

SEGMENTAL ROTOR SWITCHED RELUCTANCE MACHINES FOR USE IN AUTOMOTIVE TRACTION

James D Widmer

A thesis submitted for the degree of
Doctor of Philosophy



© Newcastle University 2013

School of Electrical and Electronic Engineering

Abstract

This thesis explores the development of the Segmental Rotor Switched Reluctance Machine (SRM) to provide electric vehicle traction. This electrical machine, which has a topology distinct from the conventional SRM and has been previously shown to offer enhanced torque density, is selected based on its potential to offer a low cost, sustainable alternative to today's state-of-the-art electric vehicle traction motors.

With the launch, as long ago as 1997, of the Toyota Prius Hybrid Electric Vehicle and of the more recent Nissan Leaf Electric Vehicle in 2010, volume produced vehicle traction drives are an established reality. However hurdles remain in order to reduce the cost of electric and hybrid electric vehicles so that they become cost-competitive with more conventional vehicles. From an electrical machine perspective, one clear cost driver stands out; the rare-earth metals which form the key ingredient in today's class leading electrical machines. These materials are both expensive ($>100\text{USD/kg}$) and, as was seen in 2011 / 2012, subject to significant price volatility. Equally the mining and refinement of rare-earth materials, such as Neodymium, Dysprosium and Samarium, has been shown to have a much higher environmental footprint than that of the other materials typically used in electrical machines.

Beyond the elimination of rare-earths, the thesis looks to further improve the sustainability and cost of the Segmental Rotor SRM. Copper conductors, expensive and difficult to recycle at an electrical machine's end-of-life, are replaced by more easily recycled aluminium. Aluminium windings are compressed, prior to assembly with the electrical machine, in order to achieve very high fill factors to overcome their relatively low electrical conductivity. Methods are also sought to reduce overall material waste and simplify assembly processes; these include computer based optimisation of the motor structure along with the use of modular manufacturing techniques.

With the Nissan Leaf's Neodymium Iron Boron based Interior Permanent Magnet machine selected as a comparator, an 80kW Segmental Rotor SRM is constructed and tested. The design is shown to have promise and a number of industrially funded follow-on projects are now underway in order to develop the technology further for use in a volume electric vehicle application.

Table of Contents

Abstract	II
Table of Contents	III
List of Figures	XI
List of Tables.....	XXII
Acknowledgements	XXIV
List of Acroynms	XXV
Chapter 1. Introduction	1
1.1 Thesis Objectives	1
1.2 Background	1
1.3 Automotive Traction	2
1.4 Rare-earth and Other Critical Materials	4
1.5 Application of Switched Reluctance Motors to Automotive Traction.....	6
1.6 Traction Motor Design for Manufacture	7
1.7 Goal Driven Optimisation	8
1.8 Thesis Structure	10
1.9 Contribution to Knowledge	12
1.10 Published Work.....	12
Chapter 2. Literature Review	14
2.1 Switched Reluctance Machine History	15
2.2 Segmental Rotor Switched Reluctance Machines	16
2.3 Use of Switched Reluctance Machines for Automotive Traction Applications	22
2.4 Finite Element Based Optimisation of Switched Reluctance Machines	23
2.5 Performance Improvement of Conventional Switched Reluctance Machines .	27
2.6 Efficiency Improvement in Conventional Switched Reluctance Machines	30
2.6.1 Copper Loss Reduction	30

2.6.2	Iron Loss Reduction	33
2.7	Volume Manufacturing Approaches	35
2.8	Literature Survey Conclusions	36
PART 1: STATIC PERFORMANCE OPTIMISATION AND THE BASELINING OF THE SEGMENTAL ROTOR SRM DESIGN		38
Chapter 3. Static Optimisation of Segmental Rotor Switched Reluctance Machines		39
3.1	Segmental Rotor SRM Design Principles	39
3.2	Optimisation Process	43
3.3	Optimisation Results	47
3.3.1	Impact of Optimisation on a Single Machine	47
3.3.2	Optimisation Results for Differing Stator Slot and Rotor Segment Combinations.	51
3.3.3	Dynamic Operation.	54
3.4	Conclusions	58
Chapter 4. Construction of a 12-16 Segmental Rotor SRM and Validation of Static Optimisation		60
4.1	Detailed Design and Construction Process	60
4.1.1	Motor Lamination Design	61
4.1.2	Stator Design and Construction	63
4.1.3	Motor Windings	64
4.1.4	Rotor Support Structure and Shaft Design	66
4.1.5	12-16 Motor Design Parameters	69
4.2	12-16 Motor Testing and Model Validation	70
4.2.1	Pulse Test	70
4.2.2	Static Torque Test	74
4.2.3	Thermal Tests	75
4.3	Conclusions	77

PART 2: DYNAMIC PERFORMANCE OPTIMISATION AND COMPRESSED ALUMINIUM

WINDINGS	78
Chapter 5. Dynamic Optimisation of Outer Rotor Brushless PM Machine for use in a Solar Powered Aircraft.....	79
5.1 Requirements for Electrical Machines for Solar Powered Aircraft	79
5.2 6kW Outer Rotor PM Motor Design	80
5.2.1 Basic Motor Design	80
5.2.2 Pre-Optimisation Study	81
5.3 Optimisation Objective Function	83
5.3.1 Sources of Loss	84
5.4 Optimisation Approach	85
5.4.1 Feasible Motor Design Selection	87
5.4.2 Parameterised Motor Geometry	88
5.4.3 Iterative Winding Current Search Algorithm.....	88
5.4.4 Full Transient Solution and Objective Function Calculation.....	89
5.5 Optimisation Results	90
5.6 Detailed Design and Construction of Optimised Motor.....	94
5.6.1 Mechanical Design.....	95
5.6.2 Winding Design	96
5.6.3 Impact of Detailed Design on Motor Performance	97
5.7 Prototype Test and Validation of Optimisation Findings.....	99
5.8 Motor Mass and Winding Resistance;.....	99
5.8.1 Back EMF Test	101
5.8.2 Dynamo based Motor Efficiency Test	101
5.8.3 Run-Down Tests	103
5.9 Conclusions	105
Chapter 6. Application of Outer Rotor Brushless PM Machine with Compressed Aluminium Windings in solar powered aircraft.....	107

6.1	Aluminium as a Conductor.....	108
6.2	Solar Plane Motor Requirements and Constraints	109
6.3	Selection of Compressed Aluminium Windings	110
6.4	Winding Configuration Selection.....	112
6.5	Compressed Aluminium Coil Considerations	113
6.5.1	Coil Manufacture	113
6.5.2	Stator Design for Compressed Coils	116
6.5.3	Coil Termination	118
6.5.4	Coil Thermal Performance	119
6.5.5	Coil Reliability	121
6.6	Prototype Motor Validation.....	122
6.7	Conclusions	125
PART 3: HYBRID OPTIMISATION OF AN 80kW SEGMENTAL ROTOR SRM WITH COMPRESSED ALUMINIUM WINDINGS.....		127
Chapter 7.	Hybrid (Static / Dynamic) Optimisation of Automotive Segmental Rotor SRM	128
7.1	Nissan Leaf Comparator Interior Permanent Magnet Motor	128
7.2	Basic Segmental Rotor SRM Design Selection	130
7.3	Optimisation Requirements	131
7.4	Limitations of SRM fully Dynamic Optimisation.....	134
7.5	Hybrid Static and Dynamic Optimisation Approach.....	138
7.5.1	Optimisation Process.....	138
7.5.2	Static Prediction of Number of Turns	139
7.5.3	Static Prediction of Peak Torque at Base Speed	141
7.5.4	Dynamic Assessment of Motor Losses	143
7.6	Hybrid Optimisation Results	144
7.7	Finite Element based Validation of Optimisation	146

7.8	Conclusions	150
Chapter 8.	Detailed Design of Automotive Segmental Rotor SRM.....	151
8.1	Limitations of University Dynamometers	152
8.2	Segmental Rotor Detailed Design	152
8.2.1	Limitations of Standard Segment Root Design.....	152
8.2.2	Fir Tree Root base Rotor Segment Fixture	155
8.2.3	Impact of Fir Tree Root on Electromagnetics.....	157
8.2.4	Rotor Support Eddy Current Losses	161
8.3	Stator Detailed Design.....	163
8.3.1	Stator Coreback Design.....	163
8.3.2	Compressed Coil Detailed Design	167
8.3.3	Water Jacket Design.....	172
8.4	Predicted Motor Performance Envelope	174
8.4.1	Predicted Motor Efficiency	174
8.4.2	Thermal Modelling.....	175
8.5	Prototype Safety: Airgap Closure Modelling.....	180
8.6	Final Prototype SRSRM4 Motor Design.....	181
8.7	Conclusions	182
Chapter 9.	Construction of an Automotive Segmental Rotor SRM	185
9.1	Stator Construction.....	185
9.1.1	Stator Laminations	185
9.2	Coil Manufacture.....	187
9.2.1	Tooling	187
9.2.2	Stranded Wire Manufacture	188
9.2.3	Bobbin Winding.....	188
9.2.4	Coil Pressing	189
9.2.5	Coil Assembly with Stator Components.....	194

9.2.6	Stator Assembly into Water Jacket	196
9.3	Rotor Construction	199
9.4	Final Motor Assembly	201
9.5	Conclusions	203
Chapter 10.	Validation of 80kW Segmental Rotor SRM Design	205
10.1	Winding Resistance	205
10.2	Static Flux Linkage / Current Tests	206
10.3	Static Torque Estimation	210
10.4	Static Thermal Testing	211
10.4.1	Thermal Testing 1kW-4kW	212
10.4.2	Thermal Model Validation	212
10.4.3	3kW and 4kW Winding Loss Test Results	216
10.5	Winding Interconnection Thermal Failure	216
10.5.1	5kW Winding Loss Test	216
10.5.2	Failure Investigation and Mitigation	217
10.5.3	Thermal Ageing of Standard Crimp to Aluminium Wire	220
10.5.4	Temperature Gradient between Crimp and Al Wire	221
10.5.5	Composite Crimp and Potted Crimp Performance with 100A	221
10.5.6	Composite Crimp and Potted Crimp Performance with 250A	222
10.5.7	Duplication of 5kW Thermal Test Conditions	222
10.5.8	Thermal Test Failure Conclusions	223
10.6	Motor Rebuild	223
10.7	Motor Test: Optimised Operating Point	225
10.7.1	Dynamic Test Limitations	226
10.7.2	Friction and Windage Tests	227
10.7.3	Tests at 3500rpm, 40Nm	228
10.7.4	Rotor Expansion into Stator Bore	234

10.7.5	Other Qualitative Test Observations	240
10.8	Conclusions.....	241
Chapter 11.	Conclusions	243
Chapter 12.	Future Work	247
12.1	Tata Steel funded Electric Vehicle Motor / Gearbox Project	247
12.2	Technology Strategy Board funded Low Cost Electric Drivetrain (LCED) Project	249
12.3	Technology Strategy Board funded High Density Switched Reluctance Drivetrain System (HDSRDS) Project.....	249
Appendix 1.	Segmental Rotor SRM Parameterisation Script	251
A1.1.	Script File.....	251
Appendix 2.	Fully Pitched 12-16 Motor Drawings.....	278
A2.1.	12-16 Motor Assembly	278
A2.2.	Rotor Laminations	279
A2.3.	Rotor Support.....	280
A2.4.	Stator Laminations	281
A2.5.	Winding Scheme.....	282
Appendix 3.	Motor Run-down Testing	283
A3.1.	Friction and Windage Loss Estimation.....	283
A3.2.	Hysteresis and Lamination Eddy Current Loss Estimation	284
Appendix 4.	Base Speed / Peak Torque Estimation Script	285
A4.1.	Script File.....	285
Appendix 5.	Derivation of Airgap Heat Transfer Coefficient	294
A5.1.	Derivation	294
Appendix 6.	SRSRM4 Motor Drawings	297
A6.1.	Motor Active Assembly.....	297
A6.2.	Rotor Segment	298

A6.3.	Rotor Support.....	299
A6.4.	Stator Wound Tooth.....	300
A6.5.	Stator Intermediate Tooth	301
A6.6.	Aluminium Compressed Coil	302
A6.7.	Winding Scheme.....	303
	References	304

List of Figures

Figure 1-1: Price trends for Light Rare-earth Oxides (LREO) which includes Neodymium and Heavy Rare-earth Oxides (HREO) which includes Dysprosium [23] ..	4
Figure 1-2: Life Cycle Assessment of materials commonly used in electrical machines, showing the high impact of NdFeB compared to other materials.....	5
Figure 1-3: Showing Operation of Segmental Rotor (left) and Conventional SRMs (right) with a single phase energised in the aligned position.	7
Figure 1-4: Showing the different manufacturing design of Toyota (left) and Honda (right) traction motors.	8
Figure 2-1: Standard Switched Reluctance Machine Topology.	15
Figure 2-2: Horst's [38] 2 phase, unidirectional Segmental Rotor SRM.	16
Figure 2-3: Mecrow's [29] Segmental Rotor Switched Reluctance Machines showing (left) a fully pitched machine and (right) a single tooth wound variant.....	17
Figure 2-4: Oyama's [39] SRM showing the construction of the rotor where segments are embedded in an aluminium block.	18
Figure 2-5: Higuchi's stepped Segmental Rotor SRM rotor which reduces torque ripple	19
Figure 2-6: Top: Chen's [44] figure showing the source of flux collisions in even phase number Segmental Rotor SRMs with unipolar excitation. Bottom: Chen's [45] design showing use of 'toroidal' type windings in a Segmental Rotor SRM.....	20
Figure 2-7: Three configurations of Chen's [45] Axial Flux SSRMs	21
Figure 2-8: Vandana 's [46] proposed Circular Slot Segmental Switched Reluctance Machine. Notation XP and XN indicate positive and negative phase windings.RPA and SPA refer to rotor and spator pitch arch respectively.	22
Figure 2-9: Showing Brisset's [60] use of the Design of Experiments method to produce an optimisation solution surface. β_r and β_s are measures of the rotor and stator tooth pitch angle and the solution (indicated as a percentage) is that of the maximum objective function.	24
Figure 2-10: A 12-10 SRM with short flux loops from Pollock and Michaelides [69]..	27
Figure 2-11: Mecrow's [70] SRM with fully pitched windings.	28
Figure 2-12: Jun-Young's [71] SRM with increased airgap surface area	28
Figure 2-13: Higuchi's [72] 'Cylindrical Type' SRM	29
Figure 2-14: Hamdy's [73] rotor design	29

Figure 2-15: Amreiz's Transverse Flux SRM [75], which enabled the use of 55% fill factor hoop windings.....	31
Figure 2-16: Showing Jack's [76] compressed winding as wound and in cross section.	32
Figure 2-17: A comparison between B-H curves for Permendur and a standard electrical steel [77].....	32
Figure 2-18: Lobo et al [80] 3 phase 12-4 SRM winding configuration with leads to unidirectional flux in the complete stator and in rotor coreback. Sections of the stator coreback can be removed as these do not carry flux.....	33
Figure 2-19: Reduction in Iron Losses offered by 10JNEX900 6.5% Silicon Steel [49].	35
Figure 2-20: Honda Modular Stator construction[32] .	36
Figure 2-21: Denso's modular stator using preformed, square section distributed windings [82]. Detail (right) shows the modular coreback.....	36
Figure 3-1: Segmental Rotor SRM with fully pitched windings showing flux paths with the Phase A excited and in the aligned position.....	40
Figure 3-2: Flux plot showing two classes of segmental rotor SRM, with fully pitched windings in (a) the aligned and (b) the unaligned positions and with single tooth windings in (c) the aligned and (d) the unaligned positions.	41
Figure 3-3: Optimisation Process.....	44
Figure 3-4: Parameterised variables varied during Segmental Rotor SRM optimisation. The motor outer diameter is fixed and therefore the tooth tip depth is derived from the other motor variables. Motor stack length is also fixed.	45
Figure 3-5: Showing the difference between 12-8 fully pitched winding Segmental Rotor SRMs before (a. & c.) (from [30]) and after (b. & d.) optimisation. Shown in the aligned position (a. & b.) and the maximum torque position (c. & d.) with a current density of 10A/mm^2 in the active winding. Flux density levels are indicated in stator tooth and coreback.	49
Figure 3-6: Flux per turn vs MMF for unoptimised and optimised 12-8 fully pitched winding Segmental Rotor SRMs; in each case vertical lines indicate MMF for 300W of Copper Loss.	49
Figure 3-7: Torque vs Current Density for unoptimised and optimised 12-8 fully pitched winding Segmental Rotor SRMs, assuming ideal current control.	50

Figure 3-8: Torque vs Copper Loss for unoptimised and optimised 12-8 fully pitched winding Segmental Rotor SRMs, assuming ideal current control.	50
Figure 3-9: Single Tooth Wound Segmental Rotor SRMs with differing slot-segment combinations following optimisation.....	51
Figure 3-10: Showing the comparison between Torque for 300W of Copper Loss for the differing, optimised Fully Pitched (FP) and Single Tooth Wound (STW) Segmental Rotor SRMs and contrasting this with the performance of baseline SRMs. Both modelled and experimental data, where available, are presented. Ideal current control is assumed.	51
Figure 3-11: Fully Pitched Segmental Rotor SRMs with differing slot-segment combinations following optimisation.....	52
Figure 3-12: Showing Torque per Unit Active Mass for each optimised Segmental Rotor SRM. 300W of copper loss and perfect current control are assumed.	53
Figure 3-13: Showing Flux per turn versus MMF for the optimised 12-8 and optimised 12-16 Fully Pitched Segmental Rotor SRMs. Vertical lines indicate MMF for 300W of Copper Loss.	54
Figure 3-14: Torque-Speed and Total Loss curves for 12-16 Segmental Rotor and 12-8 / 12-16 Conventional SRMs (from FE Analysis, excluding friction and windage).	57
Figure 4-1: EDM cut, 50mm stator lamination sub-stack.....	62
Figure 4-2: Rotor Laminations were cut as a continuous ring in order to simplify prototype construction.....	63
Figure 4-3: Showing wound stator with large end windings.	65
Figure 4-4: Finished motor showing winding termination ring.	66
Figure 4-5: Showing construction of rotor with lamination rings being fitted to slotted, aluminium rotor support.....	68
Figure 4-6: Completed rotor after machining to final outer diameter. This figure also shows how the rotor was balanced by fitting additional washers to the end-cap bolts...	68
Figure 4-7: Pulse Generator schematic	70
Figure 4-8: Implemented Pulse Generator	71
Figure 4-9: Experimentally measured Flux Linkage per Phase versus Phase Current and Rotor Angle for the 12-16 Segmental Rotor SRM.....	72

Figure 4-10: Comparing experimental and modelled Flux per Phase data for 12-16 Segmental Rotor SRM in the aligned and unaligned positions over a range of Phase Currents (peak).....	73
Figure 4-11: Comparing experimental and modelled Torque data for 12-16 Segmental Rotor SRM over a range of Phase Currents (peak), assuming perfect current control (experimental results derived from measured flux linkage curves). Static Torque curves are calculated from the experimental data presented in Figure 4-12.	74
Figure 4-12: Comparison of experimental and modelled Static Torque characteristics for 12-16 Segmental Rotor SRM at a Phase Current of 20A, 40A and 60A.	75
Figure 4-13: Results of a thermal test for the 12-16 machine with 5A/mm ²	76
Figure 5-1: Zephyr demonstrator motor with outer rotor and single tooth wound inner stator.....	80
Figure 5-2: Winding prototype used to estimate winding fill factor.....	83
Figure 5-3: Optimisation Processed applied to the Outer Rotor PM Machine.	86
Figure 5-4: An example, fractional model of a 36/40 outer rotor permanent magnet motor.	88
Figure 5-5: Results of the initial optimization runs; the chart compares the results of the optimisation of machines with different slot and pole combinations. Blue line is the iso-line for the best objective function achieved.....	90
Figure 5-6: Results of the final optimisation runs; considering only 36 slot, 40 pole machines, with both 45% copper and 75% compressed aluminium windings. The green arrows link the objective functions of motors with the same geometry but with either copper or aluminum windings. Blue line is the isoline for the best Objective Function achieved. The red circle indicates the previous, best design taken from Figure 5-5.	91
Figure 5-7: Flux plot showing the 35 slot, 40 pole motors operating in the Cruise condition.....	92
Figure 5-8: Showing castellated stator coreback design.	95
Figure 5-9: Showing Rotor Coreback Design with cut-outs to aid magnet location.	95
Figure 5-10: Showing the motor winding configuration for a single phase.	96
Figure 5-11: Constructed 36 slot, 40 pole motor.	98
Figure 5-12: Showing relationship between Winding Mass and Resistance for a Copper Coil. The intersection indicates the only possible solution of winding diameter and length which reflects the experimental observations.	100

Figure 5-13: Motor installed on dynamo test rig	101
Figure 5-14: Measured Torque per RMS Amps versus Prediction.....	102
Figure 5-15: Measured and Curve Fit Speed vs Time data for Rotor Rundown Test with Dummy Stator Fitted.....	104
Figure 5-16: Measured and Curve Fit Speed vs Time data for Rotor Rundown Test with Real Stator Fitted.	104
Figure 6-1: Results of the final optimisation runs; considering only 36 slot, 40 pole machines, with both 45% copper wound and 75% compressed aluminium windings. The green arrows link the objective functions of motors with the same geometry but with either copper or aluminium windings. Blue line is the isoline for the best Objective Function achieved.	110
Figure 6-2: Compressed winding die (left) suitable for compaction of 6 coils simultaneously. Compressed coil fitted to bobbin, pictured with punch above (right).	114
Figure 6-3: Compressed coil showing copper interconnecting leads. Inset shows the level of compression achieved at 250MPa (~2x magnification).....	115
Figure 6-4: Showing the keyed tooth stator coreback, which is castellated, and tooth concept which enables the use of compressed windings.	117
Figure 6-5: Aluminium wound motor during construction showing six coils, assembled with their keyed teeth, attached to the motor.	117
Figure 6-6: Showing (left) cold pressure welded joint between 1.4mm copper and 1.4mm aluminium enamelled wires. (Right) demonstrates the mechanical integrity of the joint.	119
Figure 6-7: Motor coil temperature versus time for Copper and Aluminium stator coils under the same test conditions ($14A_{rms}$ per phase, equivalent to 20Nm motor torque).	121
Figure 6-8: Rear view of the constructed prototype motor with aluminium compressed windings.....	122
Figure 6-9: Comparison between torque versus phase current for copper and aluminium wound motors.....	124
Figure 7-1: The Interior Permanent Magnet Synchronous Motor used by Nissan in the Leaf Electric Vehicle [31].....	129
Figure 7-2: A 12-10, single tooth wound Segmental Rotor SRM.	130

