

Control and Performance of a Cascaded H-Bridge Photovoltaic Power System

Nathan Daniel Marks

B.E. (Elec.)(Hons. 1)

April 2016

A thesis submitted to embody the research carried
out to fulfil the requirements for the degree of:

Doctor of Philosophy

in **Electrical Engineering**

at **The University of Newcastle**

Callaghan, NSW, 2308, Australia

Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

Nathan Daniel Marks

B.E. (Elec.)(Hons. 1)

April 2016

Acknowledgements

The work presented in this thesis was undertaken during the author's Ph.D. candidature at the University of Newcastle, Australia in the School of Electrical Engineering and Computer Science.

I would firstly like to thank my wife Mandy for the incredible and unwavering support you offered throughout this PhD. You always seemed to know what to say when it wasn't going well and you kept me grounded. I was lucky to have such strong support and I thank you for understanding when the PhD seemed more important.

I would like to acknowledge the considerable support of my primary supervisor Doctor Terrence Summers. You and Bob approached me almost 5 years ago and suggested I do a PhD and I haven't looked back. You have provided me with the right advice and expertise when I needed it. I'm thankful for the teaching opportunities offered to me and the memorable experiences in attending many international conferences with you that wouldn't have been possible without your support. Ultimately, I believe this PhD would have been far less enjoyable without you as a supervisor.

I would also like to thank my secondary supervisor Professor Bob Betz. Your expertise, experience and friendship have been invaluable throughout my studies.

Thank you to my family and friends. It probably wasn't easy to understand what I was doing or why I was doing it, but I appreciate your understanding and support in the many forms it was offered.

Thank you to my fellow power electronics postgraduate students for their friendship and lively, constructive discussions on many different topics.

Contents

| | |
|--|--------------|
| Abstract | xxix |
| Nomenclature | xxxii |
| 1 Introduction | 1 |
| 1.1 Principles of Photovoltaic Power Conversion | 3 |
| 1.1.1 Characteristics of Photovoltaic Modules | 6 |
| 1.1.2 Maximum Power Point Tracking | 8 |
| 1.2 General PV System Topologies | 11 |
| 1.2.1 Inverter Topologies | 12 |
| 1.2.2 Centralised Photovoltaic Power System Topology | 17 |
| 1.2.3 String Photovoltaic Power System Topology | 18 |
| 1.2.4 Multistring Photovoltaic Power System Topology | 20 |
| 1.2.5 Conclusions from Basic Inverter Topologies | 21 |
| 1.3 Multilevel Converter Topologies | 22 |
| 1.3.1 Diode Clamped Converter | 22 |
| 1.3.2 Flying Capacitor Converter | 25 |
| 1.3.3 Cascaded H-Bridge Converter | 28 |
| 1.3.4 Modular Multilevel Converter | 30 |

| | | |
|----------|--|-----------|
| 1.3.5 | Suitability of Multilevel Topologies for PV Power Systems | 32 |
| 1.4 | Multilevel Converter Photovoltaic Power System Topologies | 36 |
| 1.4.1 | Diode Clamped Converter Topologies | 36 |
| 1.4.2 | Cascaded H-Bridge Topologies | 39 |
| 1.5 | Control and Modulation Strategies | 42 |
| 1.5.1 | Control Strategies | 43 |
| 1.5.2 | Modulation Strategies | 51 |
| 1.6 | Thesis Scope and Contributions | 56 |
| 1.7 | Thesis Outline | 58 |
| 2 | Analysis of the Cascaded H-Bridge PV Topology | 59 |
| 2.1 | Introduction | 59 |
| 2.2 | Power Flow Analysis | 63 |
| 2.3 | Control Scheme | 65 |
| 2.3.1 | Power Control | 66 |
| 2.3.2 | Converter Control | 71 |
| 2.4 | Phase Power Imbalance | 77 |
| 2.5 | Individual Cell Imbalance and Voltage Regulation | 83 |
| 2.5.1 | Analysis of Cell Imbalance and Capacitor Voltage Regulation | 87 |
| 2.5.2 | Conclusions | 94 |
| 2.6 | Reactive Power Requirements/Minimum Number of PV Supplied Cells | 94 |
| 2.6.1 | The Real and Reactive Power Ratio | 95 |
| 2.6.2 | Minimum Number of H-Bridges with PV Arrays Connected | 100 |
| 2.6.3 | Minimum Number of H-Bridges with PV Arrays Connected with Restrains on Switching Combinations | 103 |

| | | |
|----------|---|------------|
| 2.6.4 | Reactive Power Requirements with Restraints on Switching Combinations | 107 |
| 2.7 | Maximum Power Point Tracking | 120 |
| 2.7.1 | Instantaneous PV Array Power | 121 |
| 2.7.2 | Effect of Power and Voltage Ripple on MPPT Design and Performance | 123 |
| 2.7.3 | Impact on Output Current Magnitude | 127 |
| 2.7.4 | Impacts of Changes in Irradiance | 129 |
| 2.7.5 | Conclusions | 131 |
| 2.8 | Chapter Conclusions | 131 |
| 3 | Control Developments for the Cascaded H-Bridge PV Topology | 135 |
| 3.1 | Introduction | 135 |
| 3.2 | Phase Shifted Perturb and Observe Maximum Power Point Tracking . . . | 136 |
| 3.3 | PV Array Power Estimation | 146 |
| 3.4 | Current Sensorless Ripple Correlation Maximum Power Point Tracking . . | 152 |
| 3.5 | Combining PV Array Power Estimation with RC-MPPT | 156 |
| 3.6 | Comparisons to Phase Shifted Carrier PWM Based Implementations . . . | 156 |
| 3.7 | Chapter Conclusions | 159 |
| 4 | Simulation Studies | 161 |
| 4.1 | Introduction | 161 |
| 4.1.1 | The Saber Simulation | 162 |
| 4.1.2 | Modelling the PV Arrays | 164 |
| 4.2 | Analysing the Performance | 166 |
| 4.2.1 | Converter Output Currents | 166 |

