MASSEY UNIVERSITY
COLLEGE OF SCIENCES

Switched Reluctance Electronic Drive:

Reverse Engineering To Improve The Quality And Manufacturability Of A Commercial Application

A thesis presented in partial fulfilment of the requirements for the degree of

Masters Of Engineering

In

Electronics and Computer Systems Engineering

At Massey University, Palmerston North

New Zealand

Michael John Lusby

2012

Abstract

This thesis presents a new prototype for a low maintenance and high quality switched reluctance electronic drive. Switched reluctance machine technology describes a modern brushless electric motor topology that is perhaps the most simple of all rotating electric machines. However, a switched reluctance machine requires power electronic switching and sophisticated digital control to be a viable competitor against alternative electronic machine topologies.

Commercial switched reluctance machine systems are normally designed and built by pairing the motor and the electronic drive together. This pairing increases the difficulty and cost of quality improvement. The motivation for this research is to improve the quality within a commercial switched reluctance machine electronic drive.

This particular electronic drive suffers from repeated common modes of failure. To achieve this, an accurate understanding of the interactions between functional components of the drive is crucial to reducing this complexity. This reduction in complexity can be achieved through appropriate separation of these functional components. Reverse engineering the electronic drive provides the detailed information required to design a component separated prototype solution.

The complexity of the electronic drive has been reduced by separation into power and control functional components; these components are present on separate circuit boards. This has reduced the complexity of investigating each circuit in detail and for isolating the cause of failures within each circuit. This has also standardised the necessary connections required between the power and control components should one of the circuits need to be redesigned.

Acknowledgements

I would like to thank Dr. Ibrahim Al-Bahadly for his guidance and instruction. He consistently went above and beyond his commitments as a supervisor and for that I am grateful. I also want to thank Ibrahim for maintaining a strong conviction that I would find the necessary answers, even when I believed I could not.

I received a great deal of knowledge and understanding in the subjects of analysis, reverse engineering, design, control, and critical thinking through his supervision. I would like to extend my appreciation for his mastery of the Switched Reluctance Machine.

I would also like to thank Roger Latimer, Brian Latimer, and Nathan Stantiall of Teknatool International Limited for their continued support and patience with this project. They provided me with the challenge to prove myself, and the opportunity to work co-operatively with them on this challenging and interesting project.

To my family I extend my gratitude for their endless support, and for the countless hours they provided an ear to relieve the stress of the work effort. I would like to especially thank them for continuing to believe in me.

I extend my sincere thank you to my friends, colleagues, and staff members of the School of Engineering and Advanced Technology for their continued support and inspiring words.

Thank you to everyone, without your contributions this work would not have been possible.