Figure 7-3: Generalised automotive traction torque speed curve showing common operating points.	131
Figure 7-4: Optimisation torque speed envelop and selected optimisation operating point.	133
Figure 7-5: Showing SRM transition between current and voltage control modes. This demonstrates the non-sinusoidal nature of SRM current waveforms.	135
Figure 7-6: Process used to trial fully dynamic optimisation.	136
Figure 7-7: Proposed optimisation process which makes use of both static and transient finite element analysis techniques.	138
Figure 7-8: Representative torque waveform at base speed, peak torque assuming voltage control, optimised winding turns and advance angle.	140
Figure 7-9: Conduction and Advance Angles selected for base speed / peak torque confirmation.	142
Figure 7-10: Comparing the estimated current waveform for the assessment of motor losses during optimisation and a full, ‘bang-bang’ current control waveform for the same operating point.	144
Figure 7-11: Showing optimisation results for the differencing optimisation runs. Blue line is the iso-line for the best Objective Function achieved.	145
Figure 7-12: Phase current waveforms for motor at base speed / peak torque. Phases A, B and C are shown operating together. ‘Phase B Alone’ is operating with phases A and B inactive.	148
Figure 7-13: Torque characteristic for motor operating at base speed / peak torque with voltage source PWM based current control. Individual phase torque characteristics are from a finite element run where only a single phase was active. ‘Sum A, B & C’ is the sum of these three individual torque characteristics. ‘Combined’ is the torque resulting from a finite element run under the same conditions, but will all phases active.	148
Figure 7-14: Segmental Rotor SRM R3-2, resulting from the hybrid optimisation process. Finite element plot shows motor operating at base speed peak torque.	149
Figure 8-1: Showing Maximum Principal Stresses in a standard rotor segment root structure at 12,500rpm. Distortion is shown magnified by a factor of 100.	153
Figure 8-2: Principal stress is defined such that the shear stress on the three principal planes (the planes normal to the principal stresses, σ_1 , σ_2 and σ_3) is zero.	154
Figure 8-3: Showing the variables considered in the optimisation of the fir tree root.	156

Figure 8-4: Showing maximum principal stress in the Fir Tree root at 12,500rpm.....	156
Figure 8-5: Showing the impact of the fir tree root on motor flux linkage - current characteristic.	157
Figure 8-6: Showing the impact of the Fir Tree Root on Motor Torque (calculated from Phi-MMF). Assumes perfect current control.	158
Figure 8-7: SRSRM4 Fir Tree Root design showing Maximum Principal Stress at 12,500 rpm.	159
Figure 8-8 ‘Case 1’ operating point (base speed, peak torque) showing (left) phase current and (right) torque.	161
Figure 8-9 ‘Case 2’ operating point (rated speed, peak power) showing (left) phase current and (right) torque.	161
Figure 8-10 ‘Case 3’ operating point (optimisation condition) showing (left) phase current and (right) torque.	161
Figure 8-11: Plot of magnetic flux density showing show relatively high flux densities are present in the aluminium rotor support. Motor operating at 10,500rpm, 80kW.	162
Figure 8-12: 3D Finite Element analysis of eddy current losses in the rotor support structure.....	162
Figure 8-13: Showing reduced eddy currents in a 2mm rotor support lamination.	164
Figure 8-14: From Chapter 6, showing the keyed tooth stator design applied to an outer rotor permanent magnet machine.....	164
Figure 8-15: New stator core construction concept. Wound tooth is shown left, fitted with transparent coil. Inter-coil segment is shown right.	166
Figure 8-16: Showing line over which B vs distance was plotted for different rotor angles, in order to allow dB/dt to be plotted at different depths in the stator coil.	168
Figure 8-17: Bobbin, die and punch 3D CAD model, shown in section.	170
Figure 8-18: Winding layup onto bobbin.....	171
Figure 8-19: Aluminium coreback prototype with compressed coil.....	172
Figure 8-20: Cut-outs implemented in coreback to prevent slot liner bunching.....	173
Figure 8-21: Water jacket, with the outer jacket shown as transparent (green).....	173
Figure 8-22: Finite element model used for thermal analysis.....	176
Figure 8-23: Lumped parameter model used for thermal analysis.	177
Figure 8-24: Predicted thermal distribution after 60s, Case 1 (2750rpm, 280Nm)	179

Figure 8-25: Temperature at various location of the motor for Case 1 (2750rpm, 280Nm)	179
Figure 8-26: Steady state temperatures in the stator core and rotor at at 10,500rpm, 80kW.....	180
Figure 8-27: Differential thermal expansion of the rotor vs stator at 10,500rpm, 80kW showing resulting closure of the airgap.	181
Figure 8-28: SRSRM4 final design without water jacket	184
Figure 8-29: SRSRM4 final design with water jacket.	184
Figure 9-1: Showing stator laminated stator parts. (Left) is the wound tooth and (right) the spacer tooth part.	186
Figure 9-2: M270-35A bonded lamination stack showing how all motor lamination steel could be cut from a single 300mm by 300mm block.....	186
Figure 9-3: Showing final punch (left), die (bottom) and bobbin (right) set.	187
Figure 9-4: Showing a bobbin wound coil, prior to compression.....	189
Figure 9-5: Coils at three stages of construction (left to right); following bobbin winding, the ‘blank’ following first stage compression and completed coil following final compression.	190
Figure 9-6: Showing how aluminium wire extruded between die tooling under compression.	191
Figure 9-7: The rapid prototyped insert to prevented extrusion of the aluminium wire between bobbin and die.....	191
Figure 9-8: Showing the top insert, used to protect the coil from extrusion between the punch and the bobbin / die.	191
Figure 9-9: Die tooling positioned in 500 tonne press ready for compression. Wire terminations are shown laid flat in specially prepared channels.....	191
Figure 9-10: Punch pressed flat into die under 400 tonnes force. Termination wires remain undamaged.	192
Figure 9-11: Bobbin and Punch removed from die, clearly showing compressed coil and both top and bottom inserts.	192
Figure 9-12: Showing final compressed coil details.	193
Figure 9-13: Showing the cross section of a coil, with the deformed, hexagonal conductors indicating that a very high fill factor has been achieved.	194
Figure 9-14: Slot liner cutting template.	195

Figure 9-15: Wound tooth end-cap insert.	195
Figure 9-16: (Left) wound tooth fitted with slot liner, end cap and compressed coil. (Right) wound tooth assembled with inter-winding teeth in fitment.	196
Figure 9-17: Stator water jacket components: (left) assembled and (right) the inner jacket showing water channels.....	196
Figure 9-18: Stator bore was machined to final dimensions using a milling machine. Picture shows how a 0.25mm step in the lamination stack was reprofiled in this way.	198
Figure 9-19: Stator laminations fitted into inner-water jacket and under test with Baker Instruments motor winding test system.	198
Figure 9-20: Rotor segment shown with stator lamination parts.	199
Figure 9-21: Showing (top right) rotor shaft fitted with aluminium rotor support laminations. (Bottom right) is shown a rotor support lamination, (bottom left) the nut used to clamp the assembly axially and top left the rotor end cap.....	200
Figure 9-22: Rotor support fitted with two rotor segments.	201
Figure 9-23: Showing the segmental rotor fitted to the stator.	202
Figure 9-24: Showing completed 80kW Segmental Rotor SRM mounted on the test rig.	202
Figure 10-1: Showing Experimentally Measured Aligned and Unaligned FLux Linkages for each Phase of Prototype Segmental Rotor SRM.	206
Figure 10-2: Showing Flux Linkage vs Phase Current and Rotor Angle (mechanical degress). This characteristic is the average of the three phase characteristics recorded.	207
Figure 10-3: Comparison of Flux Linkage vs Current plots from Experimental measurements and from 3D Finite Element Analysis.....	207
Figure 10-4: Comparison of Flux Linkage vs Current plots from Experimental measurements and from revised 3D Finite Element Analysis which assumed 0.36mm airgap, 98% lamination stacking factor and reduced material saturation to 98% of previously modelled values.....	208
Figure 10-5: Average Torque vs Peak Phase Current calculated from Flux Linkage for both Prototype Motor and from both baseline and revised 3D Finite Element Analysis.	209
Figure 10-6: Static Torque for different levels of DC phase current. (Solid Lines) are taken from test, (dotted lines) from 3D finite element modelling.	210

Figure 10-7: Thermocouple locations on prototype motor.	211
Figure 10-8: Thermal Test Results compared to Thermal Modelling - 1kW of Copper Loss	213
Figure 10-9: Thermal Test Results compared to Thermal Modelling - 2kW of Copper Loss	213
Figure 10-10: Thermal Test Results compared to Thermal Modelling - 3kW of Copper Loss	214
Figure 10-11: Thermal Test Results compared to Thermal Modelling - 4kW of Copper Loss	214
Figure 10-12: Thermal Test Results compared to improved Thermal Modelling - 2kW of Copper Loss	215
Figure 10-13: Showing damage to the winding interconnections following 5kW winding loss test.	217
Figure 10-14: Wire and Crimp Thermal Test Pieces. (Left) comparing the performance of standard copper, on the left, and composite Al/ Cu crimps. (Right) test piece potted in a high thermal conductivity polyurethane potting compound.....	218
Figure 10-15: Advanced Al to Cu crimp.	219
Figure 10-16: Three thermal tests of the same, standard, copper butt-crimp in each case carrying 100A. (Cycle 1) temperature of new butt crimp, (Cycle 2) butt crimp temperature following one cycle of 200A test, (Cycle 3) butt crimp temperature following two cycles of 200A test.	220
Figure 10-17: Comparison of copper crimp, composite crimp and potted composite performance with 100A input current (3 rd test cycle).	221
Figure 10-18: Comparison of time for copper crimp, composite crimp and potted composite performance to reach 115°C above ambient with 250A input current.	222
Figure 10-19: Repaired Motor Stator showing new winding termination scheme.	224
Figure 10-20: (Left) deformed blue-coloured stator end-cap insert and (right) end-cap inserts being machined away as part of motor repair.....	225
Figure 10-21: Repaired motor on test rig with University developed asymmetric half bridge converter shown in the background.	225
Figure 10-22: Friction and windage from experimental measurement and showing curve fitted estimations of friction and windage components.	227

Figure 10-23: Phase A phase voltage and phase current. The motor is operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.	229
Figure 10-24: Phase C phase voltage and phase current. The motor is operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.	230
Figure 10-25: Phase A phase current and Phase C phase current. The motor is operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.	230
Figure 10-26: Phase A flux linkage versus current (5 electrical cycles) compared to aligned and unaligned flux linkage characteristics; operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.	231
Figure 10-27: Phase C flux linkage versus current(5 electrical cycles) compared to aligned and unaligned flux linkage characteristics; operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.	231
Figure 10-28: Temperature rise observed during Test 2 and Test 3 (see Table 10-5) ..	235
Figure 10-29: Witness marks on rotor and stator following Test 3.	236
Figure 12-1: Rapid prototype of the Tata Steel Funded 30krpm Segmental Rotor SRM and Gearbox.	248
Figure 12-2: 3 Phase Bridge driving a 6 Phase SRM ref [125].	249
Figure 12-3: Showing the distinction between conventional SRM operation (left) and short flux path operation (right) [126]	250

List of Tables

Table 1-1: Comparison between differing types of motor drives for use in transient automotive traction applications [6, 14-19]	3
Table 1-2: Key features of the Nissan Leaf Interior Permanent Magnet Motor	9
Table 3-1: Segmental Rotor SRM slot – segment combinations selected for or excluded from optimisation; only 3 phase machines are considered.	44
Table 3-2: Limits set on parameterised optimisation variables.	46
Table 3-3: 12-8 Segmental Rotor SRM dimensions before and after optimisation.	48
Table 3-4: Total Loss Comparison at 1500RPM, 30Nm.	55
Table 4-1: 12-16 Segmental Rotor SRM Design Parameters	69
Table 4-2: Coefficients from curve fit with 12-16 thermal test experimental data for $5A/mm^2$	76
Table 5-1: A Comparison of materials used by Zephyr and proposed for use as the starting point for optimization of the new Motor.....	81
Table 5-2: Comparing 36 slot, 40 pole motor dimensions for four optimisation runs. ..	93
Table 5-3: Comparing 36 slot, 40 pole data in the Cruise condition.	93
Table 5-4: Table comparing the Take-Off (maximum torque) copper losses between the differing optimised 36 slot, 40 pole motors.	94
Table 5-5: ‘36-40r4 Cu 0.45’ motor windings configuration.	97
Table 5-6: 36 pole, 40 slot motor performance in Take-Off condition pre and post detailed design modifications.....	97
Table 5-7: 36 pole, 40 slot motor performance in Cruise condition pre and post detailed design modifications.	98
Table 5-8: Table comparing test results in the Cruise Condition with the prediction from optimization (please note that speed and torque data is not made available at the request of the client).	105
Table 6-1: Outer Rotor Brushless Permanent Magnet Motor Design Parameters	109
Table 6-2: Winding data for Copper and Aluminium Wound Motors (predicted).	113
Table 6-3: Comparison between performance of prototype aluminium and copper wound motor (results are restated at -50°C ambient, see note).....	125
Table 7-1: Key features of the Nissan Leaf Interior Permanent Magnet Motor [9]	129
Table 7-2: Comparison of Segmental Rotor SRM Designs resulting from a series of five optimisation runs and the Nissan Leaf’s IPM machine	145

Table 7-3: Comparing the results of base speed peak torque (2750rpm, 280Nm) analysis from estimates during optimisation and full 2D FE.....	146
Table 7-4: Comparing the results of analysis of motor performance at 3500rpm / 40Nm from the optimisation process and full 2D FE analysis.	149
Table 8-1: Key conditions for the static mechanical analysis of a standard Segmental Rotor fixing.	153
Table 8-2: Comparing the SRSRM4 design with the optimum SRSRM2 and Nissan Leaf Machines.	158
Table 8-3: SRSRM4 performance at key operating points with final fir tree root. Copper loss stated at winding temperature of 150°C.	160
Table 8-4: SRSRM4 performance at key operating points with final fir tree root. Copper loss stated at winding temperature of 150°C.	175
Table 8-5: Material properties assumed in thermal analysis.....	177
Table 8-6: Thermal performance of the SRSRM4 Segmental Rotor SRM. Maximum temperatures are recorded.	178
Table 8-7: Final 80kW Segmental Rotor SRM Design	183
Table 10-1: Measured Phase Resistance vs Prediction (20°C).	206
Table 10-2: Summary of baseline, measured and predicted copper losses for 280Nm at low speed. Assumes perfect current control with a 180degree conduction angle.	210
Table 10-3: Crimp test conditions.....	219
Table 10-4: Motor phase resistances for repaired motor (20°C).	223
Table 10-5: Results of Motor Tests at 3500rpm, 40Nm compared with modelling.	232
Table 10-6: Airgap closure test cases based on modelling developed in Chapter 8. Design airgap length at 20°C is 0.35mm.....	238
Table 10-7: Comparison between the properties of Stainless Steel and Aluminium for use in a Segmental Rotor SRM rotor support [121].	239
Table 10-8: Airgap closure test cases, contrasting the use of Aluminum and 316 stainless steel in the rotor support. Design airgap length at 20°C is 0.35mm.	239
Table 11-1: Comparison between 80kW Segmental Rotor SRM and the Nissan Leaf's Interior Permanent Magnet Motor.	246
Table A5-2: Calculated Airgap Heat Transfer Coefficients	295

Acknowledgements

I would like to thank the many people who have assisted me in the preparation of this Thesis.

Firstly Barrie Mecrow who not only gave a slightly disillusioned, machine's illiterate industrialist an academic post (enabling this PhD in the first place) but has also tirelessly supported me throughout.

I would also like to acknowledge Andy Steven's role in this thesis. As unofficial mechanical engineering supervisor, he has helped me to understand the intricacies of stress analysis and manufacturing engineering.

Equally it is important to recognise the efforts of Chris Morton, John Bennett, Mingyao Ma and Dave Winterbourne in pulling together the power converter used to support the testing in Chapter 10. This is been a hard task and many hours of labour have gone into making it work.

I would also like to thank Richard Martin, Glynn Atkinson, Chris Spargo and the rest of the Newcastle University machines team for their help and advice throughout. I have learnt a huge amount from all of you.

I would like to thank Chris Manning, Alan Wheatley and Jack Noble for their help in pulling together my three prototypes. I know my crazy design ideas have kept them up nights...

Finally I must also thank my wife Claire and children Oli, Fifi and Benni for allowing me to dedicate four years of my life to this project. Their love and support has made it possible for me to get it done.

List of Acroynms

AC	Alternating Current
BSP	British Standard Pipe
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DC	Direct Current
EDM	Electrical Discharge Machining
EM	Electromagnetic
EMF	Electro Motive Force
FE	Finite Element
HREO	Heavy Rare-earth Ore
ID	Inner Diameter
IEEE	Institue of Electrical and Electronics Engineers
IPM	Interior Permanent Magnet
LREO	Light Rare-earth Ore
MMF	Magneto Motive Force
OD	Outer Diameter
PM	Permanent Magnet
PTFE	Polytetrafluoroethylene
PWM	Pulse Width Modulation
RMS	Root Mean Square
SMC	Soft Magnetic Composite
SRM	Switched Reluctance Machine
STW	Single Tooth Wound
TSB	Technology Strategy Board
VA	Volt Ampere

Chapter 1. Introduction

This doctoral thesis presents work undertaken to develop the Segmental Rotor Switched Reluctance Machine (SRM) for use in an automotive traction application. This chapter outlines at a top level the full list of objectives of the research and then provides more detail as to how each objective has been approached. Details are also provided of the structure of the thesis.

1.1 Thesis Objectives

This project develops the Segmental Rotor SRM technology such that it could be competitive with leading Permanent Magnet traction motor designs. This project focuses on the following objectives:

1. The elimination of critical materials, including rare-earth metals and copper from the electrical traction machine (Section 1.4);
2. To deliver the first objective, the application of a Segmental Rotor SRM topology to automotive traction (Section 1.5);
3. The development of a motor which could feasibly be manufactured in high volumes (Section 1.6);
4. The optimisation of this motor topology to provide performance as close as possible to that of the leading rare-earth permanent magnet motors, with the Nissan Leaf Interior Permanent Magnet motor being used as a comparator (Section 1.7).

Supporting the development of these objectives is also discussion relating to two specific aspects of the development of a highly efficient Brushless Permanent Magnet (PM) motor for an aerospace application. This includes the discussion of the optimisation approach employed, which very much informed that later applied to these Segmental Rotor SRMs. In addition the PM motor's use of compressed aluminium motor windings is discussed. This also leads the Segmental Rotor SRMs development, replacing copper whilst leading to a net decrease in motor mass for no increase in motor winding losses.

1.2 Background

The electrical machine is one of the most significant technologies underpinning the development of the modern world. Today almost all electrical energy [1], worldwide

some 15,000 TWh annually, is developed using electrical generators; 45% of this generated energy is then again converted into mechanical power using electrical machines.

The move to greener technologies has led to a further increase in demand for new, more efficient classes of electrical machines. Bodies such as the United States Department of Energy [2] and European Union [3] have introduced legislation which requires improvements in the efficiency of industrial electrical machines. Equally the growth in energy generation from renewable technologies has led the development of new categories of electrical machines, for example to support generation of energy from wind and wave.

However, demand for electrical machines in the next century is perhaps most likely to be driven by the growth in demand for electrical motors for automotive traction applications. It is predicted [4] that by 2020 there will be annual production of 9 million electric and hybrid electric vehicles, each requiring highly torque dense electrical machines. The International Organisation of Motor Vehicle Manufacturers [5] shows that, in 2011, 80 million vehicles were produced internationally. Should these all become electrified then clearly this category of electrical machine production will take on enormous significance.

1.3 Automotive Traction

Automotive traction is a very different application for an electrical machine when contrasted, for example, with traditional industrial drives. Automotive demands the development of machines with very high torque / power densities and large overload capabilities [6], ensuring small size and low mass whilst offering the expected vehicle performance. Machines must also often have a large speed range in order to be able to provide drive, most often without the assistance of different gearbox ratios, across a vehicle's full operating speed range. These motors are also required to be most efficient in the normal operating regions of the vehicle, which will tend to be at moderate torques across the mid-region of the motor speed range [7].

To date the leading vehicle manufacturers have generally focused on two motor technologies. Induction machines have been seen as a good choice, perhaps due to their familiarity from use in industrial applications; in particular these have been championed

by new car maker Tesla [8]. However the market leader has been the Interior Permanent Magnet motor favoured by vehicles ranging from the Nissan Leaf [9] to GM Volt [10]. Other technologies have also been explored, with Renault using wound rotor synchronous machines in its Fluence [11] whilst Holden investigated use of a Switched Reluctance Motor in its ECOMmodore [12] and Jaguar in its C-X75 concept car [13]. These technologies have been frequently compared [6, 14-19] and their features are contrasted in Table 1-1.

Table 1-1: Comparison between differing types of motor drives for use in transient automotive traction applications [6, 14-19]

Feature	Induction Machine	Permanent Magnet Machine	Wound Rotor Synchronous Machine	Switched Reluctance Machine
Torque Density (active mass)	8Nm/kg (active)	15 to 20Nm/kg (active)	10Nm/kg (active)	15Nm/kg (active)
Peak Efficiency	96%	98%	96%	98%
Drive VA Rating	Drive circa 20% larger than output power	>2 times output power (assuming motor is field weakened)	Close to unity	> 2 times output power
Torque Ripple	Low	Low	Low	> 100% (worst case)
Cost⁽¹⁾	\$144	\$242	\$144	\$74
Other		50kW machine contains circa 1.5kg NdFeB magnet	Slip ring (or contactless system) to rotor is required	

Notes: 1) Material costs only, for a 300Nm, 30kW machine [18].

All of these technologies have both advantages and disadvantages, as listed in Table 1-1, however clearly, from a performance perspective, the rare-earth permanent magnet based machines offer significant torque density advantages. However, even in 2009 when this project commenced, it was clear that the price of the rare-earth elements required by these motors – including Neodymium, Dysprosium and potentially Samarium – was a significant disadvantage. Even at the then price of \$132/kg for Neodymium Iron Boron (NdFeB) magnets [18] this was a significant proportion of the

manufacturing cost of a traction machine. It appears likely from a review of [9, 20] that the magnet content of automotive electrical machines ranges from 1.5kg to 3kg leading to a estimated cost of between \$200 and \$400 per motor. This is a large proportion of the US Freedom Car initiative's target of \$275 [21] for a 55kW electrical machine, making it difficult to see how these machines can be long-term cost competitive.