| | | |
|--------|--|-----|
| 4.2.2 | Nominal Capacitor Values | 166 |
| 4.2.3 | Variable Capacitor Values Throughout the Phase Leg | 167 |
| 4.2.4 | Performance Indicators | 167 |
| 4.3 | Cascaded H-Bridge Photovoltaic Power System Configuration | 170 |
| 4.4 | Start-Up Sequencing and Nominally Balanced Power | 171 |
| 4.5 | Phase and Cell Power Imbalances | 177 |
| 4.5.1 | Interphase Power Imbalance | 177 |
| 4.5.2 | Intercell Power Imbalance | 181 |
| 4.6 | Investigating Tradeoffs Between Capacitor Voltage Regulation and Switching Transitions | 184 |
| 4.7 | Reactive Power Requirements/Minimum Number of PV Supplied Cells . . | 190 |
| 4.8 | PV Array Power Estimation | 196 |
| 4.8.1 | Implementation of Estimation Technique | 196 |
| 4.8.2 | Performance of the Estimation Technique | 197 |
| 4.9 | Perturb and Observe Maximum Power Point Tracking | 203 |
| 4.10 | Phase Shifted P&O MPPT | 208 |
| 4.10.1 | Comparison to Standard P&O MPPT | 216 |
| 4.11 | Current Sensorless Ripple Correlation MPPT | 217 |
| 4.11.1 | Implementation of the RC-MPPT Scheme | 217 |
| 4.11.2 | Performance of the RC-MPPT Scheme | 218 |
| 4.11.3 | Comparison to P&O MPPT | 228 |
| 4.12 | Power Estimation with RC-MPPT | 230 |
| 4.13 | Chapter Conclusions | 237 |

| | | |
|----------|--|------------|
| 5 | Experimental Results | 239 |
| 5.1 | Introduction | 239 |
| 5.2 | Practical Considerations and Test Conditions | 241 |
| 5.3 | Phase Power Imbalances | 243 |
| 5.4 | Cell Power Imbalances | 252 |
| 5.5 | Reactive Power Requirements/Minimum Number of PV Supplied Cells . . | 256 |
| 5.6 | PV Array Power Estimation | 262 |
| 5.7 | Chapter Conclusions | 268 |
| 6 | Conclusions and Contributions | 269 |
| 6.1 | Future Work | 273 |
| A | Experimental System | 277 |
| A.1 | Introduction | 277 |
| A.2 | Hardware Configuration | 278 |
| A.2.1 | Converter Hardware | 278 |
| A.2.2 | PV Modules and Current Measurement Hardware | 286 |
| A.3 | Software Configuration | 286 |
| A.3.1 | Converter Control Software Structure | 286 |
| A.3.2 | PV Current Measurement Software | 289 |
| B | Modelling of Capacitor Voltage Regulation | 291 |
| B.1 | Introduction | 291 |
| C | Extending the Prediction Horizon of Finite Control Set Model Predictive Control | 295 |
| C.1 | Introduction | 295 |

| | | |
|----------|--|------------|
| C.2 | Extending the Prediction Horizon | 296 |
| C.3 | Simulation Results | 297 |
| C.3.1 | Ideal System Conditions | 298 |
| C.3.2 | Capacitor Voltage Balancing Included in Cost Function | 299 |
| C.3.3 | Voltage Sag at Point of Common Coupling | 300 |
| C.3.4 | Harmonic Pollution in Grid Voltage | 301 |
| C.4 | Experimental Results | 303 |
| C.5 | Applicability to PV Power Systems | 306 |
| C.6 | Contributions & Conclusions | 307 |
| D | Papers Published | 309 |
| D.1 | Photovoltaic Power Systems: A Review of Topologies, Converters and Controls | 309 |
| D.2 | Finite Control Set Model Predictive Control with Increased Prediction horizon for a 5 Level Cascaded H-Bridge StatCom | 317 |
| D.3 | Challenges for Capacitor Voltage Balancing in a Cascaded H-Bridge Stat-Com Utilising Finite Control Set Model Predictive Control | 329 |
| D.4 | Control of a 19 Level Cascaded H-Bridge Multilevel Converter Photovoltaic System | 337 |
| D.5 | Current Sensor-less Control of a Cascaded H-Bridge Photovoltaic System | 347 |
| D.6 | Reactive Power Requirements for Cascaded H-Bridge Photovoltaic Systems | 355 |
| D.7 | Phase Shifted Maximum Power Point Tracking in a Cascaded H-Bridge Photovoltaic Power System | 365 |
| D.8 | Current Sensorless Maximum Power Point Tracking in a Cascaded H-Bridge Photovoltaic Power System | 377 |

