
1.4 Thesis Structure	7
2 State of the Art	8
2.1 Introduction	8
2.2 Control of <i>ac</i> -Microgrids	9
2.2.1 Primary Control of <i>ac</i> -Microgrids	9
2.2.2 Secondary Control of <i>ac</i> -Microgrids	12
2.3 Control of <i>dc</i> -Microgrids	14
2.3.1 Primary Control of <i>dc</i> -Microgrids	14
2.3.2 Secondary Control of <i>dc</i> -Microgrids	16
2.4 Control of Hybrid <i>ac/dc</i> -Microgrids	17
2.5 Cooperative Control of Multi-Agent Systems	19
2.5.1 Adjacency Matrix	19
2.5.2 Cooperative Regulator	20
2.5.3 Cooperative Tracking	21
2.6 Distributed Secondary Control in the Literature	21
2.6.1 DSC for <i>ac</i> -Microgrids	22
2.6.2 DSC for <i>dc</i> -Microgrids	25
2.6.3 DSC for Hybrid <i>ac/dc</i> -Microgrids	27
2.7 Summary	28
3 Control Strategy Proposed for Power-Sharing	30
3.1 Introduction	30
3.2 Control Strategy for Power-Sharing	30
3.3 Control Strategy Proposed for <i>ac</i> -Microgrid	31
3.3.1 Inner and Primary Control Loops	31
3.3.2 Secondary Control Loops	32
3.4 Control Strategy Proposed for <i>dc</i> -Microgrid	34

3.4.1	Inner and Primary Control Loops	34
3.4.2	Secondary Control Loop	34
3.5	Control Strategy Proposed for a Single <i>IC</i>	35
3.5.1	Inner Control Loop	35
3.5.2	Secondary Control Loop	36
3.6	Control Strategy Proposed for Multiple <i>ICs</i>	38
3.7	Summary	38
4	Control Strategy Proposed to Minimize Operating Costs	39
4.1	Introduction	39
4.2	Single Interlinking Converter Formulation	40
4.2.1	System Modelling	40
4.2.2	Optimization Problem Formulation	41
4.3	Proposed Control Scheme for a Single <i>IC</i>	44
4.3.1	Control scheme proposed for the <i>ac</i> -DGs	44
4.3.2	Control scheme proposed for the <i>dc</i> -DGs	46
4.3.3	Control scheme proposed for the <i>IC</i>	47
4.4	Multiple Interlinking Converters Formulation	48
4.4.1	System Modelling	48
4.4.2	Optimization Problem Formulation	50
4.5	Proposed Control Scheme for Multiple <i>ICs</i>	52
4.5.1	Control scheme proposed for the <i>ac</i> -DGs	52
4.5.2	Control scheme proposed for the <i>dc</i> -DGs	53
4.5.3	Control scheme proposed for the <i>ICs</i>	54
4.6	Summary	56
5	Experimental <i>ac/dc</i>-Microgrid	57
5.1	Introduction	57
5.2	<i>ac</i> -Microgrid	58
5.2.1	Topology	58
5.2.2	Communication Network	59
5.3	<i>dc</i> -Microgrid	59
5.3.1	Topology	59
5.3.2	Communication Network	60
5.4	Interlinking Converter (<i>IC</i>)	61
5.4.1	Topology and Communication Network	61
5.5	Hybrid <i>ac/dc</i> -Microgrid	61
5.5.1	Topology	62
5.5.2	Communication Network	64
5.6	Summary	65
6	Closed-loop Model of a Hybrid <i>ac/dc</i>-Microgrid with the Proposed Controllers	66
6.1	Closed-loop model for a Hybrid <i>ac/dc</i> -Microgrid	66
6.2	Control Strategy Proposed for Power-sharing	69
6.3	Control Strategy Proposed for Operation Cost Minimization	71
6.4	Small-signal Analysis of the Control Strategy for Power-sharing	73

6.4.1	Eigenvalues and Participation Factors	73
6.4.2	Sensitivity Analysis	75
6.5	Small-signal Analysis of the Control Strategy for Operation Cost Minimization	78
6.5.1	Eigenvalues and Participation Factors	78
6.5.2	Sensitivity Analysis	81
6.6	Summary	84
7	Validation of the Strategy Proposed for Power-Sharing	85
7.1	Introduction	85
7.2	Experimental Test #1: Load Steps	85
7.3	Experimental Test #2: Unit Loss	89
7.4	Experimental Test #3: Communication Loss	91
7.5	Experimental Test #4: Communication Delays	93
7.6	Simulation Test #5: Comparison With Performance of Other Strategies . . .	96
7.7	Simulation Test #6: Multiple <i>ICs</i> Operation	99
7.8	Summary	101
8	Validation of the Strategy Proposed for Operation Cost Minimization	103
8.1	Introduction	103
8.2	Simulation Test #7: Single <i>IC</i> Performance	104
8.3	Simulation Test #8: Single <i>IC</i> With Load Steps	107
8.4	Simulation Test #9: Multiple <i>ICs</i> Performance	110
8.5	Simulation Test #10: Multiple <i>ICs</i> With Load Steps	113
8.6	Simulation Test #11: Comparison	116
8.7	Summary	119
9	Conclusions and Future Work	120
9.1	Conclusions	120
9.2	Future Work	122
9.3	Publications	122
9.3.1	Papers related to this Ph.D. Project	122
9.3.2	Participation in other publications	123
	Bibliography	125
	APPENDICES	138
A	Closed-loop model for a hybrid <i>ac/dc</i>-microgrid with the Power-sharing Strategy	139
A.1	Closed-loop model for the <i>ac</i> -microgrid	139
A.1.1	Power flow in the <i>ac</i> -microgrid	140
A.1.2	Voltage reference	141
A.1.3	Frequency reference	141
A.1.4	Frequency secondary control	142
A.1.5	Voltage secondary control	144
A.2	Closed-loop model for the <i>dc</i> -microgrid	145
A.2.1	Power flow in the <i>dc</i> -microgrid	145
A.2.2	Voltage reference	145

A.2.3	Secondary control loop	146
A.3	Closed-loop model for the <i>IC</i>	147
A.3.1	Secondary control loop	147
A.4	Summary	148
A.4.1	State variables	148
A.4.2	State equations	148
B	Closed-loop Model for a Hybrid <i>ac/dc</i>-Microgrid with the Operation Cost Minimization Strategy	149
B.1	Closed-loop model for the <i>ac</i> -microgrid	149
B.1.1	Power flow in the <i>ac</i> -microgrid	150
B.1.2	Voltage reference	150
B.1.3	Frequency reference	150
B.1.4	Frequency secondary control	151
B.1.5	Voltage secondary control	151
B.2	Closed-loop model for the <i>dc</i> -microgrid	152
B.2.1	Power flow in the <i>dc</i> -microgrid	152
B.2.2	Voltage reference	152
B.2.3	Secondary control loop	152
B.3	Closed-loop model for the <i>IC</i>	153
B.3.1	Secondary control loop	153
B.4	Summary	153
B.4.1	State variables	154
B.4.2	State equations	154