1.4 Rare-earth and Other Critical Materials

Subsequently the price of Neodymium and, even more so, Dysprosium (used to provide magnets with high temperature coercivity), has fluctuated significantly as shown in Figure 1-1. This price volatility, along with concerns over the security of supply, again with particular reference to the heavy rare-earth Dysprosium, has raised the political awareness of the importance of these materials in the new green economy (for example [22]). Whilst prices have subsequently fallen back from their 2012 highs, they are understood, from discussion with industry partners, to remain at circa \$150/kg (June 2013).

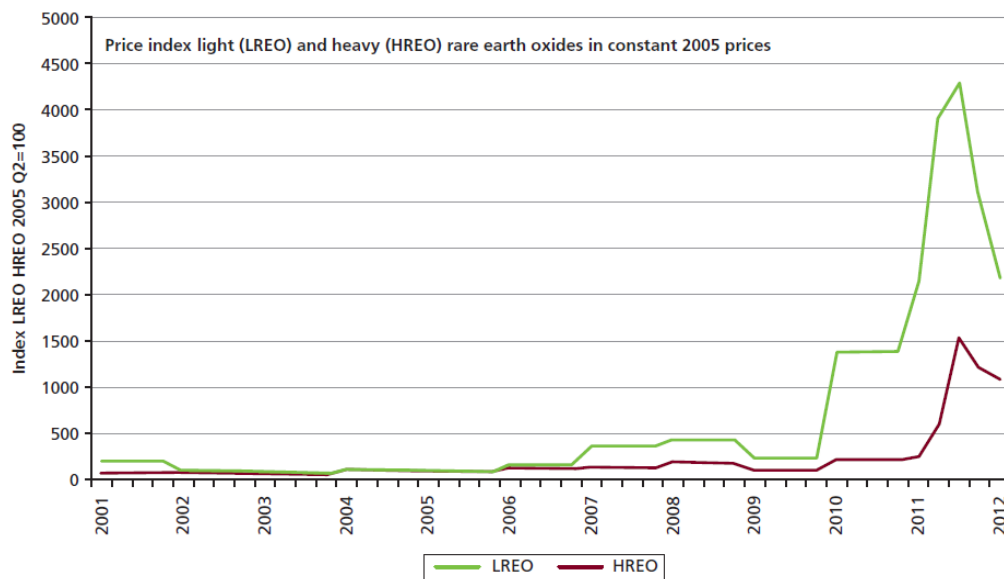


Figure 1-1: Price trends for Light Rare-earth Oxides (LREO) which includes Neodymium and Heavy Rare-earth Oxides (HREO) which includes Dysprosium [23]

However perhaps of greater concern is the environmental footprint of materials such as Neodymium Iron Boron (NdFeB). Figure 1-2 shows the life cycle assessment, a

measure of environmental impact commonly applied by the automotive and other industries, of materials commonly used in electrical machines.

Figure 1-2 shows that by mass NdFeB has a significantly higher environmental impact than the other materials. This, when coupled to concerns about the waste products generated during the extraction and refinement of these materials [24, 25], often in less developed parts of the world, and their local environmental impact makes these material's green credentials somewhat questionable.

As a result the inclusion of rare-earths in the traction motors of electric vehicles does not appear consistent with overall green objectives that have driven the development of the electric car. Therefore it was proposed that this thesis would focus investigation on a technology that would eliminate the need for these magnets.

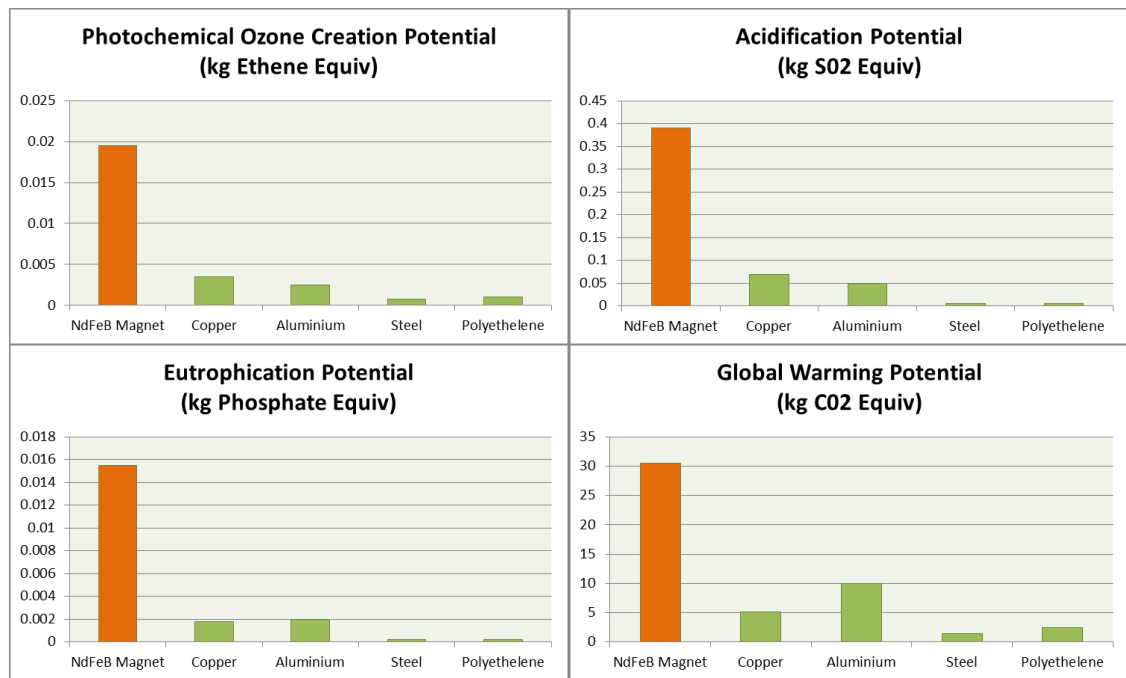


Figure 1-2: Life Cycle Assessment of materials commonly used in electrical machines, showing the high impact of NdFeB compared to other materials¹.

However it is not just rare-earth metals which have raised concern. Copper has also been raised as a potential long term resource security worry [26]. In the shorter term, industrial partners Tata Steel have also raised copper as a limiting factor for the recycling of automotive electrical machines. Copper is a contaminant in the steel recycling process and must be removed from electrical machines in order that electrical

¹ Reference details have been withheld at the request of the provider.

steel laminations be recovered. In modern encapsulated machines this can be a difficult and costly process and therefore the replacement of copper with an alternative material could also be of benefit.

Whilst aluminium had been shown, in Figure 1-2, to have a higher environmental impact per unit mass than copper, its lower mass density is expected to balance this out; aluminium has one third the mass density of copper and two thirds of the conductivity, resulting in about half the mass per unit resistance, as will be seen in Chapter 5.

Aluminium has the further benefit; it has a cost about one quarter per unit mass and one twelfth per unit volume of copper. This thesis would therefore seek also to eliminate copper from the motor design, replacing it with aluminium.

1.5 Application of Switched Reluctance Motors to Automotive Traction

As was discussed previously, there have been attempts to apply switched reluctance motors to electric vehicle traction. However, unlike with other motor technologies, as yet there is no mainstream vehicle which has successfully implemented switched reluctance motor technology. A number of reasons for this have been reported – these have included [6, 14, 16]:

- high torque ripple and acoustic noise;
- difficulties with the relative complexity of the control of these motors, necessitated by their high level of non-linearity;
- the need for these motors to have a drive with a relatively high VA rating compared to other motor types.

It is also suspected that other factors have prevented their uptake, perhaps including difficulties with achievement of the consistently small airgap required for these motors along, simply, with their relatively low power density compared to rare-earth permanent magnet machines.

Newcastle University has a long history of research into these machines, though during the last decade this has tended to be overshadowed with research into the more torque dense permanent magnet motors. In particular, one line of research has been into the Segmental Rotor SRM. This research has demonstrated that these motors could produce significantly higher torque densities than for conventional SRMs [27-30]. The reason

for these higher torque densities is evidenced by Figure 1-3 which shows that, with a single phase energised, twice as many teeth carry flux in a Segmental Rotor SRM as in a conventional machine, leading to a better magnetic utilisation.

A full literature survey is included in Chapter 2; however, at the outset, an initial review of the literature showed that so far no other switched reluctance based technology had shown this level of torque density. As a result these machines were considered a good basis for development as an automotive traction drive and so would form the basis for this project.

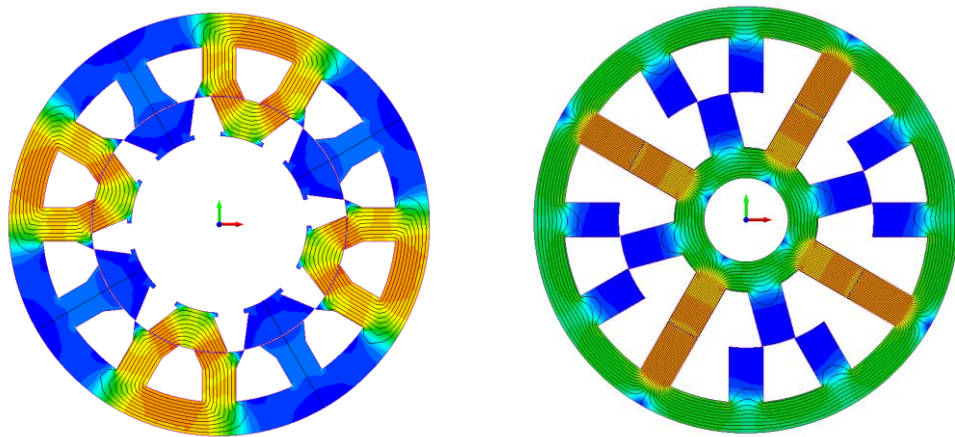


Figure 1-3: Showing Operation of Segmental Rotor (left) and Conventional SRMs (right) with a single phase energised in the aligned position.

1.6 Traction Motor Design for Manufacture

It would appear critical that any motor designed for an automotive application would need to be readily suited to high volume manufacture; it is therefore interesting to note that many leading designs do not appear to be.

For example the electrical machines in the Toyota Prius [20] (Figure 1-4) and Nissan Leaf [31] both include distributed windings and single piece (not modularly constructed) stator laminations, which is likely to be complex and costly. This design is however perhaps applied as it benefits from a high winding factor, with 0.966 estimated.

Other manufacturers, notably Honda [32] (Figure 1-4) and Hyundai [31] have applied techniques which would appear to be more suitable for mass production including the use of single tooth, bobbin wound coils and modular construction; these techniques

appear likely to result in lower cost of manufacture. The downside of this design is that the winding factor would be expected to be lower, estimated at perhaps 0.866, leading to a lower torque density. In fact, perhaps due to this characteristic, it has tended to be the machines with distributed windings, such as that in the Prius and Leaf, which have been seen as the industry leaders.

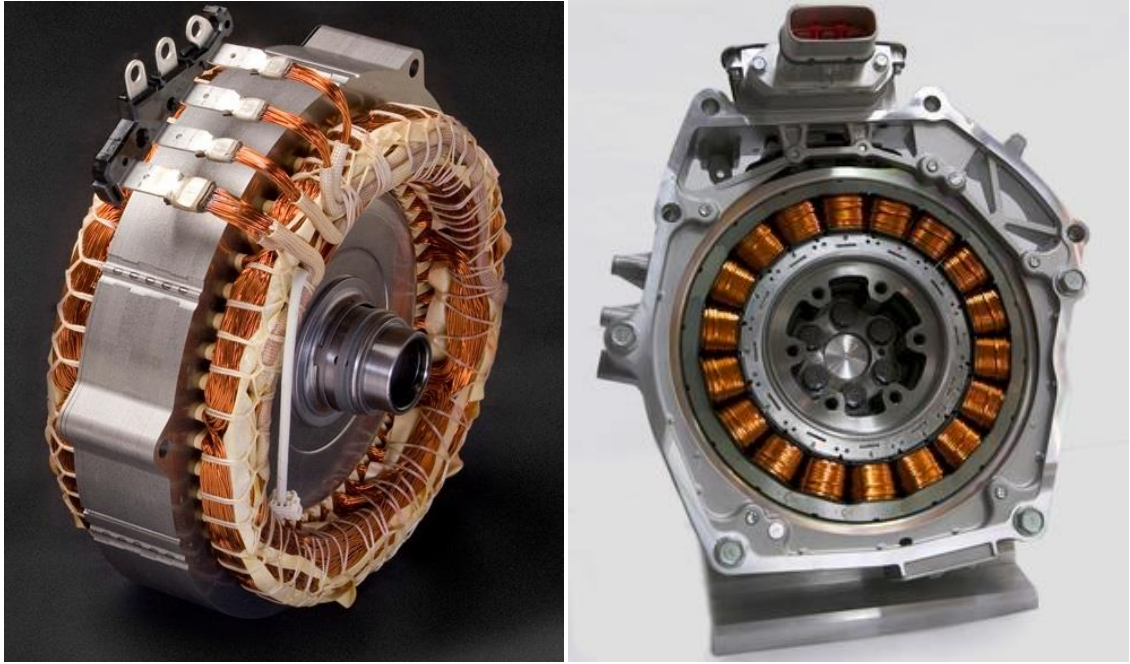


Figure 1-4: Showing the different manufacturing design of Toyota (left) and Honda (right) traction motors.

It was therefore decided that, in the generation of this thesis, best practice design for manufacture, such as applied by Honda and Hyundai should be applied as far as possible in order to develop a motor which it would be feasible to manufacture in large volumes.

1.7 Goal Driven Optimisation

Much research has recently been focused on the finite element based optimisation of electrical machines (see Chapter 2 for details). The process of optimisation has benefits as it allows a very large number of geometrical designs to be considered with minimal user intervention. It also allows an impartial assessment of what the true limits of a certain motor geometry may be, whilst allowing different aspects of an electrical machine's performance to be assessed simultaneously.

Complex optimisation has become considerably more viable over recent years with the exponential growth in computing performance [33] meaning that a finite element solution which would have taken one hour in the year 2000 (when Segmental Rotor SRMs were first researched) would, in 2010, take around ten seconds. This has allowed the use of complex finite element based optimisations to become a realistic prospect.

Electromagnetic optimisation has also been enabled by the widespread availability of validated and stable electromagnetic finite elements software as well as associated optimisation tools. Infolytica's MagNet and OptiNet software packages were available to the author and used as the basis for this work, allowing the focus to be on the objective of the optimisation rather than the mechanics of the process which underpinned it.

For this project it was decided to utilise finite element based optimisation as the tool to develop a Segmental Rotor SRM which closely matched the performance of the Interior Permanent Magnet (IPM) motor found in the Nissan Leaf electric vehicle, details of which are found in Table 1-2.

Table 1-2: Key features of the Nissan Leaf Interior Permanent Magnet Motor

Feature	Nissan Leaf
Motor Type	Interior Permanent Magnet
Max Speed	10, 390 rpm
Max Torque	280Nm (340Arms)
Peak Power	80kW (est. 154kVA)
DC Link Voltage and Current	400Vpk / 500Apk
Peak Motor Efficiency (estimated)	>96% (6.5krpm / 120Nm)
Motor Outer Diameter: Active / with Jacket	200.4mm / 280mm
Length: Active / with Jacket	231.5mm / 300mm
Volume: Active / with Jacket	7.3l / 18.5l
Motor Mass: Active / Complete	32.0kg / 58kg
Power Density: Mass / Volume	2.6kW/kg / 11.0MW/m ³
Torque Density: Mass / Volume	8.8Nm/kg / 38.4kNm/m ³
Mass of NdFeB Magnet	2.0kg

1.8 Thesis Structure

The thesis is structured as follows:

Chapter 2: Literature Survey – this section focuses on the developments in Switched Reluctance Motor technology which will inform the research described in this thesis.

Part 1: Static Performance Optimisation and the Baselining of the Segmental Rotor SRM Design

- **Chapter 3: Static Optimisation of Segmental Rotor SRMs** – this chapter describes how a static optimisation approach was developed and applied to a wide variety of Segmental Rotor SRMs with differing slot and segment numbers and with both single tooth and fully pitched windings. The results of this optimisation process are discussed and further information is provided on the subsequent analysis of these results.
- **Chapter 4: Construction of a 12-16 Segmental Rotor SRM and Validation of Static Optimisation** – following the optimisation undertaken in Chapter 3, a single validation prototype was constructed with a 12 stator slot, 16 rotor segment, fully pitched, Segmental Rotor SRM being selected; the details of this construction are discussed as are the results of subsequent static testing.

Part 2: Dynamic Performance Optimisation and Compressed Aluminium Windings

- **Chapter 5: Dynamic Optimisation of Outer Rotor Brushless PM Machine for use in a Solar Powered Aircraft** – in parallel to the development of the Segmental Rotor SRMs, discussed in this thesis, the author also undertook the design of an Outer Rotor Permanent Magnet Motor for use in a solar powered aircraft. This development is of interest as it led to the development of a new, dynamic optimisation approach which informed that later used in the development of an 80kW Segmental Rotor SRM.
- **Chapter 6: Construction of Outer Rotor PM Motor with Compressed Aluminium Windings** - whilst the use of compressed aluminium windings was first considered for use with the Segmental Rotor SRMs which form the core of this thesis, it was in fact this Outer Rotor Permanent Magnet motor which was first constructed utilising the concept. The chapter therefore discusses the

construction of the prototype machine as it again informed the design of the later Segmental Rotor SRM prototypes.

Part 3: Hybrid Optimisation of an 80kW Segmental Rotor SRM with Compressed Aluminium Windings

- **Chapter 7: Hybrid (Static / Dynamic) Optimisation of Automotive Segmental Rotor SRMs** – building on the work discussed in previous chapters, this chapter discusses an optimisation approach that was developed for the design of an 80kW, Nissan Leaf equivalent Segmental Rotor SRM. This chapter discusses why a fully dynamic approach, as discussed in Chapter 6, was discounted and instead this simplified and more computationally efficient ‘hybrid’ approach developed. Details are provided of the results of the analysis and of the concept subsequently taken forward for further development.
- **Chapter 8: Detailed Design of Automotive Segmental Rotor SRM** – this chapter deals with the detailed design of the selected, 80kW concept. The development of the modular stator construction is discussed, as is the stress analysis of the mechanical fixing of rotor segment to rotor support, which resulted in development of a fir tree root based system. It also includes a full assessment of motor losses and a resulting finite element based thermal modelling of the motor.
- **Chapter 9: Construction Techniques for Automotive Segmental Rotor SRM** – this chapter details the construction of the Segmental Rotor SRM with particular focus on the prototype development of compressed aluminium coils. Conclusions are also reached as to the appropriateness of the prototype construction techniques to mass production of these motors.
- **Chapter 10: Validation of Hybrid Optimisation of Automotive SRMs** – full details of the static and dynamic testing of the motor are provided including details of how these validate the findings of the hybrid optimisation approach.

Chapter 11: Conclusions – conclusions are drawn showing how the Segmental Rotor SRM may form the basis for a valid automotive traction motor; however it outlines the further work which will be required to complete its development.

Chapter 12: Follow-on projects – during the course of this PhD the author has worked with Tata Steel to develop new materials for use in these Segmental Rotor SRMs, whilst also working with two consortia to developed UK Technology Strategy Board (TSB) projects. These projects have focussed on the use of the technologies developed in this thesis for use in both Cummins’ hybrid trucks and in Jaguar Land Rover’s electric and hybrid electric vehicles. Some details of the work being undertaken in these projects is discussed.

1.9 Contribution to Knowledge

This thesis contributes to knowledge in the following areas:

- 1) The design characterisation of the Segmental Rotor SRMs with various stator slot and rotor segment numbers (Chapters 3 and 4);
- 2) Methodologies for the optimisation of Segmental Rotor SRMs (Chapters 3 and 7);
- 3) Development of electrical machines with compressed aluminium windings, including their comparative performance versus conventional electrical machine windings (Chapters 5, 6, 8, 9 and 10);
- 4) Development of a fir tree route based rotor segment fixing solution for use in high power Segmental Rotor SRMs (Chapters 8, 9 and 10);
- 5) Development of a Segmental Rotor SRM prototype suitable for further development for use in an electric vehicle (Chapters 8, 9 and 10).

1.10 Published Work

The following peer reviewed publications and conference papers have stemmed from this research:

- (1) Widmer JD, Mecrow BC. “Optimised Segmental Rotor Switched Reluctance Machines With a Greater Number of Rotor Segments Than Stator Slots.” *IEEE Transactions on Industry Applications* 2013, **49**(4), 1491-1498.
- (2) Widmer JD, Spargo CM, Atkinson GJ, Mecrow BC. “Solar Plane Propulsion Motors With Precompressed Aluminum Stator Windings.” *IEEE Transactions on Energy Conversion* 2014, **29**(3), 681-688.
- (3) Widmer JD, Mecrow BC, Spargo CM, Martin R, Celik T. “Use of a 3 phase full bridge converter to drive a 6 phase switched reluctance machine.” *6th IET*

International Conference on Power Electronics, Machines and Drives (PEMD). 2012, Bristol, UK: IEEE.

- (4) Widmer JD, Martin R, Spargo CM, Mecrow BC, Celik T. "Winding configurations for a six phase switched reluctance machine." *XXth International Conference on Electrical Machines (ICEM)*. 2012, Marseille, France: IEEE.
- (5) Widmer JD, Mecrow BC. "Optimised Segmental Rotor Switched Reluctance Machines with a greater number of rotor segments than stator slots." *Electric Machines & Drives Conference (IEMDC), 2011 IEEE International*. 2011, Niagara Falls, ON.
- (6) Widmer JD, Mecrow BC. "Optimisation of an 80kW Segmental Rotor Switched Reluctance Machine for Automotive Traction." *Electric Machines & Drives Conference (IEMDC), 2013 IEEE International*. 2013, Chicago, IL.
- (7) Widmer JD. "Rotor Manufacturing Challenges: 80kW Segmental Rotor Switched Reluctance Machine," *UKMagSoc Advances in Machine Manufacture*, 2013, Newcastle-upon-Tyne.

Chapter 2. Literature Review

This chapter provides a review of the published research relating to the thesis subject area. The review has two objectives. Firstly to ensure that the research to be undertaken in the course of this project is novel. Secondly to provide an indication of the work undertaken by others that may be worthy of further assessment and extension during the course of the thesis.