List of Figures

| | | |
|------|--|----|
| 1.1 | Equivalent electrical model of a solar cell | 5 |
| 1.2 | Equivalent electrical model of a practical photovoltaic device | 5 |
| 1.3 | Current vs. voltage characteristic of a solar cell | 6 |
| 1.4 | Power vs. voltage characteristic of a solar cell | 7 |
| 1.5 | Current vs. voltage characteristic for variations in solar irradiation | 7 |
| 1.6 | Current vs. voltage characteristic for variations in the operating temperature | 8 |
| 1.7 | P&O MPPT operating points on the power vs. voltage characteristic | 10 |
| 1.8 | Three phase, 2 level voltage source converter with a star connected load | 13 |
| 1.9 | Three phase, 2 level voltage source converter connected to the grid | 14 |
| 1.10 | H5 inverter based photovoltaic power system topology | 15 |
| 1.11 | HERIC inverter based photovoltaic power system topology | 16 |
| 1.12 | Full bridge with DC bypass inverter based photovoltaic power system topology | 17 |
| 1.13 | Centralised inverter based photovoltaic power system structure | 19 |
| 1.14 | String inverter based photovoltaic power system structure | 19 |
| 1.15 | Multistring inverter based photovoltaic power system structure | 20 |
| 1.16 | Single phase 5-level diode clamped converter | 24 |
| 1.17 | Single phase 5-level flying capacitor converter | 26 |

| | | |
|------|--|-----|
| 1.18 | Single phase 5-level cascaded H-Bridge converter | 31 |
| 1.19 | Single phase 3-level modular multilevel converter | 33 |
| 1.20 | Diode clamped converter with single string configuration | 37 |
| 1.21 | Diode clamped converter with multistring configuration | 39 |
| 1.22 | Cascaded H-Bridge converter with single string configuration | 40 |
| 1.23 | Cascaded H-Bridge converter with multistring configuration | 42 |
| 1.24 | Simple model of a grid connected converter system | 45 |
| 1.25 | Implementation of PSC-PWM in a cascaded H-Bridge converter | 53 |
| 1.26 | Possible voltage space vectors for a 2L-VSC | 55 |
| 2.1 | Circuit diagram of the grid connected cascaded H-Bridge photovoltaic power system | 60 |
| 2.2 | Block diagram of the cascaded H-Bridge photovoltaic power system control scheme | 66 |
| 2.3 | System Timing Diagram | 71 |
| 2.4 | Simulation results for cell imbalance investigation with balanced cell pow- ers and voltages. | 88 |
| 2.5 | Simulation results for cell imbalance investigation with one dominant power cell and voltage regulation maintained. | 89 |
| 2.6 | Simulation results for cell imbalance investigation with one dominant power cell and voltage regulation not maintained in the highest power H-Bridge. | 90 |
| 2.7 | Simulation results for cell imbalance investigation with two dominant power cells and voltage regulation maintained. | 91 |
| 2.8 | Simulation results for cell imbalance investigation with two dominant power cells and voltage regulation not maintained in the highest power H-Bridges. | 92 |
| 2.9 | Converter voltage and output current waveforms demonstrating switching times for Case 1 when exporting real power and absorbing inductive vars | 111 |

| | |
|--|-----|
| 2.10 Converter voltage and output current waveforms demonstrating switching times for Case 2 when exporting real power and absorbing inductive vars. | 116 |
| 2.11 P-V characteristic operating in the vicinity of the maximum power point . | 123 |
| 2.12 P&O MPPT scheme getting confused by the change in the irradiance . . | 130 |
| 3.1 Phase leg voltage reference for synchronously perturbed three point oscillation in each H-Bridge | 138 |
| 3.2 Phase leg voltage reference for staggered perturbation three point oscillation in each H-Bridge | 139 |
| 3.3 Three point oscillation around the MPP | 140 |
| 3.4 Phase leg voltage reference for staggered perturbation four point oscillation in each H-Bridge | 143 |
| 3.5 Flowchart of the proposed PS-P&O MPPT scheme | 145 |
| 4.1 Saber simulation schematic top level overview | 165 |
| 4.2 Simulation results for the CHB PV power system showing H-Bridge capacitor voltages during start-up and balanced PV phase power operation - Top plot: Phase 'a' voltages, Middle plot: Phase 'b' voltages, Bottom plot: Phase 'c' voltages. | 172 |
| 4.3 Simulation results for the CHB PV power system showing start-up sequencing and balanced PV phase powers - Top plot: Measured and demanded reactive power, Bottom plot: Three phase generated PV power. . | 173 |
| 4.4 Simulation results for the CHB PV power system showing start-up sequencing and balanced PV phase powers - Top plot: Three phase PV generated powers, Bottom plot: Phase 'a' H-Bridge PV powers. | 174 |

-
- 4.5 Simulation results for the CHB PV power system showing start-up sequencing and balanced PV phase powers - Top plot: Phase ‘a’ grid voltage and phase ‘a’ measured output current, Middle plot: Three phase measured output currents, Bottom plot: Phase ‘a’ measured and reference currents. 175
- 4.6 Simulation results for the CHB PV power system showing start-up sequencing and balanced PV phase powers zoomed on PV connected period - Top plot: Phase ‘a’ grid voltage and phase ‘a’ measured output current, Middle plot: Three phase measured output currents, Bottom plot: Phase ‘a’ measured and reference currents. 176
- 4.7 Simulation results for the CHB PV power system with unbalanced PV phase powers - Top plot: Phase ‘a’ H-Bridge capacitor voltages, Middle plot: Phase ‘b’ H-Bridge capacitor voltages, Bottom plot: Phase ‘c’ H-Bridge capacitor voltages. 178
- 4.8 Simulation results for the CHB PV power system with unbalanced PV phase powers - Top plot: Three phase PV generated powers, Bottom plot: PV powers for the top H-Bridge in each phase. 179
- 4.9 Simulation results for the CHB PV power system with unbalanced PV phase powers - Top plot: Phase ‘a’ grid voltage and phase ‘a’ measured output current, Middle plot: Three phase measured output currents, Bottom plot: Phase ‘a’ measured and reference currents. 180
- 4.10 Simulation results for the CHB PV power system with unbalanced PV phase powers - Top plot: Converter phase voltages, Middle plot: Effective converter output voltages, Bottom plot: Floating star point voltage. . . . 181
- 4.11 Simulation results for the CHB PV power system with unbalanced PV cell powers - Top plot: Phase ‘a’ H-Bridge capacitor voltages, Middle plot: Phase ‘b’ H-Bridge capacitor voltages, Bottom plot: Phase ‘c’ H-Bridge capacitor voltages. 182