Michael J. Lusby
January 11, 2012

Table of Contents

Chapter 1 Introduction 1

1.1 What is a “Switched Reluctance Machine” 2

1.2 Definition of Quality 2

1.3 Description of Problem Domain 2

1.4 Aim and Scope of Research 4

1.5 Research objectives 5

1.6 Organisation of the thesis 5

Chapter 2 Operating Principles 9

2.1 Switched Reluctance Machine Overview 10

2.2 Basic Principles 11

2.3 Motoring operation 13

2.3.1 Inductance 14

2.3.2 Flux-linkage 16

2.3.3 Phase Current 18

2.3.4 Power and Torque 19

2.4 Torque-Speed and Power-Speed Relationships 21

2.5 Acoustic Noise 23

2.5.1 Sound power level 23

2.5.2 Acoustic Noise Generation 24

2.5.3 Reducing Acoustic Noise 25

2.6 Summary 26

Chapter 3 Motor Construction 27

3.1 Stator Construction 28

3.2 Rotor Construction 29

3.3 Pole and Phase Configurations 30

3.3.1 Single Phase 31

3.3.2 Two phase 32

3.3.3 Three phase 34

3.3.4 Four Phase 35

3.3.5 Higher phase count motors 36

3.4 Summary 36

Chapter 4 Power Supply and Electronic Converter 37

4.1 Power Supply Overview 38

4.2 Power Supply Architecture 39

4.3 Power Factor 40

4.3.1 Reactance Phase Shift 41
4.3.2 Measurement of power quantities 43
4.3.3 Vector relationship of power quantities 44
4.3.4 Calculation of power factor 45
4.3.5 Impact of Power Factor on Circuit Performance 46
4.3.6 Harmonic Distortion 46
4.4 Power Factor Correction 48
4.4.1 Passive Power Factor Correction 49
4.4.2 Correction of harmonically distorted current 52
4.4.3 Active Power Factor Correction 57
4.5 Electronic Power Converter 61
4.5.1 Split Rail Converter 61
4.5.2 Miller converter (N+1 topology) 63
4.5.3 Resistor-dump Converter 65
4.5.4 Capacitor-dump converter 67
4.5.5 Freewheeling Capacitor-dump converter 69
4.5.6 Asymmetric half-bridge converter 70
4.5.7 Shared Switch Converter 72
4.6 Summary 74
Chapter 5 Control Methodology and Algorithms 75
5.1 Control Algorithm Overview 76
5.2 Average Torque Control 77
5.3 Low-speed motoring 78
5.3.1 Current Hysteresis Control 80
5.3.2 Current Hysteresis Control – Delta Modulation 82
5.3.3 Voltage Pulse Width Modulation Control 82
5.3.4 Singular Pulse Control 84
5.4 High – speed motoring 84
5.5 Sensor-less Control 85
5.6 Summary 87
Chapter 6 DVR SRM Implementation 89
6.1 Motor Construction 90
6.2 Phase Characteristics 91
6.3 Power Supply 94
6.4 Electronic Power Converter 96
6.5 Control Topologies 97
6.6 Torque-Speed and Power-Speed Relationships 99

6.7 Acoustic Noise 101
6.8 Summary 101
Chapter 7 Separation Process 103
7.1 Familiarisation with DVR electronic drive 104
7.2 Identification of ideal separation points 105
7.3 Detailed reverse engineering of electronic drive 107
7.4 Plausibility of proposed separation points 109
7.5 Identification of final separation points 110
7.6 Summary 113
Chapter 8 Prototype design and manufacture 115
8.1 Criteria for prototype circuit boards 116
8.2 Manufacture and assembly of circuit boards 119
8.3 Assembly testing of circuit boards 121
8.4 Revision of circuit board design 124
8.5 Delivery Of Solution 126
8.6 Summary 127
Chapter 9 Instrumentation and Testing 129
9.1 The need for isolated instrumentation 130
9.2 Waveforms of significant interest 131
9.3 Voltage measurement 132
9.4 Phase current measurement 134
9.5 Electromagnetic Interference 136
9.6 Power Factor Comparison 137
9.7 Power Supply Performance 140
9.7.1 +360V Rail 140
9.7.2 +15V Rail 141
9.7.3 +5V Rail 142
9.7.4 +2.5V Rail 142
9.7.5 -5V Supply 143
9.7.6 +5V Isolated Rail 144
9.8 Phase Winding Comparison 144
9.8.1 100rpm 145
9.8.2 1000rpm 147
9.8.3 2000rpm 148
9.8.4 3000rpm 150
9.8.5 Full-sweep acceleration 152
9.9 Summary 154

Chapter 10 Quality Improvement 155
10.1 Appropriate Isolation of Control Circuitry 156
10.2 Improved Current Sensing 159
10.3 -5V Rail Regulation 163
10.4 Phase Switching Components 165
10.5 Integration of circuit boards 167
10.6 Active Braking for Emergency Stop 167
10.7 Sensor-less Operation 168
10.8 Recommendations for improvement 169
10.9 Summary 171
Chapter 11 Conclusion 173
11.1 Research Objectives 174
11.2 Research outcome 175
11.3 Future work 176
11.4 Concluding remarks 177
Appendix A DVR Technical Information 183
Appendix B Measurement Data 197
Appendix C Research Outputs 203
Appendix D Component Datasheets 231
Appendix E Photos 301