This thesis proposes to use the Segmental Rotor Switched Reluctance Machine (SRM) topology in order to achieve a low cost automotive traction drive. However, as relatively little has been written about this type of SRM, it is also appropriate to consider conventional SRMs and even other motor topologies when reviewing the literature. As a result, this review has been undertaken by separating the subject into a number of distinct areas as follows:

- The general history of SRMs to provide a level of context (see Section 2.1);
- A review of the Segmental Rotor SRM design and developments since it was proposed, in its current form, in 2002 (see Section 2.2);
- A review of work undertaken to explore the application of SRMs to automotive traction (see Section 2.3);
- A review of the work undertaken to optimise SRMs using finite element toolsets (see Section 2.4);
- A review of the research to improve the performance of conventional SRMs through architectural changes; this review will ensure that any performance improvements resulting from this thesis are baselined from the state of the art. Changes to conventional machines may also suggest similar approaches which could be taken to improve the torque of Segmental Rotor SRMs (see Section 2.5);
- A review of the work undertaken to improve the efficiency of SRMs (see Section 2.6);
- A review of design innovations aimed at reducing the cost of high volume manufacture in electrical machines (see Section 2.7).

2.1 Switched Reluctance Machine History

The development of the modern switched reluctance motor was enabled by the development of power electronic devices in the 1970s [34]. In 1969 Nasar [35] first coined the term Switched Reluctance Motor to describe a machine whose operation was dependant on the electronic commutation of electromagnets creating torque due to the saliency of the machine's rotor.

Work by Lawrenson [36] and Byrne [37] matured and optimised the basic design of the switched reluctance machine and drive, with the resultant technology described in some detail in Miller's reference text on the subject [34]. This basic design consisted of a stator made up of an even number of individually wound teeth, which may be combined in a number of phase windings, coupled to a rotor generally with a smaller, even number of similarly dimensioned teeth (see Figure 2-1).

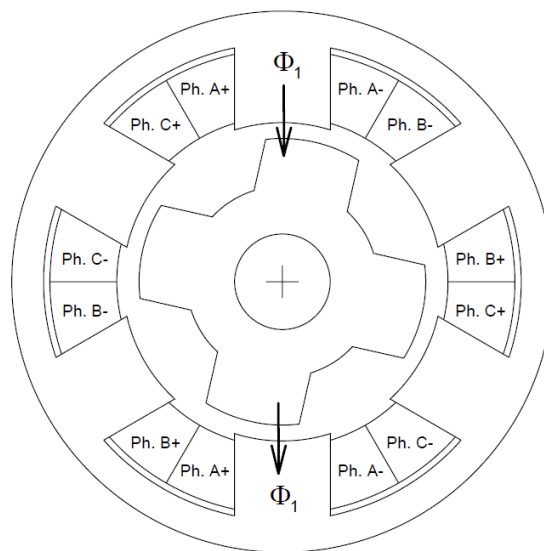


Figure 2-1: Standard Switched Reluctance Machine Topology.

When, for a given phase, stator and rotor teeth are aligned then magnetic flux generated by the coils in that phase is able to link the coil through a low reluctance path around the machine. When, for a given phase, stator and rotor teeth are out of alignment the reluctance of the flux path is much higher.

Torque is therefore generated by applying a DC current to a single phase, which is currently out of alignment with the rotor teeth. The generated flux is therefore initially forced to take the high reluctance path in order to link the coil, however due to flux's

tendency to always seek the lowest reluctance path, a torque is applied to the rotor tooth in order to bring it into alignment, therefore minimising reluctance. In this position the current in the coil is removed, releasing the rotor. This process is repeated for each machine phase, therefore setting up a constant machine rotation.

The non-linear nature of this behaviour, caused by the magnetic saturation of the machine's electrical steel core, means that parametric assessments of SRMs performance can be highly misleading [34]. Instead, assessment of machines performance is generally reliant on the use of electromagnetic finite element modelling; therefore as over time computational speed has increased so has the ability of researchers and designers to investigate new SRM topologies.

A number of drawbacks have been identified with this design of machine. Firstly due to the switched DC nature of the machine, torque ripple tends to be high [34]. Acoustic noise is also considered to be a concern as a consequence of the SRM's high torque ripple and due to its small airgap, which leads to high ovalising forces.

2.2 Segmental Rotor Switched Reluctance Machines

The first proposal to utilise a segmental rotor in a Switched Reluctance Machine was by Horst [38] (Figure 2-2). However this machine was limited to an even number of phases and unidirectional operation.

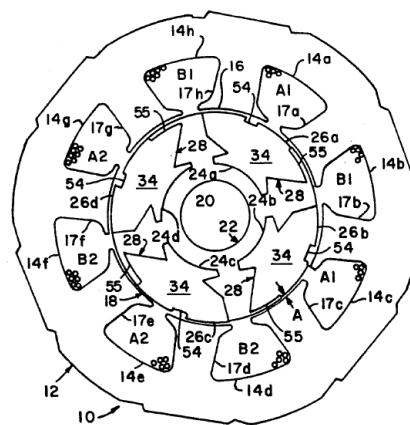


Figure 2-2: Horst's [38] 2 phase, unidirectional Segmental Rotor SRM.

For more general applications Mecrow [27, 29, 30] pioneered the use of Segmental Rotors in switched reluctance machines. The basis of this research was that the conventional SRM rotor design had long been shown not to be the optimum design when used in synchronous reluctance machines and as a result other options should be

explored for SRMs. Mecrow's resulting machines were configured such that up to twice as many stator teeth carried magnetic flux at any one time than in an equivalent conventional SRM, leading to improved magnetic utilisation. These machines were demonstrated in both single tooth pitch and multi-tooth pitched variants (see Figure 2-3) with each variant exhibiting circa 40% increase in torque density over a conventional machine.

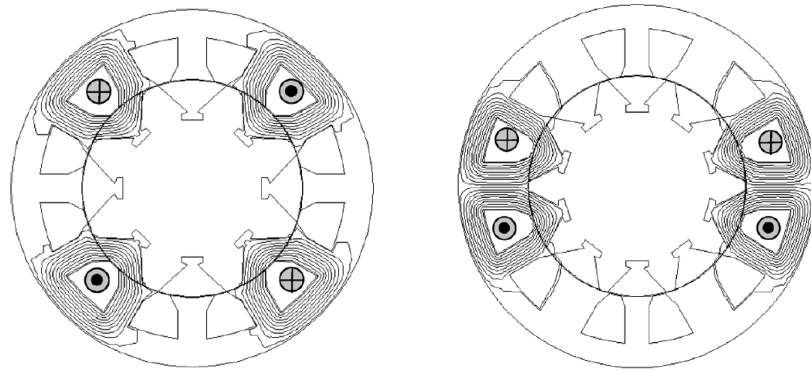


Figure 2-3: Mecrow's [29] Segmental Rotor Switched Reluctance Machines showing (left) a fully pitched machine and (right) a single tooth wound variant.

One of the underlying principles of this unconventional rotor design is that individual laminated rotor segments must be retained by a non-magnetic rotor segment support structure. It is essential that this structure is non-magnetic in order to inhibit flux from flowing between neighbouring rotor segments in the unaligned position. It is also desirable that the rotor support does not impinge on the region close to the airgap as magnetic fields will circulate in this region leading to induced eddy currents and therefore losses in the rotor support.

Oyama [39] extended this concept by improving the manufacturing process applied to the rotor, with the rotor segments being embedded directly in a solid aluminium rotor block (though unfortunately the mechanism of attachment is not explained); see Figure 2-4. This system of rotor construction led to a marginal increase in performance whilst improving the robustness of the machine and its ease of manufacture. Oyama built and tested this machine and was able to develop a substantial body of performance evidence; of most interest being an assessment that the efficiency and power factor of this class of his segmental machine would suffer compared to a standard SRM at higher output powers. However it is also unclear why the width of Oyama's stator teeth is so large compared to that of the stator coreback and rotor segments. Both Mecrow and

Oyama demonstrate that in these machines flux is linked round a single slot which would imply that a constant width flux path encompassing rotor segment, stator tooth and stator coreback may potentially be the optimum design solution. If this methodology were followed then it may be possible to increase the slot area, allowing the use of lower resistance windings and therefore decreasing loss. However it is possible that the wider stator tooth becomes appropriate once more than one phase is conducting simultaneously, as in real operation, where each tooth may need to carry flux from more than one coil.

A further concern with Oyama's design is that the aluminium rotor support impinges into close proximity with the airgap. This could be expected to result in significant eddy current losses in the support, should the support itself not be laminated.

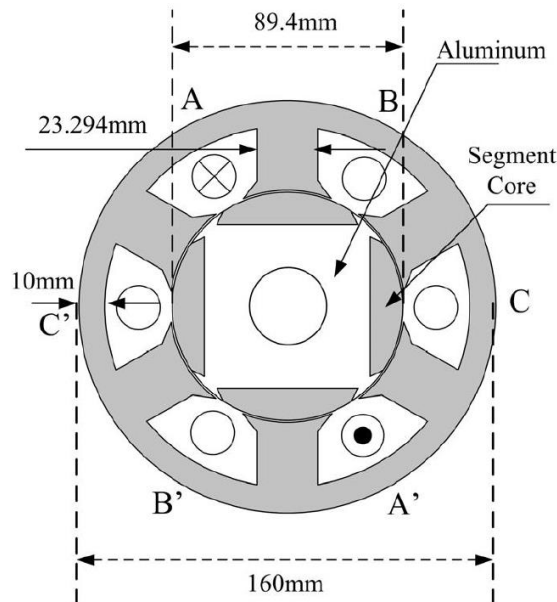


Figure 2-4: Oyama's [39] SRM showing the construction of the rotor where segments are embedded in an aluminium block.

Based closely on Oyama's design, Higuchi [40, 41] has investigated differing methods of reducing the torque ripple in Segmental Rotor machines. He proposes two approaches, firstly in terms of increasing the number of phases. In [40] he reviews the performance of four, five and six phase machines and concludes that the best performance in terms of torque ripple reduction is achieved with a four phase machine – with the additional benefit that an improvement in torque density is also observed with such a configuration.

Two observations are made with regard to this proposal. Firstly, whilst not recognised in his paper, the complexity and cost of a four phase drive will be higher than for an equivalent three phase drive. Secondly Higuchi suggests that a three phase Segmental Rotor SRM's torque ripple is dominated by an effective torque 'stall' between phases; this has not been observed in Mecrow's earlier work [30] or discussed by Oyama [39]. Further assessment however suggests that this is a result of a combination of the inductive profile of the Oyama / Higuchi machine, combined with the control strategy applied by Higuchi which does not appear to support overlap in the conduction between one phase and the next.

In [41] Higuchi proposes the inclusion of a 7° skew in the rotor segment (see Figure 2-5) as an alternative method of torque ripple reduction. He reports that this rotor design indeed resulted in a reduction on torque ripple of circa 20% due to a flattening of the inductance profile of the machine. However there was also a reduction in torque of 10% due to the introduction of the rotor skew.



Figure 2-5: Higuchi's stepped Segmental Rotor SRM rotor which reduces torque ripple

Hall [42] and more recently Nikam [43] have investigated the development of an outer rotor variant of the single tooth wound Segmental Rotor SRM. This design overcomes potential mechanical limitations with high speed variants of this motor topology, where it may be difficult to mechanically retain the rotor segments on an inner rotor due to high centripetal forces. Both papers demonstrate the feasibility of an outer rotor design.

Chen [44, 45] has also reviewed the design of Segmental Rotor SRMs. Both [44] and [45] present an approach for bipolar excitation of Segmental Rotor SRM's with even numbers of phases. This, it is claimed, will avoid flux collisions in the stator teeth

which would result from standard excitation (Figure 2-6). However it is perhaps questionable whether these collisions have a negative influence on motor torque or in fact whether they may reduce magnetic circuit saturation, therefore increasing torque.

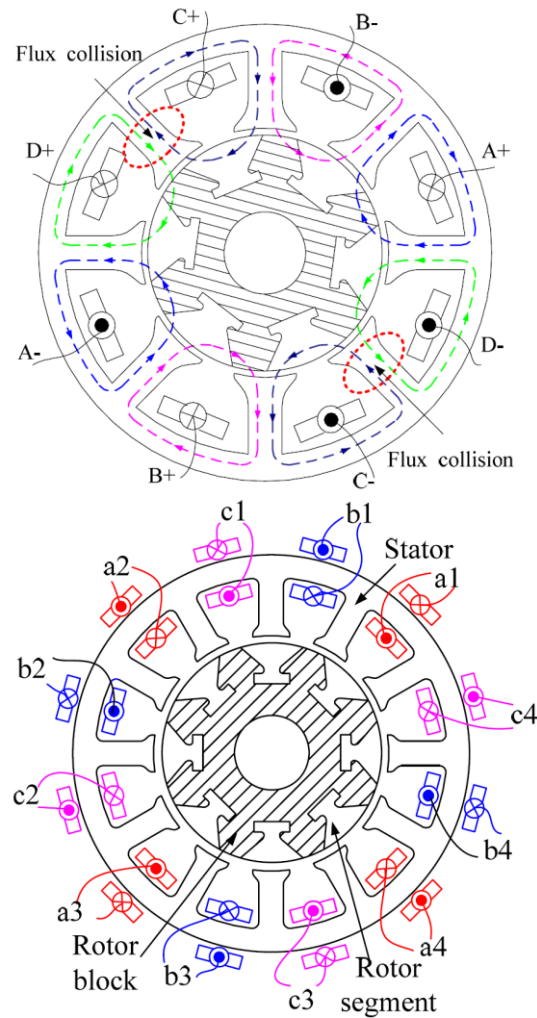


Figure 2-6: Top: Chen's [44] figure showing the source of flux collisions in even phase number Segmental Rotor SRMs with unipolar excitation. Bottom: Chen's [45] design showing use of 'toroidal' type windings in a Segmental Rotor SRM.

In [45], Chen explores a number of alternative segmental topologies which consider the modification of the design to incorporate toroidal type windings. Advantages of these machines are presented as reduced end-winding length, presumably when compared to a fully pitched machine, and fault tolerance, again when compared to a fully pitched machine. However he suggests drawbacks for this machine design which include a

increase in machine diameter. He also suggests that the manufacture of a machine with this winding configuration could be difficult.

Chen, in the same paper, also proposes a series of axial flux machines as shown in Figure 2-7. No modelling or experimental work is reported in respect to these machines, however he suggests that advantages might be simplification of manufacture, full isolation between phases and elimination of cross slot leakage flux. However an observation of these machines designs is that the aligned inductance is likely to be significantly impacted by the reduction in fluxpath area compared to a radial machine of a similar size. In a radial machine the full axial length of the machine contributes to each coil's flux circuit, whereas in Chen's machines only the stator teeth contribute, perhaps in the best case reducing flux path area by 50% and therefore aligned inductance accordingly. In addition the construction of these machines would be made more complex by the need to laminate the machine radially; this issue is however not addressed in the paper.

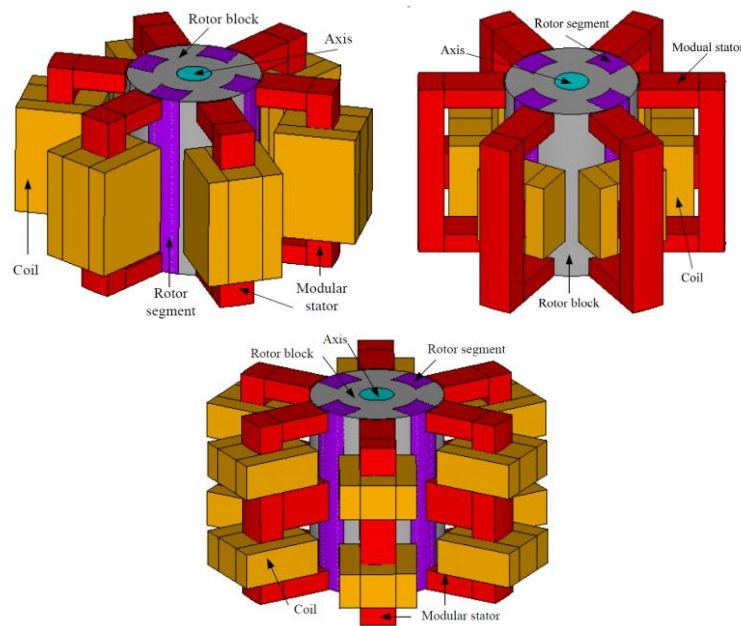


Figure 2-7: Three configurations of Chen's [45] Axial Flux SSRMs

Vandana [46] and Vattikuti [47] confirmed Mecrow's findings related to the improvement in performance of a fully pitched Segmental Rotor SRM over the conventional SRM design. Vandana also proposed a novel design for a Circular Slot Segmental SRM (see Figure 2-8). Claims of performance gains in the order of 30% were made for this design of machine, however it would appear that the underpinning

assessment of these improvements was flawed. Vandana's assessment was based on the torque performance of various machines for a given Magneto Motive Force (MMF). However a review of his proposed design leads to the conclusion that the slot area would be significantly reduced (in the region of 50%) over Mecrow's Segmental Rotor SRM design. This would lead to a large increase in current density and, for a fixed slot fill factor, also result in a large increase in copper losses. It should also be noted that Vandana does not construct a prototype machine and therefore his results have not been experimentally confirmed.

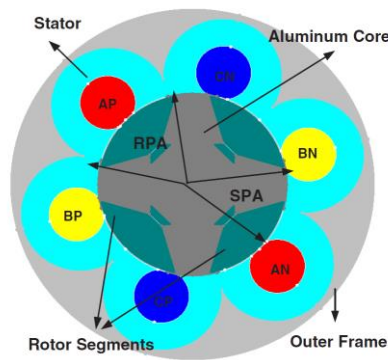


Figure 2-8: Vandana 's [46] proposed Circular Slot Segmental Switched Reluctance Machine. Notation XP and XN indicate positive and negative phase windings. RPA and SPA refer to rotor and stator pitch arch respectively.

In conclusion, a number of authors have worked to extend Mecrow's Segmental Rotor SRM design. However none of these authors appear to have moved the concept forward significantly. This leads to the conclusion that there remains significant room to further research this motor topology.

2.3 Use of Switched Reluctance Machines for Automotive Traction Applications

A number of authors have proposed the use of SRMs for automotive traction applications and indeed the Australian automotive firm Holden's ECOMmodore demonstrator was based on SRMs [48].

Where the use of SRMs has been proposed [15-17, 49-55], in particular the following characteristics have been cited:

- Simple and robust construction leading to low cost and high reliability;

- Low cost due to elimination of permanent magnets;
- Improved performance over induction machines;
- Inherent fault tolerance of conventional SRMs due to the mechanical, electrical and thermal isolation of windings.

However a number of drawbacks with the use of SRMs have also been cited:

- Lower torque density than rare-earth based, brushless Permanent Magnet machines;
- High torque ripple and high acoustic noise;
- Need for ‘specialist’ asymmetric bridge drive.

Three specific traction applications have been addressed in the literature, namely use as part of a hybrid drivetrain [49, 50, 56-58], use as an inboard motor driving through a single speed gearbox and differential (for example) and the use as an integrated in-wheel motor [51-55]).

The most recent development of SRMs for use in electric vehicles has been undertaken by Chiba and colleagues at Tokyo University of Science. In [49] Takano, part of this research group, details a 50kW SRM which is claimed to match the performance of the 2004 Toyota Prius Interior Permanent Magnet motor. This design utilises a special low loss electrical steel, 10JNEX100, more detail of which can be found in Section 2.6.

There have therefore been numerous attempts to develop SRMs for use in electric vehicles. Thus far Holden have come closest to making this a commercial reality, though this was never carried through to production. More recently it would appear that Chiba has been leading the way with SRMs now being demonstrated to achieve PM levels of performance.

2.4 Finite Element Based Optimisation of Switched Reluctance Machines

Much work has been done to investigate the optimisation of the standard SRM geometry, with a well cited paper on the topic being Faiz and Finch [59]. In this paper a number of different parametric approaches to the optimisation of these machines are reviewed and an alternative, model based approach proposed. This approach included the assessment of current density and winding loss when comparing differing machine

designs and also fully considered the non-linear behaviour of SRMs. However this approach relied on the sequential optimisation of differing motor features and assumed that once one variable, for example the tooth width to pole pitch (t/λ) ratio, was fixed then modification of the coreback thickness could be treated as an independent variable; clearly this assumption is not ideal.

Brisset and Brochet [60] extended this approach to consider a Design of Experiments (DoE) based optimisation which considered an optimisation surface (in this case with two variables – rotor and stator tooth width) and then created a solution surface based on these variables (see Figure 2-9). More recently Xue [61] has applied a very similar approach. This process made assumptions about the linearity of motor inductance, however this was overcome through the use of post processing using electromagnetic finite element software.

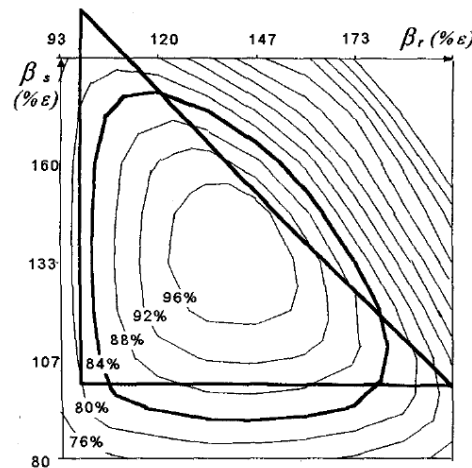


Figure 2-9: Showing Brisset's [60] use of the Design of Experiments method to produce an optimisation solution surface. β_r and β_s are measures of the rotor and stator tooth pitch angle and the solution (indicated as a percentage) is that of the maximum objective function.

A drawback of this DoE approach is that a full solution requires A^k solutions to be run where k is the number of variables and A is the number of discrete steps to be studied. This means that solutions involving large number of variables will be computationally expensive.

More recently Wei, Dunlop et al [62] applied a curve fitting based approach, using the fast 'subproblem optimisation' (implemented in the commercial package Ansys) to provide an initial 'zero order' approximation of the optimum solution and then utilising

the more time consuming ‘first order’ optimisation method to hone in on the optimum solution once the general solution surface had been identified. In this optimisation they assessed eight variables and reported a strong correlation between predicted and constructed motor performance. This was also coupled to a thermal model which assessed whether a winding temperature limit would be breached within a 30 second period. This approach was reported to have been very successful, with a 35% decrease in motor mass achieved. Unfortunately no details on the sensitivity of this optimisation or the time taken to achieve an optimised solution are provided. Also Wei suggests that two point static Φ -MMF characteristic (aligned and unaligned) can be used to assess high speed torque capability, however no explanation is provided as to how this is achieved.