-
- 4.12 Simulation results for the CHB PV power system with unbalanced PV cell powers - Top plot: Phase ‘a’ H-Bridge PV powers, Middle plot: Phase ‘b’ H-Bridge PV powers, Bottom plot: Phase ‘c’ H-Bridge PV powers. 183
- 4.13 Simulation results for the CHB PV power system with unbalanced PV cell powers - Top plot: Phase ‘a’ grid voltage and phase ‘a’ measured output current, Middle plot: Three phase measured output currents, Bottom plot: Phase ‘a’ measured and reference currents. 184
- 4.14 Simulation results for the CHB PV power system with weighting factor $\alpha_2 = 0.0$ and $C_{nom} = 13200\mu F$ - Top plot: H-Bridge capacitor voltages for phase ‘a’, Bottom plot: Average number of transitions on phase ‘a’ devices. 185
- 4.15 Simulation results for the CHB PV power system with weighting factor $\alpha_2 = 0.0$ and $C_{nom} = 5000\mu F$ - Top plot: H-Bridge capacitor voltages for phase ‘a’, Bottom plot: Average number of transitions on phase ‘a’ devices. 186
- 4.16 Simulation results for the CHB PV power system with weighting factor $\alpha_2 = 15.0$ and $C_{nom} = 13200\mu F$ - Top plot: H-Bridge capacitor voltages for phase ‘a’, Bottom plot: Average number of transitions on phase ‘a’ devices. 187
- 4.17 Simulation results for the CHB PV power system with weighting factor $\alpha_2 = 15.0$ and $C_{nom} = 5000\mu F$ - Top plot: H-Bridge capacitor voltages for phase ‘a’, Bottom plot: Average number of transitions on phase ‘a’ devices. 188
- 4.18 Simulation results for the CHB PV power system where $N_{pv} < N_{pvmin}$ with no reactive power support - Top plot: H-Bridge capacitor voltages for phase ‘a’, Middle plot: Three phase powers and two phase measured and reference reactive power, Bottom plot: Measured and reference phase ‘a’ current and phase ‘a’ grid voltage. 191

-
- 4.19 Simulation results for the CHB PV power system where $N_{pv} < N_{pvmin}$ with reactive power support - Top plot: H-Bridge capacitor voltages for phase 'a', Middle plot: Three phase powers and two phase measured and reference reactive power, Bottom plot: Measured and reference phase 'a' current and phase 'a' grid voltage. 192
- 4.20 Simulation results for the CHB PV power system where $N_{pv} = 1$ with reactive power support - Top plot: H-Bridge capacitor voltages for phase 'a', Middle plot: Three phase powers and two phase measured and reference reactive power, Bottom plot: Measured and reference phase 'a' current and phase 'a' grid voltage. 195
- 4.21 Simulation results for the CHB PV power system implementing power estimation in observation mode with an operating point below the MPP at high irradiance - Top plot: Estimated vs. actual PV power in H-Bridge 1 of phase 'a', Middle plot: Estimated vs. actual total phase 'a' PV power, Bottom plot: Error between actual and estimated phase 'a' PV power. . . 198
- 4.22 Simulation results for the CHB PV power system implementing power estimation in observation mode with an operating point at the MPP at high irradiance - Top plot: Estimated vs. actual PV power in H-Bridge 1 of phase 'a', Middle plot: Estimated vs. actual total phase 'a' PV power, Bottom plot: Error between actual and estimated phase 'a' PV power. . . 199
- 4.23 Simulation results for the CHB PV power system implementing power estimation in observation mode with an operating point at the MPP at low irradiance - Top plot: Estimated vs. actual PV power in H-Bridge 1 of phase 'a', Middle plot: Estimated vs. actual total phase 'a' PV power, Bottom plot: Error between actual and estimated phase 'a' PV power. . . 200

| | | |
|------|--|-----|
| 4.24 | Simulation results for the CHB PV power system implementing power estimation in observation mode with an operating point below the MPP at high irradiance and nominal capacitance variation of $\pm 20\%$ - Top plot: Actual PV array powers for phase 'a' H-Bridges, Bottom plot: Estimated PV array powers for phase 'a' H-Bridges. | 201 |
| 4.25 | Simulation results for the CHB PV power system implementing power estimation in observation mode with an operating point below the MPP at high irradiance and nominal capacitance variation of $\pm 20\%$ - Top plot: Estimated vs. actual total phase 'a' PV array power, Bottom plot: Error between actual and estimated phase 'a' PV array power. | 202 |
| 4.26 | Simulation results for the CHB PV power system showing phase 'a' H-Bridge capacitor voltages while implementing PS-P&O MPPT with high irradiance in each PV array - Top plot: H-Bridges 1-3, Top middle plot: H-Bridges 4-6, Bottom middle plot: H-Bridges 7-9, Bottom plot: Phase leg a voltage reference. | 209 |
| 4.27 | Simulation results for the CHB PV power system while implementing PS-P&O MPPT with high irradiance in each PV array - Top plot: Phase 'a' total PV power, Bottom plot: Phase 'a' measured and reference currents. | 210 |
| 4.28 | Simulation results for the CHB PV power system showing phase 'a' H-Bridge capacitor voltages while implementing PS-P&O MPPT with a step change in irradiance at 2.825s- Top plot: H-Bridges 1-3, Top middle plot: H-Bridges 4-6, Bottom middle plot: H-Bridges 7-9, Bottom plot: Phase leg a voltage reference. | 211 |
| 4.29 | Simulation results for the CHB PV power system while implementing PS-P&O MPPT with a step change in irradiance at 2.825s - Top plot: Phase 'a' total PV power, Bottom plot: Phase 'a' measured and reference currents. | 214 |
| 4.30 | Capacitor voltages transient back up | 215 |