List of Figures

Figure 1-1: Histogram Of Fault Mode Frequency 3
Figure 2-1: SRM Drive Architecture 10
Figure 2-2: Cross-section Of A Typical SRM 11
Figure 2-3: Simple Clockwise Rotation Excitation Sequence 12
Figure 2-4: Plausible Clockwise Rotation Excitation Sequence 13
Figure 2-5: Pole Alignment Overview 13
Figure 2-6: Inductance As A Function Of Rotor Angle 14
Figure 2-7: Inductance As A Function Of Rotor Angle And Current 15
Figure 2-8: Flux-Linkage As A Function Of Rotor Angle 16
Figure 2-9: Flux-linkage As A Function Of Rotor Angle And Current 17
Figure 2-10: Unconstrained Phase Current As A Function Of Rotor Angle 18
Figure 2-11: Chopped Phase Current As A Function Of Rotor Angle 18
Figure 2-12: Torque Generation As A Function Of Rotor Angle 20
Figure 2-13: Idealised Torque Speed Relationship 21
Figure 2-14: Idealised Power Speed Relationship 22
Figure 3-1: Switched Reluctance Stator And Winding Cross-section 28
Figure 3-2: Cross-section of rotor construction 29
Figure 3-3: Cross-section Of A Single Phase 4/4 31
Figure 3-4: Cross-section Of A Two Phase 4/4 32
Figure 3-5: Rotor Modifications For Ease Of Starting 33
Figure 3-6: Cross-section Of A Three Phase SRM 34
Figure 3-7: Cross-section Of A Four Phase SRM 35
Figure 4-1: Power Supply Architecture 39
Figure 4-2: Power Waveforms Of A Unity Load 41
Figure 4-3: Power Waveforms Of An Inductive Load 42
Figure 4-4: Power Waveforms Of A 0.6PF Lagging Load 43
Figure 4-5: Vector representation of Power Factor quantities 44
Figure 4-6: Power Waveforms For A Harmonically Distorted Load 47
Figure 4-7: AC Circuit With Resistive And Inductive Loading 49
Figure 4-8: Capacitively Corrected Inductive And Resistive AC Circuit 51
Figure 4-9: Bridge Rectified AC Supply With Smoothing Capacitor 52
Figure 4-10: AC Side Series Harmonic Distortion Filter 53
Figure 4-11: AC Side Series Band-Pass Harmonic Distortion Filter 54