Omekanda [63] also used a Design of Experiments (solution surface mapping) based approach, which applies the ‘Taguchi Robust Engineering Methodology’. This approach is applied in order to minimise the impact of manufacturing tolerances such as airgap length and material B-H curve by seeking a design which is resilient to these factors. This approach also minimises the number of designs to be considered – the design proposed would nominally require the assessment of $2^1 \times 3^7 = 4374$ solutions. However Taguchi is able to reduce this to the assessment of 18 individual combinations of variables, on the assumption that there is a degree of linearity in the solution surface between the selected points. Omekanda provides a sensitivity analysis of the differing motor design parameters and states that this approach resulted in a design which retained all of the features of the baseline but with increased insensitivity to manufacturing factors. However this approach remains limited by the need to consider only discrete values of optimisation variable, so that the number of optimisation steps remained limited to a feasible level.

Sahraroui, Zeroug et al [64] undertook a very similar optimisation to Brissett, focused on maximisation of torque and minimisation of torque ripple for different values of stator and rotor tooth arc. However they applied a neural network in order to allow the assessment of these values as continuous rather than discrete variables. Sahraroui trained the network until the stage that it was able to predict the acceptable outputs based on previously untrained inputs – effectively producing a neural network based

interpolation of the data. The authors reported that this approach led to a reduction in 12% of torque ripple with little impact on average torque.

A few authors have also sought to apply stochastic based optimisation approaches collectively known as ‘evolutionary algorithms’ to SRM optimisation. Naayagi [65] for example compares two approaches, the first using a ‘genetic algorithm’ and the second a ‘simulated annealing’ technique. The genetic algorithm assesses solutions based on their fitness to achieve certain criteria, mimicking Darwin’s evolutionary processes. Only the solutions which present a high value of fitness are then ‘mutated’ into subsequent optimisation steps to see if these mutations will provide a fitter solution. This process continues until a probabilistic global optimum is identified. Simulated annealing is also a stochastic process, however, in this case, as random solutions are generated the optimiser starts the process of narrowing down (annealing) the optimisation design space as more optimum solutions are identified. The second process, simulated annealing, was found to produce the best results. However both benefited from being able to explore large numbers of continuous variables. Phuangmalai [66] also applied a stochastic based optimisation method, the so called ‘particle swarm’ optimisation, in a similar way. Again positive results were reported when seeking to reduce torque ripple, however this was a relatively limited study.

Three optimisation strategies have been assessed and can be summarised as follows:

- **Manual, sequential optimisation** – where a manual sensitivity analysis is undertaken on one variable after another seeking to find an optimum solution. This is time consuming where multiple variables are considered and assumes that variables are to a large extent independent of one another;
- **Design of Experiments** – a solution surface is formed, either by considering all of the possible combinations of variables or by assuming that reductions can be made to the number of solutions with interpolation considered between these points. This solution has been used to good effect but does not allow the use of continuous variables and again makes some assumptions as to the independence of variables;
- **Evolutionary (stochastic) algorithms** – these rely on a random generation of variables covering the complete solution surface; they then apply one of many approaches to narrow down the selection to a global optimum. These approaches

allow many continuous variables to be considered simultaneously, however from a review of the literature, they have yet to be used extensively to optimisation SRMs.

It was therefore decided to use Infolytica's OptiNet optimisation software in support of this project; this tool is based on a simulated annealing process [67] and the above literature therefore confirms this as providing a valid and flexible basis for optimisation.

2.5 Performance Improvement of Conventional Switched Reluctance Machines

A number of authors have sought to develop the conventional SRM architecture in order to improve its performance.

Michaelides [68] firstly proposed that a simple change in winding orientation could significantly improve SRM torque. Should the stator coils be wound such that every alternative stator pole would have opposite polarity then short flux loops would result, rather than the conventional long flux loops normally associated with the SRM. Michaelides reported that an increase of torque of the region of 30% along with decreases in iron loss.

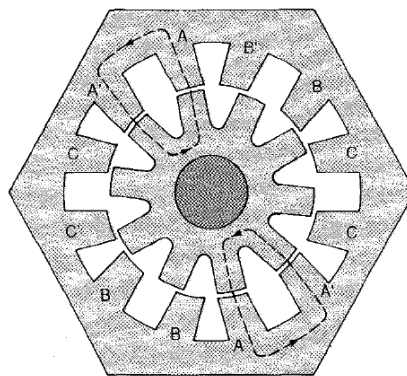


Figure 2-10: A 12-10 SRM with short flux loops from Pollock and Michaelides [69].

Mecrow [70] explored the use of fully pitched windings, as opposed to the single tooth pitched windings of a conventional SRM (see Figure 2-11). This machine operated by using the mutual inductance between phases, rather than the self inductance as in a standard machine. To magnetise a stator tooth current would be supplied to the two

adjacent phases. As a result double the winding area was available to magnetise each tooth, leading to the ability to supply a greater MMF for a given current density and therefore produce more torque per unit current density. In terms of winding loss the length of fully pitched windings is greater than for a conventional machine, however Mecrow still reports improvements in torque density per unit winding loss of circa 30% when compared to a conventionally wound machine.

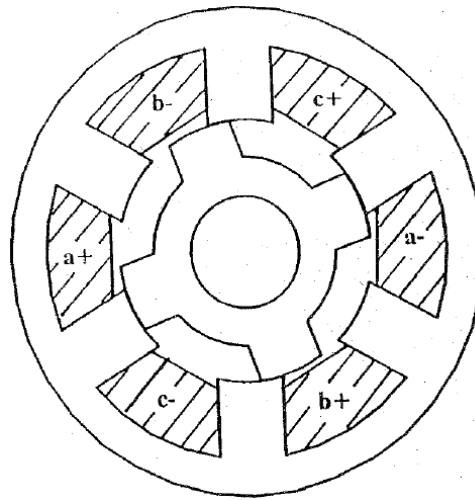


Figure 2-11: Mecrow's [70] SRM with fully pitched windings.

Jun-Young [71] proposed a method of increasing the airgap area, and hence reducing its reluctance, through the use of a stack of laminations of differing sizes for rotor and stator leading to a 'staggered' airgap interface as shown in Figure 2-12. This design therefore increases the ratio of aligned to unaligned inductance and therefore the torque capability of the machine. The drawback of this machine is the complexity of construction; the rotor will not simply slide into the stator as per a standard machine.

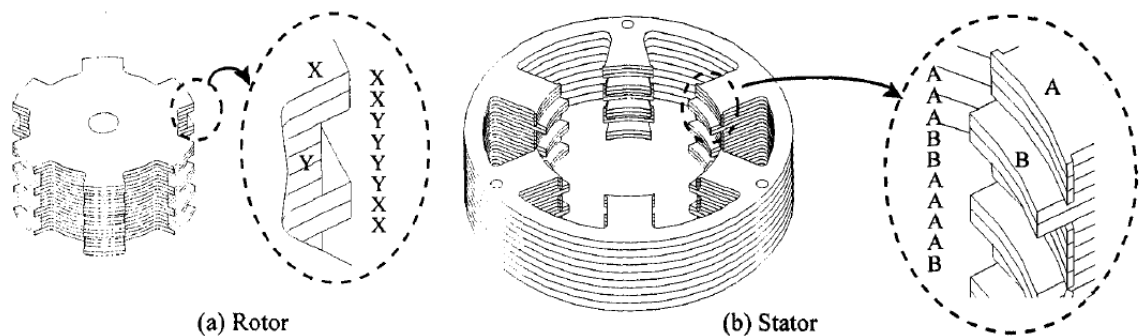


Figure 2-12: Jun-Young's [71] SRM with increased airgap surface area

Higuchi [72] in contrast proposes a mechanism for reducing the unaligned reluctance of the machine as seen in Figure 2-13. The addition of teeth with short circuited windings in the q axis are claimed to counteract the unaligned leakage flux hence reducing unaligned inductance.

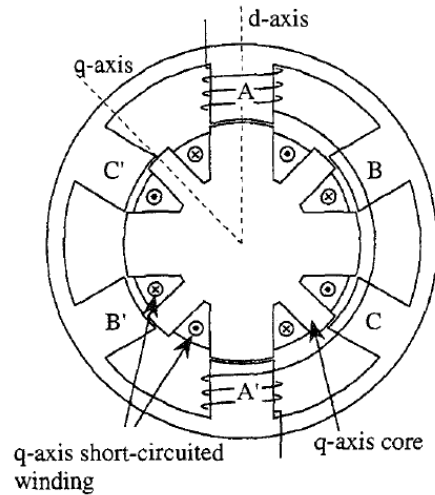


Figure 2-13: Higuchi's [72] 'Cylindrical Type' SRM

Hamdy [73] also proposes a mechanism aimed at increasing the unaligned reluctance of the machine (Figure 2-14).

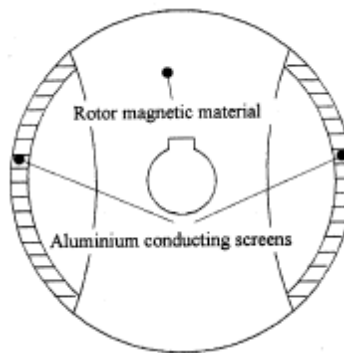


Figure 2-14: Hamdy's [73] rotor design

He proposed the use of aluminium, conducting screens between the rotor teeth which are described as behaving as a flux barrier, with eddy currents being induced in the screen which produce a field which opposes the machine's flux. This effect increases with machine frequency. During high speed operation machine performance is increased due to the reduction in unaligned inductance allowing a more rapid rise in phase current which in turn increases output torque. An increase in machine efficiency

is also claimed at high speed due to the increase in torque per unit iron loss. Mid speed performance is reduced as phase current decreases more quickly, reducing torque production, as the motor back EMF reaches the DC Link voltage.

2.6 Efficiency Improvement in Conventional Switched Reluctance Machines

The improvement of SRM efficiency is focussed on the reduction of losses within this class of electrical machine. These losses can be categorised as follows:

- **Winding Losses** – losses related to the heating of conductors within the motor due to the conduction of current. These can relate both to DC resistive losses as well as AC losses due to factors such as proximity loss, induced eddy currents and the skin effect;
- **Iron Losses** – the losses induced in the magnetic materials (generally electrical steel laminations) due to the time varying magnetic field experienced in the material. These are generally classified as hysteresis loss, eddy current loss and anomalous loss;
- **Mechanical Losses** – due to friction from bearings and windage / churning;
- **Other Losses** – in many machines there are also other sources of loss, frequently relating to induced eddy currents in parts of the motors mechanical structure, such as supporting parts or bearings.

The majority of the work to improve SRM efficiency has focused on the reduction in copper and iron losses in the motor, and as such these are the focus of this section of the literature survey.

2.6.1 Copper Loss Reduction

Generally the approaches taken to reduce SRM winding losses have focused on mechanisms for achieving increased slot fill factor. For example Hayashi [74] shows that a small increase in fill factor from 43.1% to 48.7%, coupled with motor design optimisation, could allow an improvement of SRM motor efficiency of almost 1.5%.

As an alternative approach to increase winding fill factor, Amreiz [75] looked to create a motor topology which could utilise high fill factor (55%) copper hoop windings. The resulting Transverse Flux SRM (shown in Figure 2-15) used a structure that allowed flux to flow around the coil in three dimensions; through a first set of the motor teeth

radially and then axially through the rotor coreback, radially again through a second set of motor teeth and then finally axially through the stator coreback. This required the use in the corebacks of either electrical steel, somehow axially laminated, or alternatively the use of a material such as compressed powdered iron. The constructed motor, which used a combination of laminations and powdered iron, was able to produce 50% additional torque for a given copper loss compared to a conventional machine. However it was criticised for having a high unaligned inductance which would impact on the VA requirements for its power electronic converter.

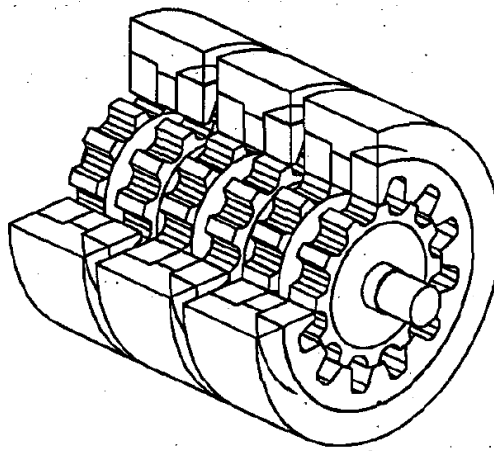


Figure 2-15: Amreiz's Transverse Flux SRM [75], which enabled the use of 55% fill factor hoop windings.

Finally, whilst Jack's [76] work focused on Permanent Magnet Motors, it is also worthy of mention here. Through the development of a process of pre-compressing electrical coils, as part of motor manufacture, it was possible to achieve a very high fill factor of 78% (Figure 2-16).

This process, for a given number of winding turns, allowed a halving of the electrical resistance of the coil and therefore a halving of copper losses. However, in this case, the process was applied to teeth made from Soft Magnetic Composite (SMC) and a technique to allow the fitting of compressed coils to electrical steel teeth would be required in order to apply it to SRMs.



Figure 2-16: Showing Jack's [76] compressed winding as wound and in cross section.

Hasegawa [77] applied the use of novel motor materials in order to reduce copper loss. The use of Permendur (cobalt steel) is proposed which has a both better permeability and higher saturation than for a standard silicon steel (see Figure 2-17). This material therefore reduces copper loss by allowing a reduction in the MMF required to achieve a certain level of flux and therefore torque. Hasegawa found that optimising his machine to make best use of the Permendur material would allow the production of the same torque for a reduction of over 50% in copper loss (though a slight increase in iron loss was also observed). However as cobalt steels contain up to 50% cobalt [78], which has a cost of circa \$30/kg compared to circa \$0.5/kg for steel [79], this would appear to be an expensive option.

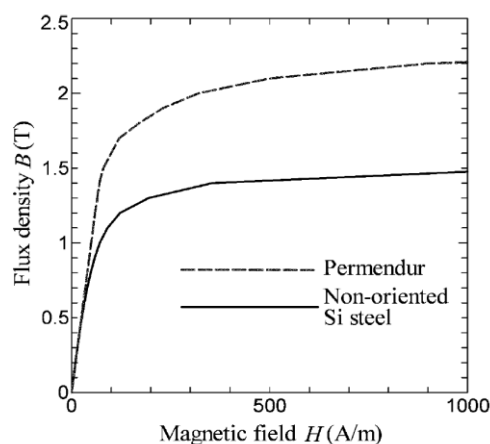


Figure 2-17: A comparison between B-H curves for Permendur and a standard electrical steel [77].

2.6.2 Iron Loss Reduction

Lobo et al [80] recognise that a proportion of the iron loss in SRMs results from flux reversals in both the complete stator and also the rotor back iron (see Figure 2-18). The avoidance of flux reversal in the major components of the motor back iron reduces both hysteresis and eddy current losses. Simplistically, the reduction in both of these losses is related to the reduction in the magnitude of magnetic field variation which is halved as flux travels in only one direction rather than reversing.

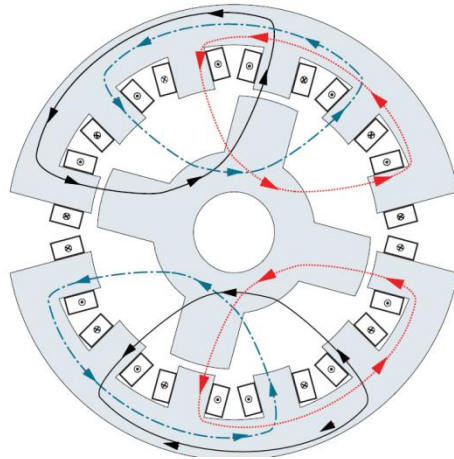


Figure 2-18: Lobo et al [80] 3 phase 12-4 SRM winding configuration with leads to unidirectional flux in the complete stator and in rotor coreback. Sections of the stator coreback can be removed as these do not carry flux.

Lobo prevents flux reversal in the majority of the motor through the use of a specific winding configuration where the windings polarities are arranged N-N-N-N-N-N-S-S-S-S rather than the conventional N-S-N-S configuration favoured in SRMs. This leads to the creation of only two rather than the usual four flux paths when any one phase is energised as is shown in Figure 2-18. This means that rather than the complete coreback carrying 50% of the flux in the teeth, with this configuration 50% of the stator and rotor coreback now carries the same level of flux as the teeth with the remaining 50% carrying no flux. Whilst this leads to a requirement to increase the thickness of the corebacks so that they are of equivalent thickness to the motor teeth as they must carry the same flux, there are now certain sections of the stator coreback which carry no flux and therefore are superfluous and can be removed. This results in a reduction in motor mass. However it would appear that, whilst there was indeed a reduction in motor iron losses (10%), that this motor design also produced less torque for a given motor volume

than for a conventional machines (also circa 10%) leading to no improvement in efficiency.

The research team at Tokyo University of Science have also approached the question of reducing iron loss [49, 56, 74, 81], but from the materials direction.

Chiba [81] has used amorphous iron (iron without the crystalline structure normally associated with a metal) to construct an SRM. Using a glued stack of laminated 25 μ m sheets, an SRM was constructed and compared against a machine manufactured from M300-35 material. The amorphous iron motor showed a reduction in iron loss of some 63%. Further improvements were gained by increasing the copper area through a reduction in the teeth and coreback; this resulted in a 27% reduction in copper losses, though also providing a poor overload capability. Overall these reductions in loss resulted in an improvement in motor efficiency of some 6%, an impressive margin. However drawbacks are that this material is costly to produce and is extremely brittle, making it difficult to stamp in mass production, and would, due to low saturation, have poor overload capability. Equally the likely poor stacking factor achievable with such a thin (25 μ m) material would likely further inhibit its magnetic performance. As acknowledged by Chiba, the first two weaknesses (cost and manufacturability) would need to be addressed before this material became a practical proposition in SRM manufacture, other than for the most specialist and cost insensitive applications.

Hayashi and then Takano [49, 56, 74] have investigated the use of steel producer, JFE Steels' 10JNEX900 6.5% silicon steel material. They found that the use of this material reduced iron losses by a factor of about 60% (Figure 2-19); however it should be noted that other optimisations had also been made to the motor design and so the reduction in losses may not be totally attributable to the material. Drawbacks of this material are its low permeability and early saturation, however these are reported as not outweighing the material's low iron loss. Whilst this material is again more expensive than for a conventional Si steel (the paper indicates a three fold increase in cost), its use is much more realistic than for amorphous iron.

In both of these cases the authors have proposed that the use of a lower loss material allows, through a process of optimisation, a reduction in the thickness of coreback and

teeth. They acknowledge that this will increase saturation (and hence reduce overload capability) but, for the chosen operating points, will lead to better efficiency overall.

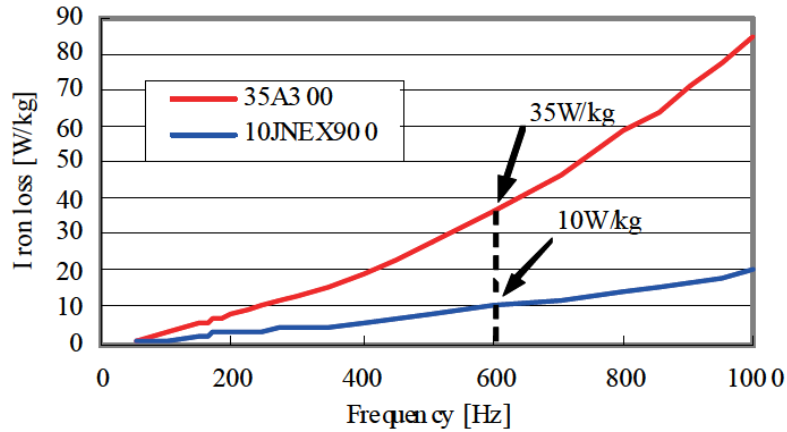


Figure 2-19: Reduction in Iron Losses offered by 10JNEX900 6.5% Silicon Steel [49].

2.7 Volume Manufacturing Approaches

As was seen in Chapter 1 (relating to Toyota Prius [20], Nisan Leaf [9] and GM Volt [10]) even in the automotive industry electrical machines are often manufactured based on traditional principles. Single piece stator laminations are stamped, stacked and then wound with a similar process applied to the manufacture of the rotor. Honda [32] and Hyundai [31] have, however, applied an approach which appears to be more in line with the modular, low cost manufacturing process that might be expected in a high volume, low cost manufacturing environment. Both companies utilise segmented, modular stator corebacks with bobbin wound coils (see Figure 2-20).

Equally Japanese manufacturer Denso [82] appears to be applying a more modular approach to stator construction (Figure 2-21). In this case segmented stator laminations are again used, this time with preformed, square section distributed windings; allowing a better winding factor than could be achieved with single tooth windings. However, given the large size of the conductors, this design would appear to be prone to proximity and induced AC winding losses should the motor operate at higher frequencies. Equally, where an SRM is used, distributed windings are not generally applicable; however this does demonstrate that the next generation of electric vehicle motors may be designed with low cost manufacture in mind.

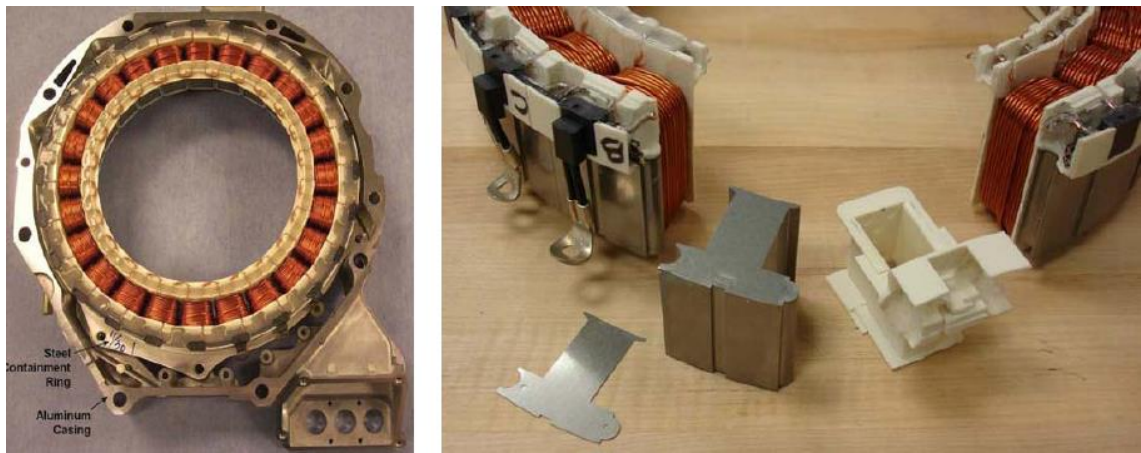


Figure 2-20: Honda Modular Stator construction[32] .