-
- 4.31 Simulation results for the CHB PV power system showing estimated proportional power difference while implementing RC-MPPT with high irradiance in each PV array. 218
- 4.32 Simulation results for the CHB PV power system showing H-Bridge capacitor voltages while implementing RC-MPPT with high irradiance in each PV array - Top plot: Phase ‘a’ voltages, Middle plot: Phase ‘b’ voltages, Bottom plot: Phase ‘c’ voltages. 219
- 4.33 Simulation results for the CHB PV power system showing H-Bridge PV array powers while implementing RC-MPPT with high irradiance in each PV array - Top plot: Phase ‘a’ powers, Middle plot: Phase ‘b’ powers, Bottom plot: Phase ‘c’ powers. 220
- 4.34 Simulation results for the CHB PV power system showing three phase total PV powers while implementing RC-MPPT with high irradiance in each PV array. 221
- 4.35 Simulation results for the CHB PV power system while implementing RC-MPPT with high irradiance in each PV array - Top plot: Three phase measured output currents, Bottom plot: Phase ‘a’ measured and reference currents. 222
- 4.36 Simulation results for the CHB PV power system showing H-Bridge capacitor voltages while implementing RC-MPPT with a step change in irradiance at 1.5s - Top plot: Phase ‘a’ voltages, Middle plot: Phase ‘b’ voltages, Bottom plot: Phase ‘c’ voltages. 224
- 4.37 Simulation results for the CHB PV power system showing H-Bridge PV array powers while implementing RC-MPPT with a step change in irradiance at 1.5s - Top plot: Phase ‘a’ powers, Middle plot: Phase ‘b’ powers, Bottom plot: Phase ‘c’ powers. 225
- 4.38 Simulation results for the CHB PV power system showing three phase total PV powers while implementing RC-MPPT with a step change in irradiance at 1.5s. 226

| | | |
|------|--|-----|
| 4.39 | Simulation results for the CHB PV power system while implementing RC-MPPT with a step change in irradiance at 1.5s - Top plot: Three phase measured output currents, Bottom plot: Phase 'a' measured and reference currents. | 226 |
| 4.40 | Simulation results for the CHB PV power system while implementing RC-MPPT with a step change in irradiance at 2.5s - Top plot: Phase 'a' H-Bridge capacitor voltages, Bottom plot: Three phase total PV powers. . | 227 |
| 4.41 | Simulation results for the CHB PV power system showing phase 'a' H-Bridge PV array powers while implementing RC-MPPT with a step change in irradiance at 2.5s - Top plot: H-Bridges 1 – 4, Top middle plot: H-Bridges 5 – 7, Bottom middle plot: H-Bridge 8, Bottom plot: H-Bridge 9. | 228 |
| 4.42 | Simulation results for the CHB PV power system while implementing RC-MPPT with a step change in irradiance at 2.5s - Top plot: Three phase measured output currents, Bottom plot: Phase 'a' measured and reference currents. | 229 |
| 4.43 | Simulation results for the CHB PV power system while implementing power estimation and RC-MPPT with high irradiance in each PV array - Top plot: Phase 'a' H-Bridge capacitor voltages, Bottom plot: Phase 'a' H-Bridge PV array powers. | 231 |
| 4.44 | Simulation results for the CHB PV power system while implementing power estimation and RC-MPPT with high irradiance in each PV array - Top plot: Phase 'a' actual and estimated PV array power, Middle plot: Three phase total PV array powers, Bottom plot: Three phase measured output currents. | 232 |
| 4.45 | Simulation results for the CHB PV power system while implementing power estimation and RC-MPPT with a step change in irradiance at 1.51s - Top plot: Phase 'a' H-Bridge capacitor voltages, Bottom plot: Phase 'a' H-Bridge PV array powers. | 233 |

-
- 4.46 Simulation results for the CHB PV power system while implementing power estimation and RC-MPPT with a step change in irradiance at 1.51s - Top plot: Phase ‘a’ actual and estimated PV array power, Middle plot: Three phase total PV array powers, Bottom plot: Three phase measured output currents. 234
- 4.47 Simulation results for the CHB PV power system while implementing power estimation and RC-MPPT with step changes in irradiance at 2.0s - Top plot: Phase ‘a’ H-Bridge capacitor voltages, Middle plot: Phase ‘b’ H-Bridge capacitor voltages, Bottom plot: Phase ‘a’ H-Bridge capacitor voltages. 235
- 4.48 Simulation results for the CHB PV power system while implementing power estimation and RC-MPPT with step changes in irradiance at 2.0s - Top plot: PV array powers for phase ‘a’ H-Bridges 1 – 4, Top middle plot: PV array powers for phase ‘a’ H-Bridges 5 – 7, Bottom middle plot: PV array power for phase ‘a’ H-Bridge 8, Bottom plot: PV array power for phase ‘a’ H-Bridge 9. 236
- 4.49 Simulation results for the CHB PV power system while implementing power estimation and RC-MPPT with step changes in irradiance at 2.0s - Top plot: Phase ‘a’ actual and estimated PV array power, Middle plot: Three phase total PV array powers, Bottom plot: Three phase measured output currents. 236
- 5.1 Block diagram of the 19-level, 415V Cascaded H-Bridge photovoltaic power system 240
- 5.2 Experimental results with unbalanced PV phase powers and low reactive power demand - Top plot: Capacitor voltages for H-Bridges 1 and 2 in phase ‘a’, Middle plot: Capacitor voltages for H-Bridges 1 and 2 in phase ‘b’, Bottom plot: Capacitor voltages for H-Bridges 1 and 2 in phase ‘c’. . . 244
- 5.3 Experimental results with unbalanced PV phase powers and low reactive power demand showing three phase measured PV powers. 245