Figure 4-12: AC Side Harmonic Distortion Trap Filtering 55
Figure 4-13: AC Side Capacitor-Fed Bridge Rectifier Harmonic Distortion Filter 56
Figure 4-14: Functional Diagram Power supply Including Active Power Factor Correction .. 57
Figure 4-15: Active Power Factor Correction Buck DC-DC Converter 58
Figure 4-16: Active Power Factor Correction Boost DC-DC Converter 59
Figure 4-17: Active Power Factor Correction Buck-Boost DC-DC Converter 60
Figure 4-18: Split Rail Converter Schematic 61
Figure 4-19: Split Rail Converter Voltage And Current Waveforms 62
Figure 4-20: Miller Converter Schematic 63
Figure 4-21: Miller Converter Voltage And Current Waveforms 64
Figure 4-22: Resistor-dump Converter Schematic 65
Figure 4-23: Resistor-dump Converter Voltage And Current Waveforms 66
Figure 4-24: Capacitor-dump Converter Schematic 67
Figure 4-25: Capacitor-dump Converter Voltage And Current Waveforms 68
Figure 4-26: Freewheeling capacitor-dump Converter Schematic 69
Figure 4-27: Freewheeling Capacitor-dump Converter Voltage And Current Waveforms 70
Figure 4-28: Asymmetric Half Bridge Converter 71
Figure 4-29: Asymmetric Half Bridge Converter Voltage And Current Waveforms 72
Figure 4-30: Shared Switch Converter 73
Figure 4-31: Shared Switch Converter Voltage And Current Waveforms 74
Figure 5-1: General Control diagram For An SRM 78
Figure 5-2: Control diagram For A Current Hysteresis Controller 81
Figure 5-3: Control Diagram For A Voltage PWM Controller 83
Figure 5-4: Control Diagram For A Singular Pulse Controller 84
Figure 6-1: Teknatool DVR SRM Inductance Profile 90
Figure 6-2: DVR Phase Characteristics Measurement Circuit 92
Figure 6-3: DVR Phase Flux-Linkage Characteristics 92
Figure 6-4: DVR Phase Inductance Characteristics 93
Figure 6-5: Teknatool DVR SRM Electronic Power Converter Schematic 96
Figure 6-6: DVR Rotor Position Sensor Capture 97
Figure 6-7: Low-Speed Control System Captures of DVR Motor 98
Figure 6-8: High-Speed Control System Captures of DVR Motor 99
Figure 6-9: DVR Torque-Speed Plot 100
Figure 6-10: DVR Power-Speed Plot 100
Figure 7-1: Drive Component Separation Diagram 104

Figure 8-1: Photo Of Prototype Separated Electronic Drive 126
Figure 9-1: Short Circuit Current For Differential Measurements 130
Figure 9-2: Differential Phase Voltage Isolated Measurement Circuit 133
Figure 9-3: Phase Current Measurement Isolation Circuit 135
Figure 9-4: Low Pass EMI Filter Schematic 136
Figure 9-5: Power factor Correction Comparison 138
Figure 9-6: AC Supply Voltage, Current, And Power Waveform Comparison 138
Figure 9-7: Power Factor Comparison of PFC Enabled And PFC Disabled 139
Figure 9-8: +360V Rail Waveform Comparison 140
Figure 9-9: +15V Rail Waveform Comparison 141
Figure 9-10: +5V Rail Waveform Comparison 142
Figure 9-11: +2.5V Rail Waveform Comparison 142
Figure 9-12: -5V Rail Waveform Compariosn 143
Figure 9-13: +5V_INT Isolated Rail Waveform Comparison 144
Figure 9-14: Current Waveform Variation At Constant Speed 145
Figure 9-15: Chopping Signal And Phase Current At 100rpm Unloaded 146
Figure 9-16: Chopping Signal And Phase Current At 100rpm Lightly Loaded 146
Figure 9-17: Chopping Signal And Phase Current At 1000rpm Unloaded 147
Figure 9-18: Chopping Signal And Phase Current At 1000rpm Lightly Loaded 147
Figure 9-19: Chopping Signal And Phase Current At 1000rpm Heavily Loaded 148
Figure 9-20: Chopping Signal And Phase Current At 2000rpm Unloaded 149
Figure 9-21: Chopping Signal And Phase Current At 2000rpm Lightly Loaded 149
Figure 9-22: Chopping Signal And Phase Current at 2000rpm Heavily Loaded 149
Figure 9-23: Chopping Signal And Phase Current At 3000rpm Unloaded 150
Figure 9-24: Chopping Signal And Phase Current At 3000rpm Lightly Loaded 151
Figure 9-25: Chopping Signal And Phase Current At 3000rpm Heavily Loaded 151
Figure 9-26: Full-sweep Acceleration Comparison Unloaded 152
Figure 9-27: Full-sweep Acceleration Comparison Lightly Loaded 153
Figure 9-28: Full-sweep Acceleration Comparison Heavily Loaded 153
Figure 10-1: Transformer T1 Defeating Control Circuit Isolation 157
Figure 10-2: +2.5V/+5V Power Supply Schematic 157
Figure 10-3: +5V_INT Isolated Power Supply Schematic 158
Figure 10-4: Proposed isolation Modification To +2.5V/+5V Power Supply 158
Figure 10-5: Converter Implementing Per-phase Resistive Current Sensing 160
Figure 10-6: Converter Implementing Per-phase Inductive Current Sensing 161