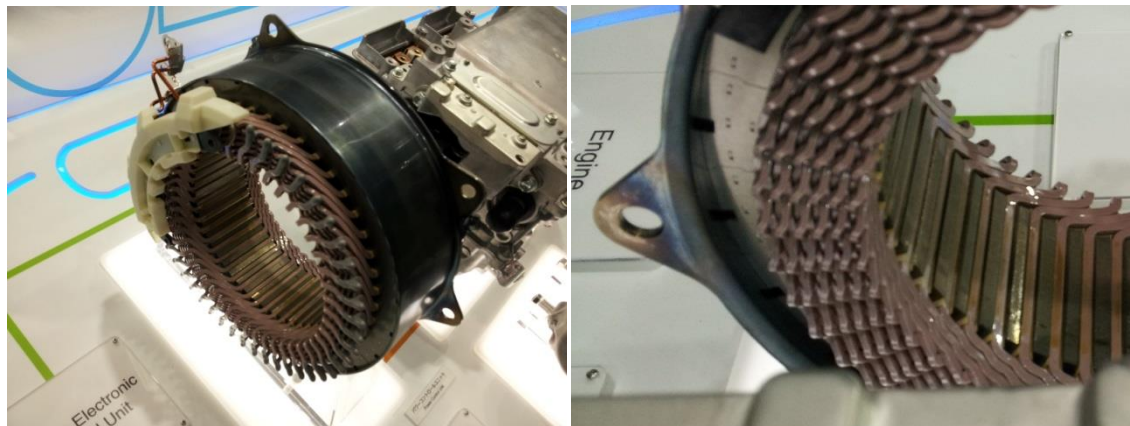


Figure 2-21: Denso's modular stator using preformed, square section distributed windings [82]. Detail (right) shows the modular coreback.

Finally, from an industrial perspective, there appear to be numerous patent applications covering different methods of stator coreback segmentation, for example [83-85].

Far less work appears in the academic literature relating to the manufacturing design of electrical machines. As exceptions, Mecrow, Jack and Haylock [86] investigated the use of a split stator coreback which would allow pre-wound coils to be fitted prior to manufacture. Equally, as has already been seen, Jack [76] developed a process for using compressed coils with soft magnetic composite teeth.

2.8 Literature Survey Conclusions

This literature survey has considered a broad range of topics which are relevant to the development of this doctoral project.

The review of work into Segmental Rotor SRMs has shown that there remains significant potential in the development of these machines. In particular their use as a

replacement for an Interior Permanent Magnet motor, such as that used in the Toyota Prius and Nissan Leaf, has not yet been considered. Whilst Chiba's work at the Tokyo Institute of Technology has been highlighted as providing a conventional SRM with performance equivalent to the motor used in the 2004 Prius, this does not invalidate the development of the potentially more torque dense Segmental Rotor SRM, also for use in this application.

The assessment of finite element based optimisation techniques has demonstrated that the Infolytica OptiNet tool, based on the use of an evolutionary optimisation technique, is likely to be valid.

In addition, a number of methods applied to conventional SRMs in order to improve their performance has been studied, with particular focus on improvements in machine efficiency and therefore on the reduction of copper and iron losses. This has led to the conclusion that the use of high fill factor windings and thin gage electrical steels is worthy of further analysis. Finally the current state of the art in terms of automotive electrical machine design for manufacture has been investigated; in particular the development of a segmented stator design appears to be noteworthy.

**PART 1: STATIC PERFORMANCE OPTIMISATION
AND THE BASELINING OF THE SEGMENTAL
ROTOR SRM DESIGN**

Chapter 3. Static Optimisation of Segmental Rotor Switched Reluctance Machines

Chapter 2 described how Segmental Rotor Switched Reluctance Machines have been shown, due to their intrinsically higher magnetic utilisation, to have the potential to produce significantly more torque than Conventional Switched Reluctance Machines. It has also shown that, in previous published research, the range of topologies studied has been relatively restricted; in particular there has been no consideration of the range of options in terms of stator tooth and rotor segment numbers. Equally the designs have not been formally optimised in any way. As these machines are relatively new and therefore incompletely understood, it was decided that effort should be made to benchmark their performance through the development of a number of optimised reference designs.

The aim of this chapter is therefore to better characterise this class of machine. A process of optimisation using static, 2D finite element analysis is undertaken in order to compare differing motor designs. Using finite element based optimisation, the credible tooth and segment options were assessed, with each option optimised to maximise torque capability. This chapter describes the resulting machines and shows how, at the chosen operating point, those with a greater number of rotor segments than stator teeth offer the highest torque densities. Conclusions are presented which contrast each machine's performance, based on criteria including torque production and loss.

In order to validate this optimisation process, a prototype machine is built and its performance compared with these predictions; whilst details of some of these experimental results are presented in this chapter, full details of the construction and test of the prototype machine are presented in Chapter 4.

This chapter is based on a journal paper by the author which can be found at [87].

3.1 Segmental Rotor SRM Design Principles

As has been discussed in Chapter 2, the Segmental Rotor SRM replaces the conventional toothed rotor with a rotor comprising of a number of separate, magnetically isolated segments. A general schematic is presented in Figure 3-1.

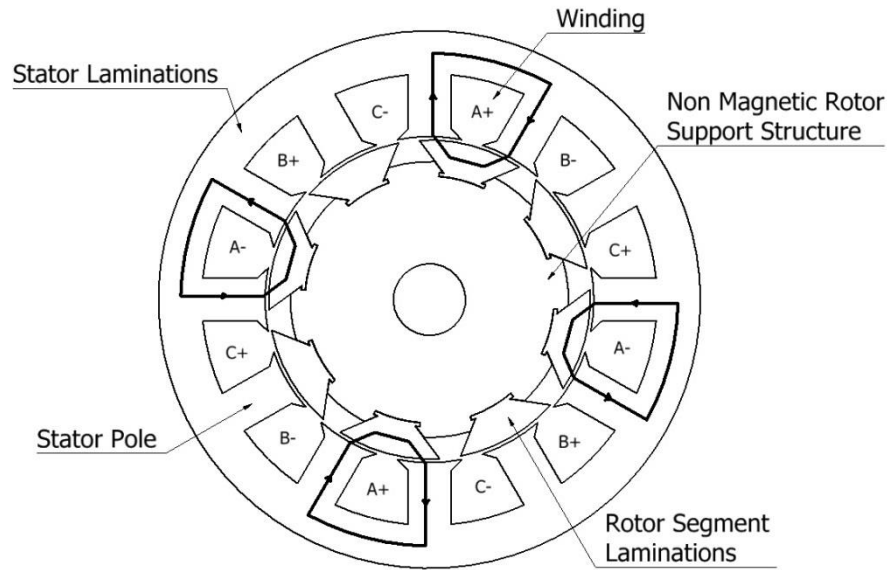


Figure 3-1: Segmental Rotor SRM with fully pitched windings showing flux paths with the Phase A excited and in the aligned position.

Two types of 3 phase, radial flux, Segmental Rotor SRM are considered: those with fully pitched windings and those with single tooth windings. Whilst there are differences between the designs of these two types of machine, the fundamental operation of both machines is the same. In the aligned position the rotor segment provides a magnetic short circuit across a stator slot. Conversely in the unaligned position the rotor segment is positioned clear of the stator slot opening. This is shown in Figure 3-2.

Work undertaken by Mecrow et al. [27, 30] suggests that a number of design rules be followed, common to both winding configurations. Firstly the width of the stator slot opening should be equal in length to the gap between neighbouring rotor segments; this ensures that the unaligned flux-path ‘airgap’ is maximised whilst also ensuring maximum overlap between the stator tooth and rotor segment in the aligned position. Secondly, as can be seen from the flux plots in Figure 3-2, maintaining an even width of flux path through stator tooth, stator core back and rotor segment is desirable in order to maintain an even level of magnetic saturation. For the single tooth wound machine, this results in an alternatively double width wound tooth and single width unwound tooth.

As with conventional SRMs, it is desirable to minimise the air-gap length in order to maximise the aligned inductance.

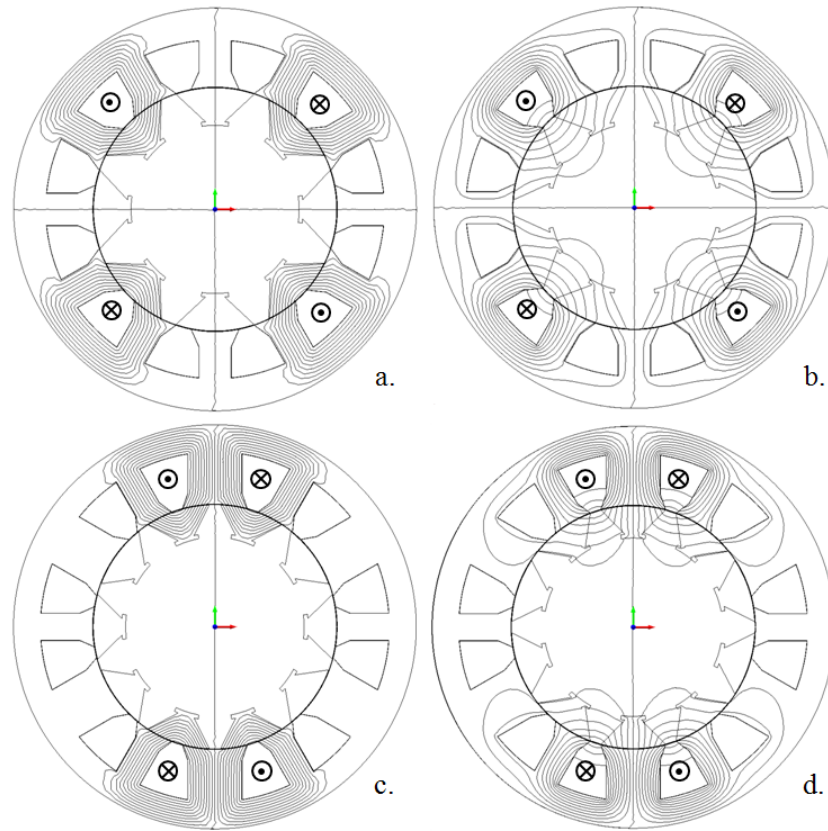


Figure 3-2: Flux plot showing two classes of segmental rotor SRM, with fully pitched windings in (a) the aligned and (b) the unaligned positions and with single tooth windings in (c) the aligned and (d) the unaligned positions.

For both types of Segmental Rotor SRM, the number of rotor segments and stator slots, along with the overall dimensions of slot and segment, need to be carefully controlled in order to ensure correct ‘commutation’ between phases. The slot / segment combinations are also affected by the choice of winding pitch, with fully pitched and single tooth wound variants requiring different combinations.

Mecrow and El-Kharashi’s [28, 30] work on fully pitched machines dealt primarily with a 12-8 fully pitched and 12-10 single tooth wound machines. However, it is possible to develop rules which define the allowable tooth and segment combinations for both types of machine.

For example, for a 3 phase, fully pitched machine it has been found that the basic stator slot - rotor segment combinations are either $6.x-4.x$ (indicating $6.x$ Stator Slots and $4.x$ Rotor Segments) or $6.x-8.x$ series, where x is an positive integer number. This finding is underpinned by a number of rules as follows:

- An even, integer number of slots per phase are required in order to provide a flux return path;
- In order to ensure that the machine is magnetically balanced, there must therefore also be an even number of rotor segments such that each slot of a given phase will be simultaneously, magnetically short circuited by its own rotor segment;
- In order that the machine produces rotational torque as current is commutated between phases, the number of rotor segments may not be an integer divisible by the number of motor phases;
- A number of other configurations fail to meet Mecrow's design rules described earlier. For example, again considering a 3 phase machine, in the case of $2.x$ rotor segments the rotor segment pitch becomes much larger than the pitch of one stator slot, meaning that it will bridge more than a single slot. In the case of the $14.x$ rotor segment design, if the gap between rotor segments is maintained equal to that between stator tooth tips then the segments become too narrow to allow a reasonable aligned flux path. In these cases, whilst the designs may produce positive torque, they no longer exhibit the design attributes of a segmental rotor SRM and therefore are excluded.

Similarly for a 3 phase, single tooth wound machine, combinations of either $6.y-5.y$ or $6.y-7.y$ series, with y being a positive, even, integer number, are appropriate. In this case the following rules apply:

- An even, integer number of slots per phase are required in order to provide a coil return path;
- Combinations with y being an odd, integer number are discounted due to their inherent magnetic asymmetry and the effect this could be expected to have on the motor's mechanical reliability due to unbalanced magnetic pull;

- In order that the machine produces rotational torque as current is commutated between phases, the number of Rotor Segments multiplied by 2 cannot be integer divisible by the number of motor phases;
- As with the fully pitched design, certain other combinations are not considered as these breach the basic design rules. These includes the rotor segment numbers not otherwise excluded and greater than 7.y; again this is to avoid the segments becoming too narrow to allow a reasonable aligned flux path.

These rules therefore limit the possible combinations of slots / segments which can be considered during the design of the Segmental Rotor SRM. As a result the performance benchmarking of these machines can be achieved through the use of a formal optimisation process, focussed only on these allowable machine designs, but allowing a complete assessment of the motor design space.

3.2 Optimisation Process

Based on the survey of motor optimisation work undertaken by others (Chapter 2, Section 2.4), a very powerful optimisation approach is the use of electromagnetic finite element modelling when coupled with an evolutionary algorithm based optimiser.

This proved to be an ideal situation as Infolytica's MagNet and OptiNet software packages, available to the author, had been designed to support motor optimisation based on these principles. This software package features a scriptable and paramaterisable toolset, allowing rapid assessment and optimisation of differing design options. The optimisation approach implemented in the package is based on the use of an Evolutionary Strategy Algorithm, details of which can be found in [67]. The Evolutionary Strategy Algorithm is based on a simulated annealing process, where an initially stochastic search is iteratively constrained (annealed) to narrower bounds as areas of likely optima are identified.

The process of optimisation employed is summarised in Figure 3-3.

Key machine dimensions (stator active diameter of 150mm, active length of 150mm, air-gap length of 0.3mm and winding fill factor of 0.40) were fixed for each case, allowing ready comparison with prototype SRMs previously constructed at the university. The rules, described in Section 3.1, which describe the acceptable stator tooth and rotor segment combinations were applied to eliminate any unworkable motor

geometries, as shown in with Table 3-1. It should be noted that whilst 24 slot fully pitched machines were considered, the later assessment of the optimised designs of these machines (see Section 3.3.2) showed both that they suffered from very small (and therefore difficult to manufacture) rotor segment sizes whilst offering no performance improvement. On the basis that the same weaknesses would be expected with 24 slot, single tooth wound machines, it was decided not to proceed with their optimisation.

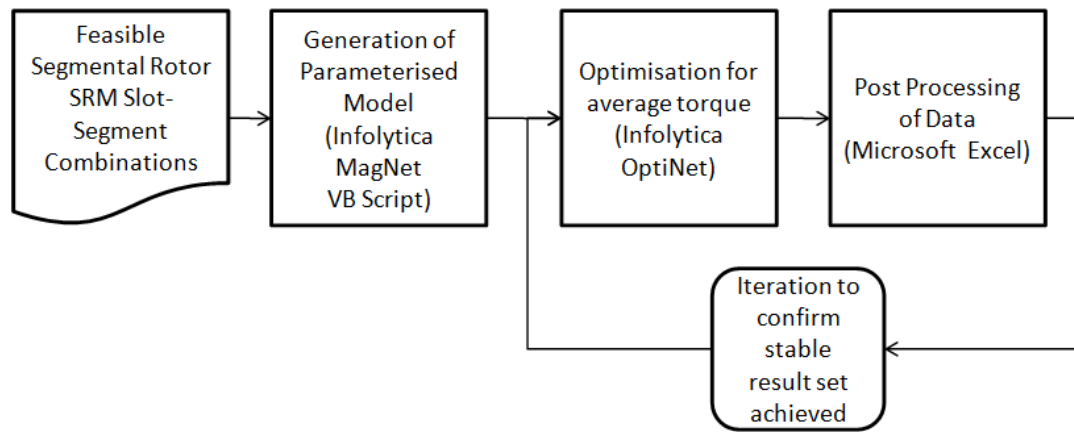


Figure 3-3: Optimisation Process

Table 3-1: Segmental Rotor SRM slot – segment combinations selected for or excluded from optimisation; only 3 phase machines are considered.

Slot Number	Fully Pitched	Single Tooth Wound
6 Slot	6 Slot – 4 Segment	<i>Excluded due to unbalanced</i>
	6 Slot – 8 Segment	<i>magnetic pull</i>
12 Slot	12 Slot – 8 Segment	12 Slot – 10 Segment
	12 Slot – 16 Segment	12 Slot – 16 Segment
18 Slot	18 Slot – 12 Segment	<i>Excluded due to unbalanced</i>
	18 Slot – 24 Segment	<i>magnetic pull</i>
24 Slot	24 Slot – 16 Segment	<i>Excluded due to small</i>
	24 Slot – 32 Segment	<i>feature sizes</i>

A Visual Basic script front-end was developed, based on the design rules outlined in Section 3.1. This allowed the rapid generation and geometric parameterisation of finite element models featuring differing stator slot / rotor segment combinations and winding

configurations (single tooth and fully pitched). A later version of this script, generated in support of Chapter 7, can be found in Appendix 1.

During optimisation the dimensions shown in Figure 3-4 were varied continuously between fixed limits, with these being set individually for each machine optimised; Table 3-2 summarises the bounds for each variable. These limits were set such that the scope of the overall optimisation would be constrained only to realistic geometries. For example, where interdependence between two variables could lead to geometric overlaps, limits were set to avoid this. Within these bounds, the optimisation was allowed to vary each variable continuously, considering all possible combinations of dimensions. In order to avoid the risk of an outlier result skewing the results set, optimisation was repeated three or more times, with differing starting conditions, until acceptably consistent results were achieved.

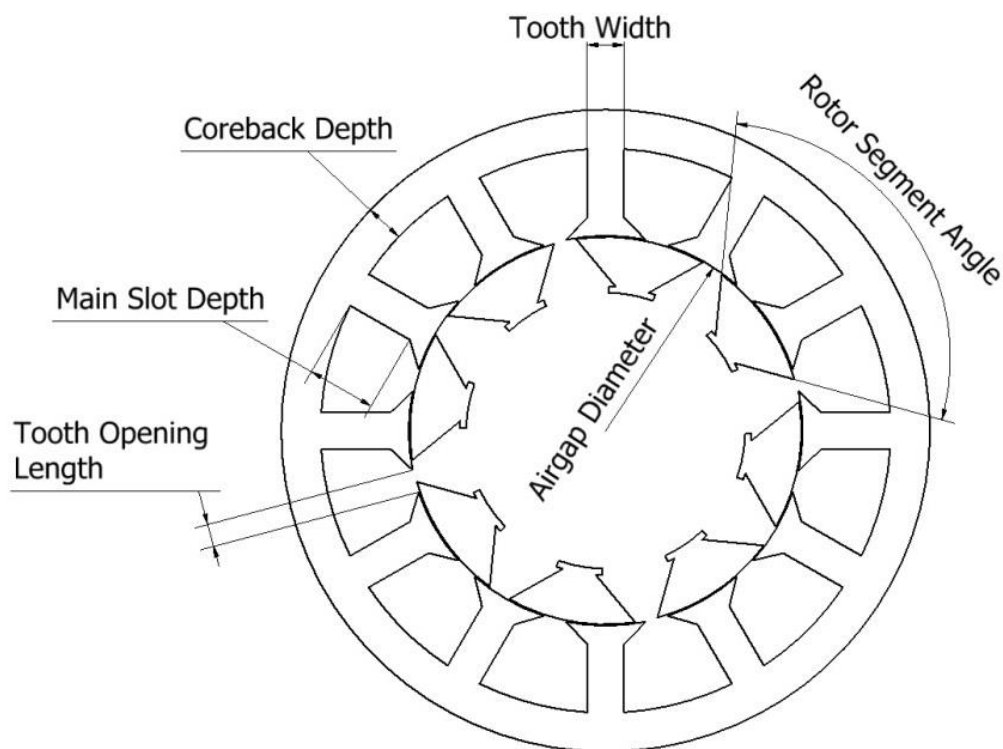


Figure 3-4: Parameterised variables varied during Segmental Rotor SRM optimisation. The motor outer diameter is fixed and therefore the tooth tip depth is derived from the other motor variables. Motor stack length is also fixed.

Table 3-2: Limits set on parameterised optimisation variables.

Dimension	Minimum	Maximum
Outer Diameter	150.0mm (fixed)	
Active Length	150.0mm (fixed)	
Airgap Length	0.3mm (fixed)	
Airgap Diameter	80mm	100mm
Tooth Width ⁽¹⁾	8mm	12mm
Coreback Depth ⁽¹⁾	8mm	12mm
Main Slot Depth	10mm	20mm
Tooth Opening Length	4mm	8mm
Rotor Segment Angle	62.5 °	105.0 °

Notes: 1) Tooth Width and Coreback Depth limits are the values selected for a 12 tooth machine. In order to reflect the change in flux per tooth, for 6 tooth machines these values were doubled, whereas they were halved for 24 tooth variants.

A number of differing optimisation options were explored in order to assess which might offer the best approach. Various multi-objective approaches were reviewed, including for example the combination of both winding loss and machine torque capability. However it was concluded that a simpler approach, focused purely on average machine torque capability, produced the most consistent results. Whilst such an approach would have its limitations, it would only consider one aspect of the motors performance, it would have the benefit of simplicity and speed in the comparison of a number of different machine designs.

Optimisation was therefore based on the maintenance of a fixed rms current density, independent of machine geometry. In order to achieve this, the slot area was calculated within the optimisation toolset, allowing an MMF to be chosen which would equate to a fixed rms current density in the motor windings. 10A/mm^2 was selected to be the optimisation constant as this was considered to be a reasonable, maximum current density for an enclosed, fan ventilated machine.