| | | |
|------|---|-----|
| 5.4 | Experimental results with unbalanced PV phase powers and low reactive power demand, zoomed - Top plot: Capacitor voltages for H-Bridges 1 and 2 in phase 'a', Middle plot:Capacitor voltages for H-Bridges 1 and 2 in phase 'b', Bottom plot: Capacitor voltages for H-Bridges 1 and 2 in phase 'c'. | 245 |
| 5.5 | Experimental results with unbalanced PV phase powers and low reactive power demand showing zoomed three phase measured PV powers. | 246 |
| 5.6 | Experimental results with unbalanced PV phase powers and low reactive power demand showing zoomed three phase currents. | 247 |
| 5.7 | Experimental results with unbalanced PV phase powers and low reactive power demand, zoomed - Top plot: Measured PV array powers for H-Bridge 1 in phase 'a' and 'b', Middle plot: Measured output current for phase 'a' and measured grid voltage for phase 'a', Bottom plot: Measured instantaneous power for phase 'a'. | 247 |
| 5.8 | Experimental results with unbalanced PV phase powers and high reactive power demand - Top plot: Capacitor voltages for H-Bridges 1 and 2 in phase 'a', Middle plot:Capacitor voltages for H-Bridges 1 and 2 in phase 'b', Bottom plot: Capacitor voltages for H-Bridges 1 and 2 in phase 'c'. | 248 |
| 5.9 | Experimental results with unbalanced PV phase powers and high reactive power demand showing three phase measured PV powers. | 249 |
| 5.10 | Experimental results with unbalanced PV phase powers and high reactive power demand, zoomed - Top plot: Capacitor voltages for H-Bridges 1 and 2 in phase 'a', Middle plot:Capacitor voltages for H-Bridges 1 and 2 in phase 'b', Bottom plot: Capacitor voltages for H-Bridges 1 and 2 in phase 'c'. | 249 |
| 5.11 | Experimental results with unbalanced PV phase powers and high reactive power demand showing zoomed three phase measured PV powers. | 250 |
| 5.12 | Experimental results with unbalanced PV phase powers and high reactive power demand showing three phase currents. | 250 |

-
- 5.13 Experimental results with unbalanced PV phase powers and high reactive power demand, zoomed - Top plot: Measured PV array powers for H-Bridge 1 in phase ‘a’ and ‘b’, Middle plot: Measured output current for phase ‘a’ and measured grid voltage for phase ‘a’, Bottom plot: Measured instantaneous power for phase ‘a’. 251
- 5.14 Experimental results showing H-Bridge capacitor voltages 1 – 6 for phase ‘a’ with unbalanced PV phase powers and individual capacitor voltage targets. 253
- 5.15 Experimental results showing three phase measured PV powers with unbalanced PV phase powers and individual capacitor voltage targets. . . . 253
- 5.16 Experimental results showing H-Bridge capacitor voltages 1 – 6 for phase ‘a’ with unbalanced PV phase powers and individual capacitor voltage targets, zoomed. 254
- 5.17 Experimental results showing three phase measured PV powers with unbalanced PV phase powers and individual capacitor voltage targets, zoomed. 254
- 5.18 Experimental results showing three phase output currents with unbalanced PV phase powers and individual capacitor voltage targets, zoomed. 255
- 5.19 Experimental results with unbalanced PV phase powers and individual capacitor voltage targets, zoomed - Top plot: Measured PV array powers for H-Bridge 1 in phase ‘a’ and ‘b’, Middle plot: Measured output current for phase ‘a’ and measured grid voltage for phase ‘a’, Bottom plot: Measured instantaneous power for phase ‘a’. 255
- 5.20 Experimental results showing H-Bridge capacitor voltages 1 – 6 for phase ‘a’ with a single H-Bridge supplied with a PV array and low reactive power demand. 257
- 5.21 Experimental results showing three phase measured PV powers with a single H-Bridge supplied with a PV array and low reactive power demand. 258
- 5.22 Experimental results showing three phase output currents with a single H-Bridge supplied with a PV array and low reactive power demand. . . . 258