Figure 10-7: Converter Implementing DC bus Inductive And Resistive Current Sensing 162
Figure 10-8: -5V Power Rail Capture Showing Cyclical Step 163
Figure 10-9: -5V Power Supply Schematic 163
Figure 10-10: Proposed Regulator Modification To -5V Power Supply 164
Figure 10-11: Asymmetric half-bridge Converter Implementing MOSFET Transistors 166
Figure A-1: DVR Control Board Schematic 189
Figure A-2: Interface Board Circuit Schematic 190
Figure A-3: Rotor Position Circuit Schematic 191
Figure A-4: Mains EMI Filter Schematic 191
Figure A-5: DVR Control Circuit Board Top Layer 192
Figure A-5: DVR Control Circuit Board Bottom Layer 193
Figure A-6: Interface Panel Circuit Board Top Layer 194
Figure A-7: Interface Panel Circuit Board Bottom Layer 194
Figure A-8: Rotor Position Sensor Circuit Board Top Layer 195
Figure A-9: Rotor Position Sensor Circuit Board Bottom Layer 195
Figure B-1: Motor Dimensions 198
Figure C-1: Major Component Areas Within DVR Electronic Drive 204
Figure C-2: Idealised Separation Points Within DVR Electronic Drive 205
Figure C-3: Identification Of Groupings And Separation Points Following Deep Analysis... 206
Figure C-4: Separation line Plotted From Proposed Separation Points 207
Figure C-5: Identification Of Proposed Separation Points Within DVR Electronic Drive 208
Figure C-6: Separation Line Plotted From Proposed Separation Points 209
Figure C-7: Revised And Final Separation Points Within DVR Electronic Drive 210
Figure C-8: Final Separation Line Plotted From Final Separation Points 211
Figure C-9: Prototype Power Supply PCB Top Layer 227
Figure C-10: Prototype Power Supply PCB Bottom Layer 227
Figure C-11: Prototype Power Supply Gerber Data 228
Figure C-12: Prototype Power Supply PCB NC Drill Data 228
Figure C-13: Prototype Controller PCB Top Layer 229
Figure C-14: Prototype Controller PCB Bottom Layer 229
Figure C-15: Prototype Controller Gerber Data 230
Figure C-16: Prototype Controller NC Drill Data 230

List of Tables

Table 6-1: DVR Acoustic Noise Levels 101
Table A-1: Fault Repair Information 186
Table A-2: Fault Mode 186
Table A-3: DVR Control LCD Board Fault Messages 187
Table A-4: DVR SRM Motor Parameters 188
Table B-1: Motor Dimensions 198
Table B-2: Phase Flux-Linkage Characteristics 199
Table B-3: Phase Inductance Characteristics 199
Table B-4: DVR Torque - Power - Speed Results 200
Table B-5: Power Factor Measurements (PFC On) 201
Table B-6: Power Factor Measurements (PFC Off) 201
Table B-7: Power Factor Measurement (PFC On) 202
Table B-8: Power Factor Measurement (PFC Off) 202
Table C-1: Capacitive Component Listing 213
Table C-2: Resistive Component Listing 216
Table C-3: Semi-Conductor and Inductive Component Listing 218
Table C-4: Connector Component Listing 218
Table C-5: Capacitive Component Location 220
Table C-6: Resistive Component Location 223
Table C-7: Semi-Conductor and Inductive Component Location 225
Table C-8: Connector Component Location 225
Table C-9: Power NET Designators 225
Table C-10: Additional Connector Information 226
Table C-11: Additional Connector Signals 226