# Contents


page

*Abstract* i
*Acknowledgements* iii
*Contents* v
*List of Figures* vii
*List of Tables* viii
*List of Symbols* xiii
*List of Abbreviations* xv

**Chapter 1: Introduction** 1
1.1 Motivation and Research Objectives 3
1.2 Concept of impedance shaping 5
*1.2.1 Virtual impedance shaping in the Single Stage Inverters* 5
*1.2.2 Virtual impedance shaping in the DC Microgrids* 6
1.3 Requirements for the SRC control 8
*1.3.1 Requirements for the SRC control in the Single Stage Inverters:* 9
*1.3.2 Requirements for the SRC control in the DC Microgrid system:* 9
1.4 Proposed Control methodologies 9
*1.4.1 Dual loop control integrated with the second-order ripple control loop* 10
*1.4.2 Linear control integrated with ISM control* 10
*1.4.3 Sliding mode control methodology* 11
*1.4.4 Adaptive sliding mode control methodologies* 12
*1.4.5 Integral Sliding Mode control based secondary control* 13
1.5 Preliminaries 13
*1.5.1 The concept of Sliding Mode and Integral Sliding Mode Control* 13
*1.5.2 Graph Theory* 14
1.6 Contributions 15
1.7 Organization of Thesis 16
1.8 Publications 18

**Chapter 2: Literature Review** 19
2.1 Effects of SRCs on the sources 19
*2.1.1 Fuel cell* 19
*2.1.2 Battery storage* 20
*2.1.3 Photo-voltaic sources* 20
*2.1.4 Wind Turbines* 20
*2.1.5 Effect of SRCs on converter components* 21
2.2 Second order ripple mitigation methodologies 21
*2.2.1 Passive Power Decoupling methodology* 21
*2.2.2 Active power decoupling methodologies* 21
2.3 Control based SRC mitigation methodologies 30
2.4 Single stage inverters with nanogrid applications 34
*2.4.1 Control of SSIs* 36
2.5 Control of microgrids 38
*2.5.1 Centralized control* 38
*2.5.2 Decentralized control* 38
*2.5.3 Distributed control* 39
2.6 Summary and Open Issues 42

**Chapter 3: Control of Single Stage Inverters and Second Order Ripple Regulation Using Sliding Mode Control** 45
3.1 Proposed Methodology 47
3.2 Control law for qZSI 48
3.3 Control law for eqSBI 49
3.4 Current and voltage reference and derivation of boundary conditions 49
*3.4.1 Bounds for qZSI* 50
*3.4.2 Bounds for eqSBI* 50
3.5 Stability of proposed control 51
*3.5.1 Derivation of low pass filter time constant for current reference generation* 51

3.6 Effect of low pass filter time constant on inductor impedance 52
3.7 PWM generation logic 52
3.8 Simulation Results 52
*3.8.1 SRC control for qZSI* 52
*3.8.2 SRC control of eqSBI* 55
3.9 Experimental Results 55
*3.9.1 DC voltage boost, without impedance control* 55
*3.9.2 With Impedance control* 55
*3.9.3 Ripple control explaination* 58
3.10 Conclusion 59

**Chapter 4: A Double Line Frequency Ripple Control using Integral Sliding Mode for qZSI and eqSBI** 61
4.1 Principle of Integral sliding mode control 62
4.2 Modelling of qZSI and eqSBI 63
*4.2.1 Modelling of Switched boost inverters (SBIs)* 64
*4.2.2 Modelling of qZSI* 65
*4.2.3 Modelling of eqSBI* 66
4.3 Dual loop control 67
*4.3.1 Impedance analysis* 67
*4.3.2 Estimation of second order component in the $d_{st}$* 67
4.4 Proposed ISM based dual loop control methodology 68
*4.4.1 Without unmatched uncertainty $\psi_u$=0* 68
*4.4.2 With unmatched uncertainty $\psi_u$* 69
*4.4.3 Selection of matrix M* 69
*4.4.4 Control law $d_n$ and reachability condition* 69
*4.4.5 Value and limitations of $\Gamma$* 70
4.5 Simulation Results 70
*4.5.1 Dynamic performance* 71
*4.5.2 Uncertainty mitigation* 71
*4.5.3 Virtual impedance analysis* 71
4.6 Experimental Results 72
*4.6.1 SRC control for qZSIs* 73
*4.6.2 SRC control for eqSBI* 73
4.7 Conclusion 75

**Chapter 5: Dynamic Virtual Impedance based Second Order Ripple Regulation in DC Microgrids** 83
5.1 Output impedance shaping 85
5.2 Proposed second order impedance control 86
*5.2.1 Reduction of magnitude of ripple content $i_{ref\triangle-n}$* 87
*5.2.2 Reduction of maximum ripple current to DC ratio- $i_{rm}/i_{dc}$* 87
5.3 Controller parameter design 87
5.4 Stability analysis with proposed control 91
5.5 Simulation 96
5.6 Experimental Validation 97
*5.6.1 Equal DC load sharing* 98
*5.6.2 SRC mitigation with AC and DC load variation* 100
5.7 Conclusion 104

**Chapter 6: Adaptive Voltage Tuning Based Load Sharing in DC Microgrid** 107
6.1 Proposed Primary Control 110
*6.1.1 Modelling of individual converter and DC Microgrid in error co-ordinates* 110
*6.1.2 Switching function* 111
*6.1.3 Control Law* 111
*6.1.4 Defining limits on value of $\lambda_j$* 112
6.2 Integral sliding mode secondary control 113
*6.2.1 Small signal Modeling* 114
*6.2.2 Estimation of duty cycle* 114
6.3 Decomposition of uncertainty $\phi(x,t)$ 115
*6.3.1 With Only matched uncertainty* 115
*6.3.2 With matched and unmatched uncertainty* 116
*6.3.3 Integral sliding surface* 117
*6.3.4 Global stability of proposed controller* 119
6.4 Simulation Results 121
*6.4.1 Case 1: With and without control* 121
*6.4.2 Case 2: Plug and play with high loaded and less loaded incoming node* 122
*6.4.3 Proportional load sharing with uncertainty in communicated p.u. load current* 124
6.5 Hardware Validation 124
*6.5.1 Load sharing* 125

6.5.2 *Plug-and-play feature* 125
6.5.3 *Load sharing with uncertainty in communication* 126
6.6 Conclusion 129

**Chapter 7: Adaptive-SMC based Output Impedance Shaping in DC Microgrids Affected by Inverter Load** 131
7.1 Second order ripple sharing 133
7.2 Proposed Control Methodology 134
7.2.1 *Model of $i^{th}$ boost converter in error co-ordinates* 134
7.2.2 *Sliding Mode Control based Adaptive Voltage Control* 134
7.2.3 *Control Law* 135
7.2.4 *Bounds and selection of the control parameters* 137
7.2.5 *Existence of sliding mode* 137
7.3 Small signal output impedance analysis 138
7.4 Stability of proposed controller 139
7.5 Proportional current sharing 142
7.5.1 *Dynamic consensus control* 142
7.5.2 *Dynamic droop control* 143
7.6 Simulation Results 143
7.7 Experimental Results 146
7.7.1 *DC component sharing* 148
7.7.2 *Equal second order ripple sharing* 148
7.7.3 *Ripple reduction through Converter-1 and 3* 148
7.7.4 *Ripple sharing among nodes* 151
7.7.5 *Ripple sharing among nodes with different ripple references* 151
7.8 Conclusion 153

**Chapter 8: Discussion and conclusion** 155
8.1 Future Work and Some Open Problems 158

**References** 161