| | | |
|------|--|-----|
| 5.23 | Experimental results with a single H-Bridge supplied with a PV array and low reactive power demand - Top plot: Measured PV array powers for H-Bridge 1 in phase ‘a’ and ‘b’, Middle plot: Measured output current for phase ‘a’ and measured grid voltage for phase ‘a’, Bottom plot: Measured instantaneous power for phase ‘a’. | 259 |
| 5.24 | Experimental results showing H-Bridge capacitor voltages 1 – 6 for phase ‘a’ with a single H-Bridge supplied with a PV array and high reactive power demand. | 260 |
| 5.25 | Experimental results showing three phase measured PV powers with a single H-Bridge supplied with a PV array and high reactive power demand. | 261 |
| 5.26 | Experimental results showing three phase output currents with a single H-Bridge supplied with a PV array and high reactive power demand. | 261 |
| 5.27 | Experimental results with a single H-Bridge supplied with a PV array and high reactive power demand - Top plot: Measured PV array powers for H-Bridge 1 in phase ‘a’ and ‘b’, Middle plot: Measured output current for phase ‘a’ and measured grid voltage for phase ‘a’, Bottom plot: Measured instantaneous power for phase ‘a’. | 262 |
| 5.28 | Timing diagram for power estimation in the experimental system. | 264 |
| 5.29 | Experimental results for first estimation technique with a single H-Bridge supplied with a PV array and high reactive power demand - Top plot: Capacitor voltage for H-Bridge 1 in phase ‘a’, Bottom plot: Actual, measured and estimated power for H-Bridge 1 in phase ‘a’. | 265 |
| 5.30 | Experimental results for second estimation technique with a single H-Bridge supplied with a PV array and high reactive power demand - Top plot: Capacitor voltage for H-Bridge 1 in phase ‘a’, Bottom plot: Actual, measured and estimated power for H-Bridge 1 in phase ‘a’. | 266 |
| A.1 | Block diagram of the 19-level 415 V Cascaded H-Bridge experimental system. | 278 |
| A.2 | The experimental setup in the laboratory. | 279 |

| | | |
|------|--|-----|
| A.3 | Block diagram of the H-bridge module used in the 19-level CHB-PV power system. | 280 |
| A.4 | The phase controller board. | 282 |
| A.5 | Block diagram of phase controller connections. | 282 |
| A.6 | Block diagram of the interface board. | 283 |
| A.7 | The interface board. | 284 |
| A.8 | Block diagram of the data acquisition board showing connections. | 285 |
| A.9 | The data acquisition board. | 285 |
| A.10 | Block diagram of the software structure. | 288 |
| A.11 | Thread structure of the front panel server process. | 289 |
| C.1 | Switching transitions vs. λ_{SW} for $N = 1$ and $N = 2$ with ideal system. | 299 |
| C.2 | Switching transitions vs. λ_{SW} for $N = 1$ and $N = 2$ with capacitor balancing. | 300 |
| C.3 | Switching transitions vs. λ_{SW} for $N = 1$ and $N = 2$ with voltage sag. | 301 |
| C.4 | Switching transitions vs. λ_{SW} for $N = 1$ and $N = 2$ with harmonics in voltage | 302 |
| C.5 | Experimental results showing ‘a’ phase capacitor voltages (top) and ‘a’ phase transitions (bottom) for $N = 1$ | 303 |
| C.6 | Experimental results showing ‘a’ phase capacitor voltages (top) and ‘a’ phase transitions (bottom) for $N = 2$ | 304 |
| C.7 | Experimental results showing ‘a’ phase current tracking for $N = 1$ | 305 |
| C.8 | Experimental results showing ‘a’ phase current tracking for $N = 2$ | 305 |

List of Tables

| | | |
|-----|--|-----|
| 2.1 | PV array characteristics used for MATLAB simulation of cell imbalance. | 88 |
| 4.1 | Voltage deviations and average number of switching transitions for $C_{nom} = 13200\mu F$ | 189 |
| 4.2 | Voltage deviations and average number of switching transitions for $C_{nom} = 5000\mu F$ | 189 |
| 4.3 | Maximum Power Point Tracking performance for measured PV array power with moving average filter on capacitor voltages and powers. | 204 |
| 4.4 | Maximum Power Point Tracking performance for measured PV array power with low pass filter on capacitor voltages and powers. | 205 |
| 4.5 | Maximum Power Point Tracking performance for estimated PV array power with moving average filter on capacitor voltages and powers. | 206 |
| 4.6 | Maximum Power Point Tracking performance for estimated PV array power with low pass filter on capacitor voltages and powers. | 207 |
| C.1 | System Parameters | 298 |

Abstract

This thesis presents the control and performance of a Cascaded H-Bridge photovoltaic power system. The cascaded H-Bridge multilevel converter offers a number of attractive features for use in photovoltaic power systems. They provide opportunities for increases in efficiency, superior tracking of the maximum available power and direct connection to higher voltages. This system topology is a relatively immature technology and a number of key areas exist for research. In particular, the individual maximum power point tracking performance requires further analysis and development, the operation of the system in the presence of variable power generation in the photovoltaic arrays requires further investigation and the ability of the system to maintain operation under different array configurations is an interesting area for investigation.

The details and the performance of a heuristic model predictive control scheme are presented, as well as the control techniques used to compensate for the power variability. The operation of the system when some arrays have zero power is also investigated. Two new maximum power point tracking techniques are proposed and the performance relative to the established Perturb and Observe technique is evaluated. A photovoltaic array current sensorless technique is also developed to exploit the switching characteristics produced by the model predictive control scheme.

Finally, simulation and experimental results are presented that evaluate and validate the performance of the proposed control techniques. The results show that the proposed control techniques offer excellent performance.