An assessment of average torque was used as the basis for comparing solutions. Torque was calculated using a 2D Finite Element model; a number of static solutions were run, calculating average torque across ten equal, angular steps between the unaligned and aligned rotor position. The average value of these torque steps was then used to make a comparison between each candidate geometry.

A more detailed 2D finite element assessment of the resulting, optimised machines was then undertaken in order to generate Flux-MMF characteristics for each machine. This allowed the calculation of motor torque, derived from the numerical estimation of the co-energy contained by an ideal motor energy conversion loop. Therefore it was possible to calculate a number of performance metrics as follows:

1. Torque per Unit Current Density, giving an indication of the torque density of the machine;
2. Torque per Unit Winding Loss, indicating low speed machine efficiency;
3. Torque per Unit Mass, providing an indication of motor torque density.

Comparisons were made with previously designed conventional and Segmental Rotor SRMs, described in [27, 30], as well as between the newly optimised designs.

3.3 Optimisation Results

As has been discussed, for each design optimised, at least three optimisation runs were undertaken. Optimisation was relatively fast, with each design optimisation taking on average of three hours to converge, with in total ~150 solutions having been considered. The optimisation led to a number of observations which are summarised in this section.

3.3.1 Impact of Optimisation on a Single Machine

Firstly, it was found that the 12-8 Fully Pitched Winding and 12-10 Single Tooth Wound machines, presented in [27, 30], can be further optimised with some gain in performance. Table 3-3 provides a quantitative comparison between the design of a 12-8 fully pitched winding machine before (taken from [30]) and after optimisation.

Figure 3-5 provides a flux plot demonstrating the geometric changes pictorially. The flux plot shows that, for a fixed current density (10A/mm^2 shown), the optimised machine has a significantly higher level of saturation. Whilst this may appear a

surprising result, all types of switched reluctance machine are frequently operated at a high levels of saturation. As it is the area of the Flux – MMF locus which defines the torque producing capability of this type of machine, high levels of saturation are not in isolation a limiting factor for machine performance.

Table 3-3: 12-8 Segmental Rotor SRM dimensions before and after optimisation.

Dimension	Before Optimisation	After Optimisation
Outer Diameter	150.0mm (fixed)	
Active Length	150.0mm (fixed)	
Airgap Length	0.3mm (fixed)	
Airgap Diameter	45.6mm	45.6mm
Tooth Width	11.1mm	8.5mm
Coreback Depth	11.1mm	9.1mm
Main Slot Depth	12.3mm	15.9mm
Tooth Opening Length	5.0mm	6.7mm
Rotor Segment Angle	93.3 °	100 °

Figure 3-6, Figure 3-7 and Figure 3-8 contain graphs which show respectively the flux linkage characteristic, mean torque versus current density and torque versus copper loss for the motor, in each case pre- and post-optimisation.

In all cases optimisation resulted in an increase in slot area, at the expense of a reduction in the width of the machine's flux path. Whilst this leads to earlier magnetic saturation, as was shown in Figure 3-5, this effect is, at lower current densities, offset by the increase in copper area and therefore reduced phase resistance. In this case, assuming a fixed number of turns, the reduction in phase resistance would be from 3.75Ω to 2.64Ω, circa 30%. Figure 3-6 shows how the MMF for 300W of copper loss is greater in the case of the optimised machine, due to the larger slot area, offsetting its earlier saturation and therefore leading to increased torque production. This advantage is lost as copper loss passes 550W, where the effect of earlier magnetic saturation starts to dominate.

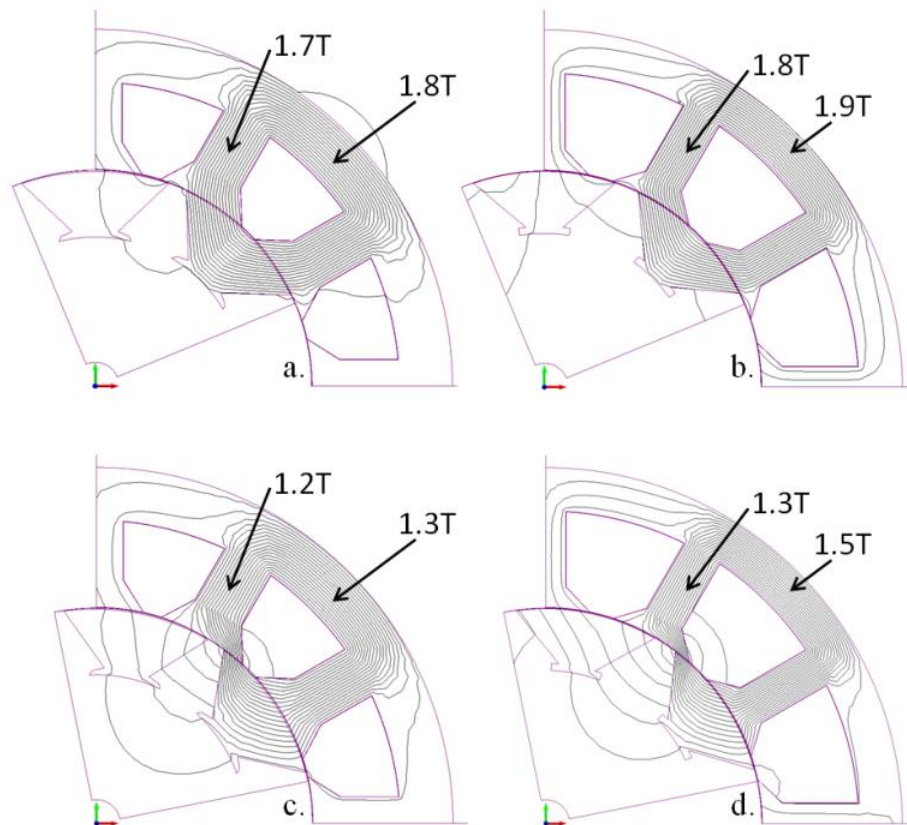


Figure 3-5: Showing the difference between 12-8 fully pitched winding Segmental Rotor SRMs before (a. & c.) (from [30]) and after (b. & d.) optimisation. Shown in the aligned position (a. & b.) and the maximum torque position (c. & d.) with a current density of 10A/mm^2 in the active winding. Flux density levels are indicated in stator tooth and coreback.

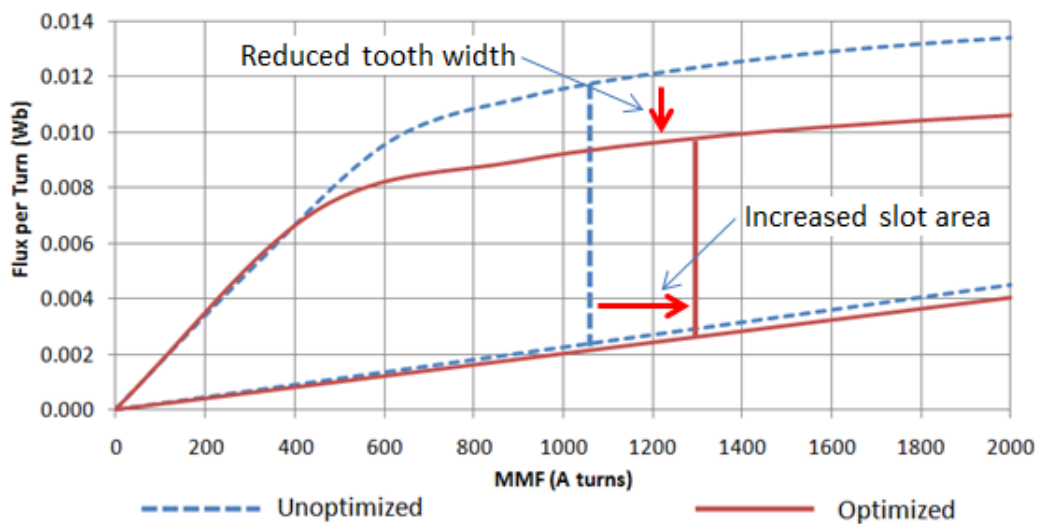


Figure 3-6: Flux per turn vs MMF for unoptimised and optimised 12-8 fully pitched winding Segmental Rotor SRMs; in each case vertical lines indicate MMF for 300W of Copper Loss.

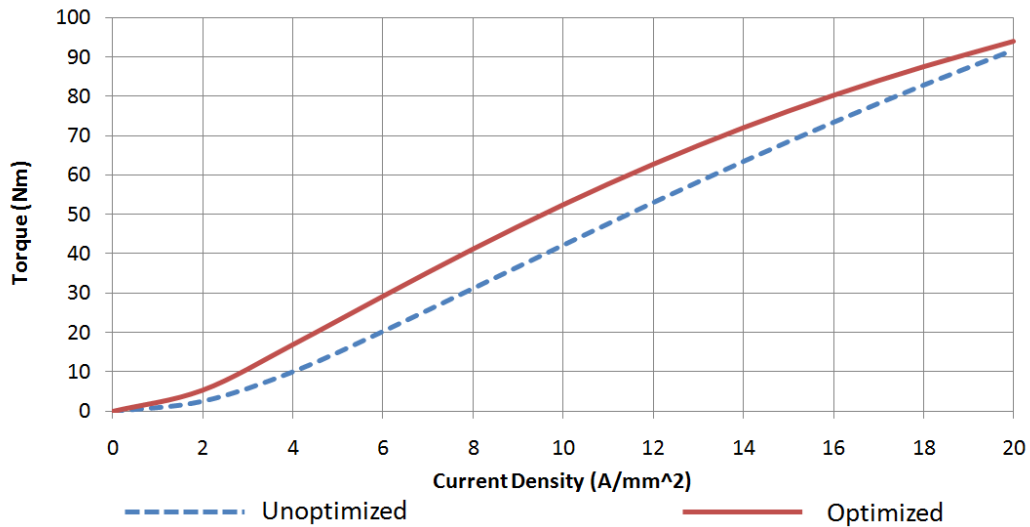


Figure 3-7: Torque vs Current Density for unoptimised and optimised 12-8 fully pitched winding Segmental Rotor SRMs, assuming ideal current control.

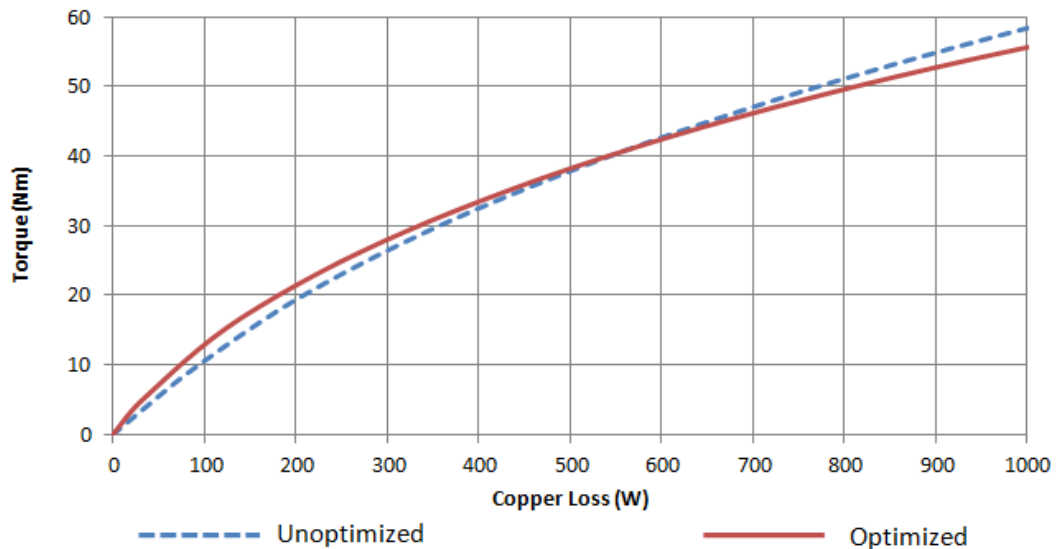


Figure 3-8: Torque vs Copper Loss for unoptimised and optimised 12-8 fully pitched winding Segmental Rotor SRMs, assuming ideal current control.

The resulting improvement in performance is a small increase in torque of 6% for 300W of copper loss, with a larger increase (24%) in torque per unit current density at 10A/mm^2 . These improvements could potentially lead to an increase in the torque at the thermal limit, assuming consistent design and manufacturing methods; however this may be offset to some degree by the larger slots in the optimised machine having a longer thermal path and therefore being more difficult to cool.

3.3.2 Optimisation Results for Differing Stator Slot and Rotor Segment Combinations.

When optimisation is extended to the complete range of feasible stator slot and rotor segment combinations a greater range of improvement is seen, in particular with machines with greater numbers of rotor segments than stator slots. Figure 3-9 shows two optimised Single Tooth Wound Segmental Rotor SRM designs whilst Figure 3-11 presents each of the Fully Pitched motor designs. As can be seen in Figure 3-10, for 300W of copper loss, certain Segmental Rotor SRMs with a greater number rotor segments than stator slots were predicted to have an increased torque capability.

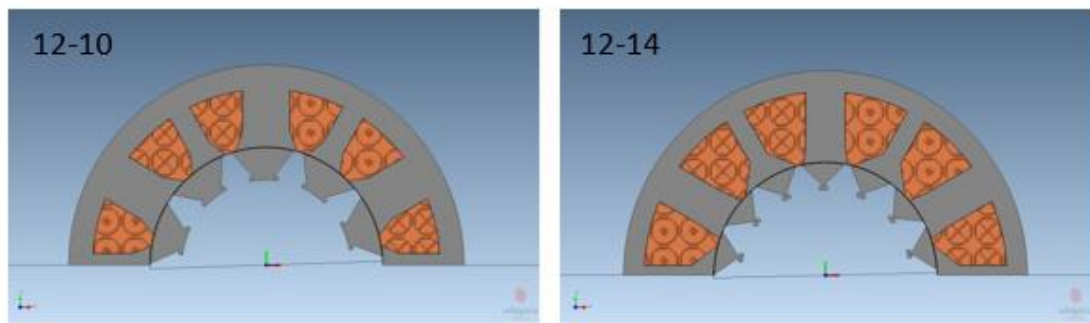


Figure 3-9: Single Tooth Wound Segmental Rotor SRMs with differing slot-segment combinations following optimisation.

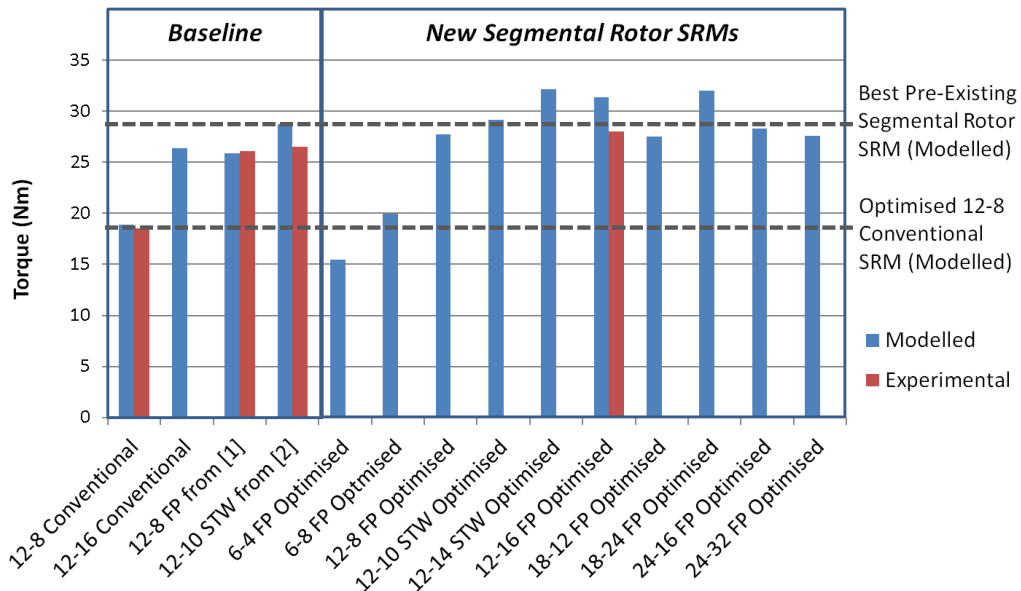


Figure 3-10: Showing the comparison between Torque for 300W of Copper Loss for the differing, optimised Fully Pitched (FP) and Single Tooth Wound (STW) Segmental Rotor SRMs and contrasting this with the performance of baseline SRMs. Both modelled and experimental data, where available, are presented. Ideal current control is assumed.

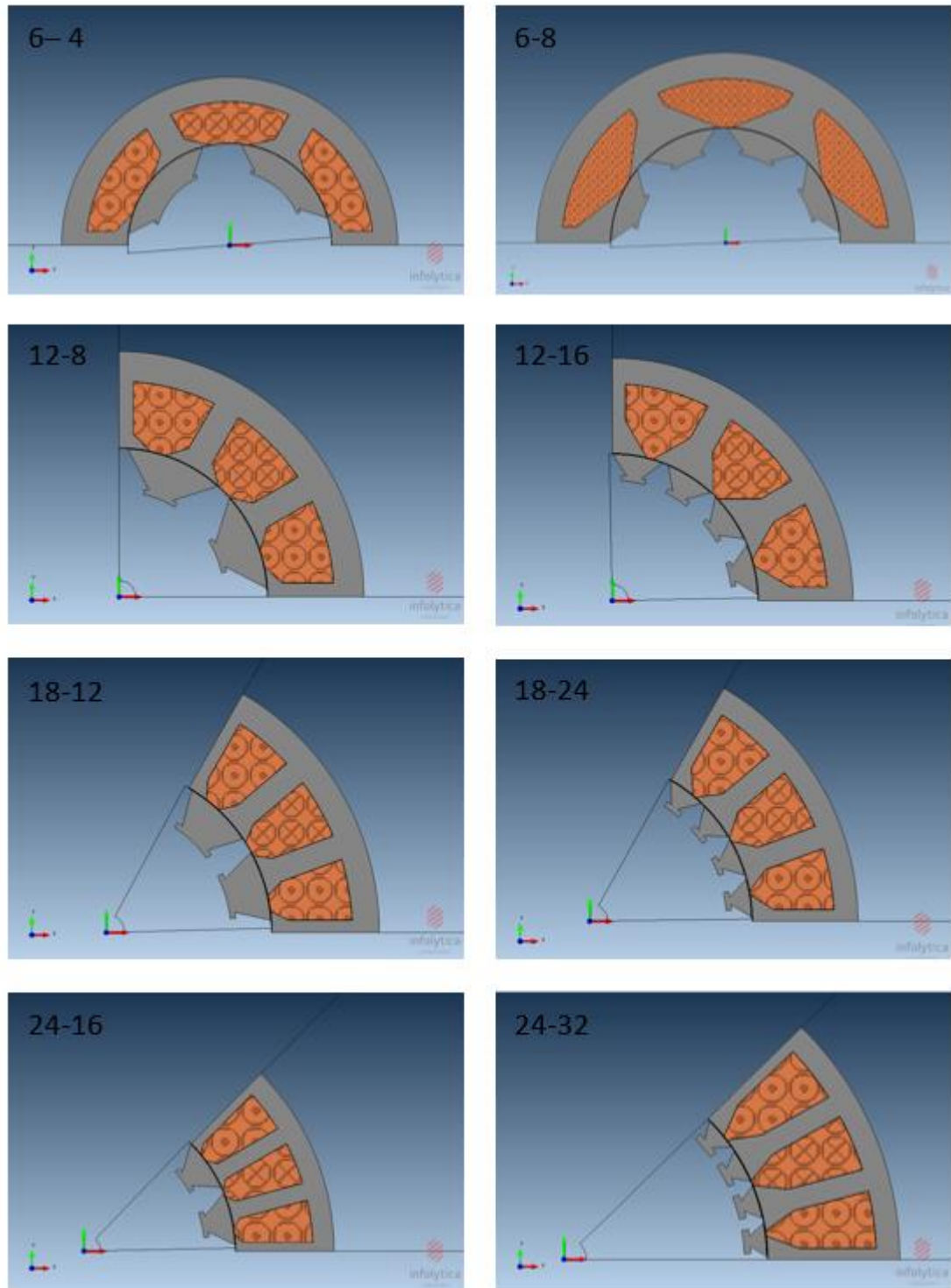


Figure 3-11: Fully Pitched Segmental Rotor SRMs with differing slot-segment combinations following optimisation.

In Figure 3-10, the optimised Segmental Rotor machines are compared against two conventional SRMs. The first, a conventional 12-8 segmental machine has been drawn

from [28]. The second, a conventional 12-16, has been optimised by the author in accordance with the rules set out in [59].

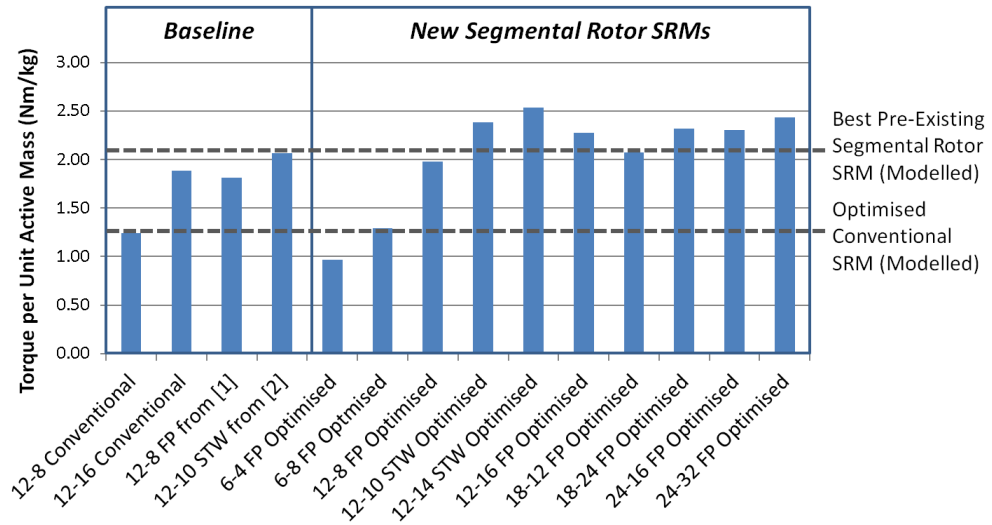


Figure 3-12: Showing Torque per Unit Active Mass for each optimised Segmental Rotor SRM. 300W of copper loss and perfect current control are assumed.