Nomenclature

| | |
|-------------------------|--|
| α_0 | Angle of the injected zero sequence voltage, page 81 |
| Δv_{MPPT} | Voltage perturbation size , page 123 |
| ω_0 | Fundamental system frequency in rad/s, page 44 |
| \underline{i}_{k+1} | Predicted instantaneous current vector at the end of the control interval from $kT \rightarrow (k+1)T$, page 50 |
| \underline{i}_{k+1}^* | Reference instantaneous current vector at the end of the control interval from $kT \rightarrow (k+1)T$, page 50 |
| \underline{i}_P^* | Demanded current vector for real power, page 66 |
| \underline{i}_Q^* | Demanded current vector for reactive power, page 66 |
| \underline{v}_{k+1} | Applied voltage vector for the interval $kT \rightarrow (k+1)T$, page 49 |
| C_k | Nominal capacitance of the k th H-Bridge, page 76 |
| f_{MPPT} | MPPT update frequency , page 123 |
| i_q | Instantaneous synchronously rotating frame q axis current, page 44 |
| i_{cap} | H-Bridge capacitor current, page 148 |
| i_d | Instantaneous synchronously rotating frame d axis current, page 44 |
| $i_{k+1\alpha/\beta}^*$ | Reference instantaneous two phase stationary currents at the end of the control interval $kT_s \rightarrow (k+1)T_s$, page 72 |

| | |
|-----------------------|---|
| $i_{k-1\alpha/\beta}$ | Sampled instantaneous two phase stationary currents at time $(k-1)T_s$, page 72 |
| $i_{k\alpha/\beta}$ | Estimated instantaneous two phase stationary currents at time kT_s , page 72 |
| I_{pvk} | Mean capacitor voltage for the k th H-Bridge over a fundamental period, page 64 |
| K_I | Integral Gain, page 43 |
| K_P | Proportional Gain, page 43 |
| L | Connection inductance between CHB converter and the grid, page 45 |
| N | Number of H-Bridge modules per phase, page 98 |
| N_C | Number of capacitors in a flying capacitor multilevel converter, page 28 |
| N_D | Number of diodes in a diode clamped multilevel converter, page 25 |
| N_H | Number of H-Bridge cells per phase in a cascaded h-bridge multilevel converter, page 29 |
| N_M | Number of half H-Bridge modules per arm in a modular multilevel converter, page 32 |
| $N_{C_{bulk}}$ | Number of bulk capacitors partitioning the DC bus in a multilevel converter, page 24 |
| $N_{C_{clamp}}$ | Number of clamping capacitors in the flying capacitor multilevel converter, page 27 |
| N_{cell} | Number of cells in a flying capacitor multilevel converter, page 27 |
| N_{pv} | Number of H-Bridge modules with PV arrays connected per phase, page 99 |
| N_{sw} | Number of semiconductor devices in a multilevel converter, page 24 |

| | |
|---------------------|---|
| N_V | Number of voltage levels in a multilevel converter, page 24 |
| P_{avg} | Average desired phase leg power, page 68 |
| P_{grid} | Average power transferred to the grid over one fundamental period per phase, page 63 |
| P_{jleg} | Power component required to regulate the total voltage of the j th phase leg, page 67 |
| P_j^* | Desired power for j th phase leg, page 67 |
| P_{pvj} | Sum of the incoming PV array power in the j th phase leg, page 67 |
| P_{pv} | Average PV array power over one fundamental period, page 64 |
| Q^* | Demanded reactive power, page 67 |
| T_g | Length of the grid period, page 63 |
| T_s | Length of the control period, page 46 |
| T_{MPPT} | MPPT update period , page 123 |
| V_0 | RMS magnitude of the injected zero sequence voltage, page 81 |
| V_k | Mean capacitor voltage for the k th H-Bridge over a fundamental period, page 64 |
| $V_{caperror}$ | Cumulative capacitor voltage regulation error, page 74 |
| v_{capmin} | Minimum capacitor voltage within a phase leg, page 74 |
| v_{comb} | Voltage applied by a switching combination, page 74 |
| $V_{conv} [0, T]$ | Average converter voltage over the time interval from $0 \rightarrow T_s$, page 46 |
| v_{conv}^* | Instantaneous reference converter voltage, page 74 |
| $V_{gridav} [0, T]$ | Average grid voltage over the time interval from $0 \rightarrow T_s$, page 46 |
| v_{jleg} | Measured total voltage of the j th phase leg, page 68 |

| | |
|--------------------------------|--|
| v_{jleg}^* | Desired total voltage of the j th phase leg, page 68 |
| $v_{k+0.5\alpha/\beta}^{sys}$ | Predicted instantaneous two phase stationary grid voltages at time $(k + 0.5)T_s$, page 72 |
| $v_{k+1\alpha/\beta}^*$ | Reference instantaneous two phase stationary converter voltages for the control interval $kT_s \rightarrow (k + 1)T_s$, page 72 |
| $v_{k-0.5\alpha/\beta}^{grid}$ | Sampled two phase stationary grid voltages at time $(k-0.5)T_s$, page 72 |
| CHB | Cascaded H-Bridge multilevel converter, page 28 |
| DCC | Diode Clamped Converter, page 22 |
| DLL | Dynamic Link Library, page 161 |
| EPLD | Electrically Programmable Logic Device, page 281 |
| FCC | Flying Capacitor multilevel converter, page 25 |
| FCS-MPC | Finite Control Set Model Predictive Control, page 49 |
| HDL | Hardware Description Language, page 162 |
| HVDC | High Voltage Direct Current, page 30 |
| INC MPPT | Incremental Conductance Maximum Power Point Tracking, page 9 |
| MMC | Modular Multilevel Converter, page 30 |
| MPC | Model Predictive Control, page 48 |
| MPP | Maximum Power Point, page 6 |
| MPPT | Maximum Power Point Tracking, page 8 |
| P&O MPPT | Perturb and Observe Maximum Power Point Tracking, page 9 |
| PCI | Peripheral Component Interconnect, page 282 |
| PS-P&O MPPT | Phase Shifted Perturb and Observe Maximum Power Point Tracking, page 137 |

| | |
|---------|---|
| RC-MPPT | Ripple correlation Maximum Power Point Tracking, page 152 |
| RCC | Ripple Correlation Control, page 152 |
| RTX | Real Time Extension, page 286 |
| TCP/IP | Transmission Control Protocol/Internet Protocol, page 287 |