Also included in Figure 3-10 is static experimental data which has been collected for prototype machines (see Chapter 4 for details of construction and test of the 12-16 Segmental Rotor SRM). For the 12-16 machine an improvement of 51% over the conventional 12-8 SRM was achieved and 9% over the 12-10 Single Tooth Wound Segmented machine. These improvements are more modest than predicted by modelling; however it is clear that a variation in terms of winding fill factor and end winding length, is a major factor here. This is discussed in more detail in Chapter 4.

With the 12-16 segmental rotor results revised to remove these factors (variation in end winding length and fill factor, to be discussed in Chapter 4), then improvements over the conventional machine of 66% could be expected, matching the prediction from 2D finite element modelling, and achieving 16% more than in the 12-10 machine. This latter improvement is higher than predicted by 2D finite element modelling; it is felt that this is due to the relative effect, noted in [27], of 3D end winding inductance on torque production observed in the Single Tooth Wound machines was higher (17% reduction) than in the case of Fully Pitched Machines (10% reduction).

Figure 3-12 presents the Torque per Unit Active Mass of each machine. The relative performance of the machines with higher stator slot and rotor segment numbers are

more favourable in this comparison: this is due to the reduction in coreback width inherent in the design of any motor as pole number increases. The strong performance of the 12-14, 12-16 and 18-24 machines also remains clear.

The reason for the increase in torque density of the machines with a greater number of rotor segments than stator slots is illustrated in Figure 3-13. This figure shows that whilst the area of the Flux-MMF locus for the 12-16 machine is smaller than for the optimised 12-8 machine, it retains more than half the area at 300W of copper loss. As a result it is simply the doubling in strokes per revolution of the 12-16 machine compared to the 12-8 which leads to the increase in torque.

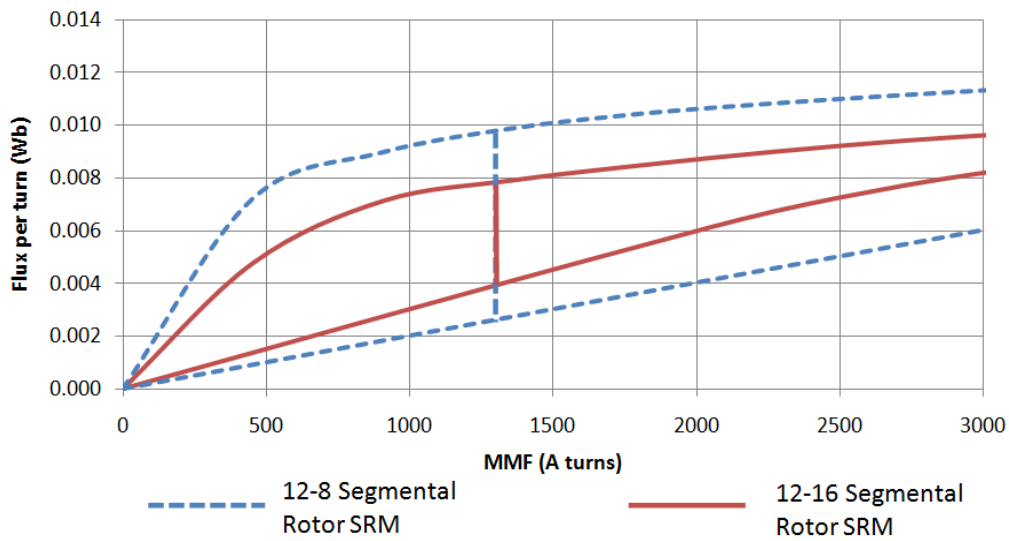


Figure 3-13: Showing Flux per turn versus MMF for the optimised 12-8 and optimised 12-16 Fully Pitched Segmental Rotor SRMs. Vertical lines indicate MMF for 300W of Copper Loss.

3.3.3 Dynamic Operation.

Iron loss estimation, utilising 2D FE transient with motion analysis, was undertaken for each of the segmental rotor prototypes which have been constructed and also for the conventional 12-16 machine. Data for operation at 1500rpm can be found, along with an overall estimation of efficiency, in Table 3-4.

It was necessary to apply an approach to the modelling of iron loss which would allow a consistent comparison between the differing machines. In order to achieve the required consistency, 2D finite element, transient with motion runs were made for each machine with turns and advance angle adjusted such that, for a DC link voltage of 560V, each

motor is operating in voltage control and producing torque of approximately 30Nm (see Table 3-4).

Table 3-4: Total Loss Comparison at 1500RPM, 30Nm.

	Conventional SRM		Segmental Rotor SRM			Units
	12-8	12-16	12-8 ⁽¹⁾	12-10 ⁽¹⁾	12-16	
Speed	1,500	1,500	1,500	1,500	1,500	rpm
Torque	30.9	30.5	30.0	30.5	30.3	Nm
Power	4,817.5	4,784.8	4,717.4	4,791.9	4,766.7	W
Copper Loss	769.6	519.9	521.4	498.5	413.1	W
Iron Loss	35.46	157.4	69.6	75.3	151.4	W
Total Loss	882.3	677.3	591.0	573.8	564.5	W
Efficiency	85.7	88.6	88.9	89.3	89.4	%
DC Link Voltage	560	560	560	560	560	V
RMS Phase Current	7.0	9.9	7.2	7.3	12.4	A
Phase Turns	296	152	290	304	178	
Advance Angle	90	90	80	85	80	° _(elec)

Notes: 1) Unoptimised designs from [27, 30].

This was achieved by the development of a script working in conjunction with the 2D FE solver running in voltage control. The script undertakes an iterative search, with the variables being number of turns and advance angle, until 30Nm was achieved. The script operates as follows:

- 1) Initially a very high number of turns per phase is selected such that motor MMF, with the motor running in voltage control at 1500rpm, would not be sufficient to produce a torque of 30Nm or greater. Conduction angle was fixed at 180degrees;
- 2) Iterative, 2D finite element with motion solutions were then undertaken with differing advance angles (5 degree increments, reducing from 90 degrees) until a peak torque maxima was identified;

- 3) If this maxima is less than 30Nm then the number of turns were reduced by 10 and the process repeated until peak torque of greater than 30Nm is achieved;
- 4) Should peak torque overshoot 30Nm by more than 5% then an additional turn was added iteratively until, when the optimum advance angle is identified, a torque of less than 30Nm plus the 5% error margin is achieved.

In all cases the resulting iron loss calculations assume the use of M270-35 steel, as used in the construction of the prototypes. Iron losses are calculated by the Infolytica MagNet tool and, based on work undertaken by Hargreaves in [88], a factor of 1.6 was applied to the calculations in order to allow for manufacturing effects during motor construction. Copper losses were calculated based on the rms phase currents predicted by the FE tool and the calculation of the phase resistance, including end windings, assuming a winding temperature of 20°C and ignoring proximity effects.

The resulting Table 3-4 shows the improvement in performance of Segmental Rotor SRMs over conventional machines when the machines are compared in this way. Losses for a given torque output were found to be significantly lower for the segmental rotor machines, in particular in the case of the optimised 12-16 Segmental Rotor SRM. Table 3-4 shows that the two 12-16 machines are predicted to have circa double the iron loss of the other machines; this is the consequence of the increased electrical frequency resulting from the higher number of rotor segments in this machine. The conventional 12-8 motor exhibits lower iron loss than the 12-8 Segmental Rotor machine; this is expected to be due to lower levels of magnetic saturation in the conventional motor.

Table 3-4 also shows that at this power level, the 12-16 Segmental Rotor machine gains in efficiency over the other designs due to its low copper loss, with the 12-10 segmental rotor a close second. However as motor speed and load increase, first the 12-10 and then the 12-8 Segmental Rotor will have the advantage over the 12-16 machine due to the effects of high electrical frequency on iron loss, at speed, and saturation on torque production, at high load.

A potential drawback of the 12-16 machine is that, for a given operating point, it has a comparatively high reactance; this is due to both its high electrical frequency and high unaligned inductance. As a result the maximum number of turns in order to achieve sufficient MMF to deliver the required torque is about 40% lower than for the other

machines, resulting in a 40% higher input current for the same torque. In this respect the conventional 12-8 SRM has the advantage of lowest current requirement, with the conventional 12-16 machine also offering benefits. This will translate into a lower power converter VA rating requirement for the conventional machine as opposed, in particular, to that required by the 12-16 Segmental Rotor.

Figure 3-14 shows the predicted torque/speed and loss/speed characteristic for the 12-16 Segmental Rotor Machine and conventional 12-8 and 12-16 machines. These characteristics were generated by running each motor in transient with motion FE at zero, 750rpm, 1500 rpm, 3000rpm and 4500rpm. At each speed a conduction angle of 180degrees was assumed and the optimum advance angle selected which provided the peak torque. The resulting torque-speed characteristics for all machines are similar, however the Segmental 12-16 can be seen to offer significantly lower losses until twice base speed.

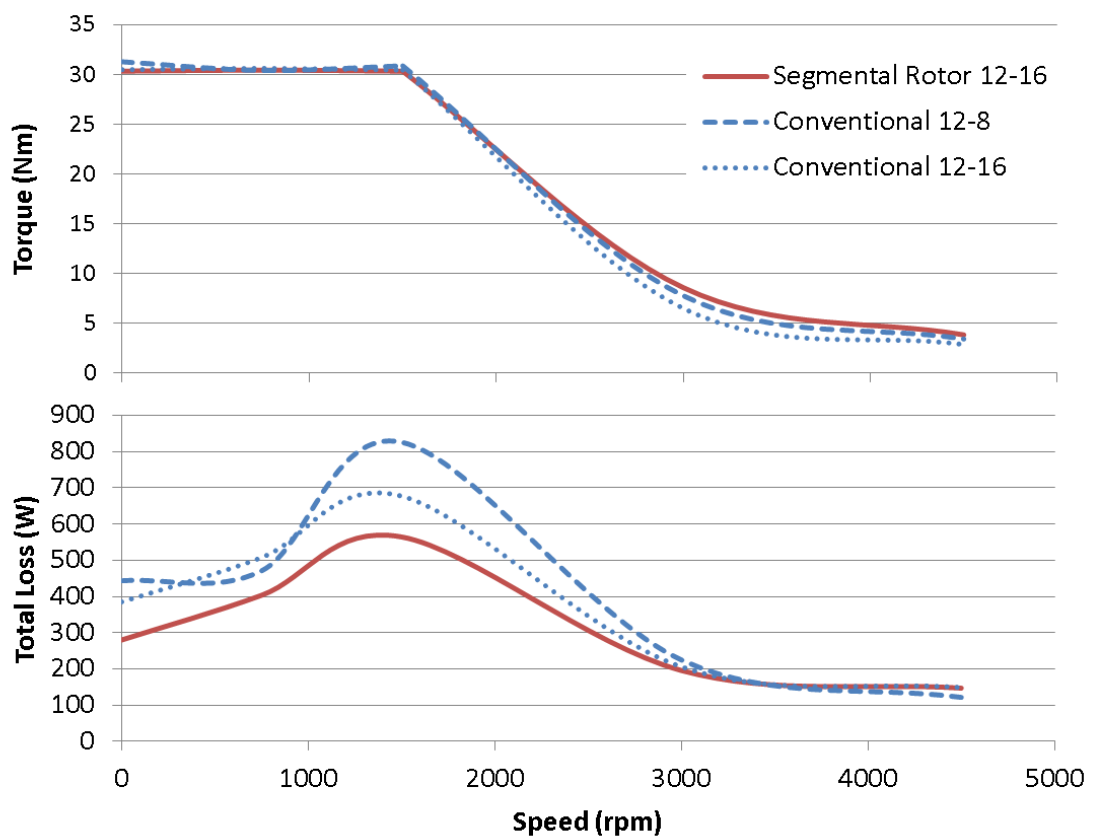


Figure 3-14: Torque-Speed and Total Loss curves for 12-16 Segmental Rotor and 12-8 / 12-16 Conventional SRMs (from FE Analysis, excluding friction and windage).

At speeds greater than 1500rpm the Segmental Rotor SRMs were found to operate under voltage control in the same manner as for a conventional SRM. Under normal operation they exhibit a less than constant power response at speeds above base speed, with base speed influenced by the supply voltage and selection of winding turns in the same way as for conventional machines.

As for conventional SRMs [89], it is anticipated that it will be possible to apply measures to achieve an extended constant power characteristic; for example the use of Constant Current Mode control (where phase current is never allowed to fall to zero) would increase high speed torque but at the expense of reduced efficiency.

3.4 Conclusions

This work presented in this chapter has led to a number of conclusions:

- Firstly it confirms that Segmental Rotor SRMs may offer torque density and efficiency benefits (subject to certain caveats, summarised below) over conventional SRMs and as such their use in a variety of applications should be considered;
- Secondly it demonstrates that Segmental Rotor SRMs with a greater number of rotor segments than stator teeth offer advantages at low speeds and lower current densities; in this study they have been shown to increase the improvement in torque density, for 300W of copper loss, over conventional SRMs from the 40% reported in previous studies to potentially in excess of 65%. This improvement, above that of previously documented Segmental Rotor SRMs, is a result of two factors. The first factor is the increase in copper area and therefore reduction in loss per unit MMF resulting from the optimisation process that has been applied. The second is that, whilst both aligned and unaligned inductance per coil is degraded as segment number increases, this effect is more than compensated for by the simple increase in strokes per revolution in machines with a higher number of rotor segments. It is also clear that at higher speeds this improvement is limited by iron loss, which increases with segment number, and at higher current densities by earlier saturation of the motor's smaller lamination features. However perhaps the most significant weakness identified is that the high phase inductance that results in these machines limits the high speed performance of

these motors, demanding a higher converter VA rating than would be necessary for a machine with fewer rotor segments;

- Finally that simple 2D FE based optimisation techniques offer the opportunity to further improve the performance of any specific stator slot, rotor segment combination, demonstrating in particular improvements in torque per unit current density. However as will be seen in the following Chapter 4, whilst 2D FE techniques offer the ability to undertake rapid and less computationally intensive (when compared to 3D techniques) optimisation, the effects of end windings must be considered;

These findings therefore have implications as to the overall objectives of this doctoral project as follows:

- FE based optimisation has proven to be of value and so should be applied to the later stages of this project. However the static optimisation discussed in this chapter is limited so that it cannot directly take into account dynamic effects. For example iron losses, a significant driver to motor efficiencies at higher electrical frequencies, are not considered. As a result a dynamic simulation based optimisation process is needed;
- The Segmental Rotor SRMs with higher numbers of rotor segments than stator slots may be attractive in terms of torque density, however for an automotive application it is likely that their need for a power converter with a higher VA rating may limit their usefulness. A drive with a high VA rating may be expected to be more expensive than one with a lower rating, potentially offsetting any savings in cost due to the elimination of rare-earth magnets.

Chapter 4. Construction of a 12-16 Segmental Rotor SRM and Validation of Static Optimisation

Chapter 3 has discussed the optimisation of the differing Segmental Rotor SRM designs, with varying numbers of rotor segments and stator teeth. All machines were optimised in order to maximise torque for a fixed current density, providing a consistent comparison of performance between different motor designs. As a result of this analysis it was decided to build a prototype motor with fully pitched windings, featuring 12 stator slots and 16 rotor segments (12-16). This would be used in order to validate the results of the optimisation process such that lessons could be learnt and applied to larger, automotive machines.

This machine was chosen over the better performing, single tooth wound configurations as the fully pitched winding machines previously constructed by the university [28] were no longer available and it was therefore desirable to once more have access to one of these machines.

In order to allow for comparison with a number of previously constructed machines, it was decided to use a D100L frame size (150mm lamination stack length, 150mm active diameter) as the basis of the design.

This chapter addresses the process of detailed design and construction of the prototype motor as well as providing details of the tests undertaken.

4.1 Detailed Design and Construction Process

The detailed design of the motor consisted of four key elements:

- Selection of motor lamination material and finalisation of the rotor and stator lamination stack designs;
- Design of the stator housing in order to cool and support the motor stator components;
- Modelling of the dynamic response of the motor, via a Matlab Simulink SRM model, in order to decide the motor winding design;
- Design of the mechanical support structure and bearings for the machine.

4.1.1 Motor Lamination Design

The general dimensions of the motor laminations were based on the FE Model for the 12-16 machine resulting from the optimisation study. M270-35A steel was selected for construction; this was the material used in previous motor construction and therefore would support easy comparison. Assuming a stacking factor of 98.6%, achieved during previous constructions, the 150mm stack length would require 423 laminations.

Wire erosion (otherwise known as Electrical Discharge Machining – EDM) was selected as the cutting technology for the prototype. The advantages of using this cutting technology were its ease of use for one-off manufacture and the ability to achieve extremely tight tolerances. However there was also a potential disadvantage; the possible difference between the effects of this process (EDM) on lamination material properties when contrasted with the laser cutting process, previously applied to the University's SRM prototypes. No academic literature has been found which compares the effect of these differing processes on lamination steels, however discussions with three electrical steel suppliers (JFE Steel, Japan; Tata Steel, UK; L&H Components, UK) have suggested that laser cutting may produce more local heating in a material which may lead to greater edge effects in the lamination stacks, potentially reducing permeability and increasing iron losses.

4.1.1.1 Stator Laminations

Small modifications were made to the design of the stator stack such that:

- A small radius (1mm) was added to all internal corners in order to allow for the limitations of the EDM process. This also has the additional benefit of avoiding localised stress raisers common where radii are not applied;
- A key was added to allow the locating of the stator laminations within the stator housing.

It was decided to glue the stator laminations into 50mm sub-stacks prior to cutting with the EDM wire erosion machine. There were a number of reasons for this decision as follows:

- The stator laminations would be shrunk into the stator housing, in order to achieve an interference fit. This would mean that the stator lamination stack would need to be fixed into manageable subassemblies prior to insertion into the jacket. Whilst techniques such as welding and interlocking would tend to be

used commercially, in the case of a one off prototype gluing had been shown to be effective;

- This approach would produce very good stack tolerances ($\pm 0.03\text{mm}$) which would mean that, in order to achieve a consistent 0.3mm air gap length, it would not be necessary to machine the stator bore after assembly with the jacket.

The stacks were bonded using an Araldite two part epoxy resin, consisting of Araldite LY5052 epoxy and Araldur 5052CH hardener. For each 50mm stack, 141 laminations were bonded, with the resulting stacks being compressed between plates in order to achieve a 98.6% stacking factor; indicating an average glue layer of $0.5\mu\text{m}$. Once each lamination stack had been glued, start holes for the EDM wire were then drilled and finally the 50mm stator sub-stack cut (see Figure 4-1).



Figure 4-1: EDM cut, 50mm stator lamination sub-stack.

4.1.1.2 Rotor Laminations

In order to simplify the process of prototype motor manufacture, it was decided to apply a new technique to assembly of the rotor lamination segments. The previously applied

assembly techniques, [90] [91], had required each rotor segment to be individually assembled into a stack.

This would be less practical with the 12-16 machine due to the very high number of physically small rotor segments involved (6,768 individual segments assuming a packing factor of 98.6%). Instead it was decided to manufacture the rotor segments as part of continuous ring (see Figure 4-2). This would allow each layer of 16 rotor segments to be handled as a single unit, with a final machining processes being required to establish the correct rotor outer diameter.



Figure 4-2: Rotor Laminations were cut as a continuous ring in order to simplify prototype construction.

4.1.2 Stator Design and Construction

The stator was to be air cooled, again to provide a good comparison with previously constructed machines. Stator cooling fins were cut into the motor housing in order to increase motor surface area and therefore heat transfer; the design of these fins was based on previously constructed motors in order to allow a direct comparison to be

made. The stator housing was constructed from 6082-T6 aluminium; this material was selected for the prototype as it offers both high strength and good machining properties.

The stator housing was made 0.15mm per side smaller than the stator lamination stack; this would allow a good shrink fit to be achieved. Aluminium expands at $23.1\mu\text{m}/\text{m}/\text{K}$ and so at this diameter (150mm) and with the housing heated to 200°C ($\Delta T = 180^{\circ}\text{C}$) this would mean an expansion of 0.62mm, allowing therefore a clearance of 0.15mm per side to fit the lamination stack.

The stator laminations were located in the stator housing by a shoulder at the axial end of the stack and by a single radial keyway. The stator housing was therefore heated to 200°C and each of the three stator lamination sub-stacks fitted one at a time, with the housing reheated between the fitting of subsequent stacks.

4.1.3 Motor Windings

The 12-16 motor was wound with double layer fully pitched windings, with each winding spanning three stator teeth.

Static Flux linkage - MMF characteristics, from the finite element modelling, were used as the basis for Matlab Simulink modelling of the motor performance. For SRMs, this approach to dynamic modelling is well understood; in this case a Simulink model, developed by Celik [92], was modified and used to model the motor with a number of different turns. Based on this process, 50 turns was chosen to provide an appropriate torque speed profile with the machine operating in current and voltage control modes. This assumed the use of a drive operating at 560V and the objective to achieve a basespeed of circa 1500rpm.

With this number of turns set, a 2.02mm diameter conductor (3.21mm^2) would be required in order to achieve 0.4 fill factor. Based on records from the previously constructed, fully pitched 12-8 machine constructed by [28] it was assumed that a turn length of 540mm would be achievable.

Recent experience with winding short-circuits led to conservative winding approach. Motor winding was subcontracted to a specialist armature winder. In conjunction with this company, the decision was taken to use 3 conductor strands (2 of 1mm and 1 of 1.5mm diameter) resulting in a total per conductor cross sectional area of 3.33mm^2 and a fill factor of 0.415. The use of stranded conductors would simplify the winding

process, allowing tighter bend radii to be achieved. However it was also agreed that windings should be pre-wound off the machine; from discussion with the winding company this was expected to lead to an increase in the length per turn to 600mm from the predicted 540mm. However it would increase the reliability and speed of the winding process. A combination of the increased winding diameter and increased winding length would be expected to result in a net increase in phase resistance and therefore copper loss of 5 to 10%, depending on the final dimensions achieved.

However, once the wound stator was completed it was found that actual turn length (estimated based on the known fill factor and 5.77×10^7 S/m conductivity) achieved was 730mm, leading to an increase in phase resistance to 0.38Ω (measured) from 0.29Ω (modelled). Clearly this 31% increase would have a significant and proportional impact on copper loss. End windings were found to protrude axially from the stator lamination stack by 39mm at the non-connecting end (Figure 4-3), comparable with El-Karahsi's [28] fully pitched machine, where end windings were reported to protrude by 37mm.

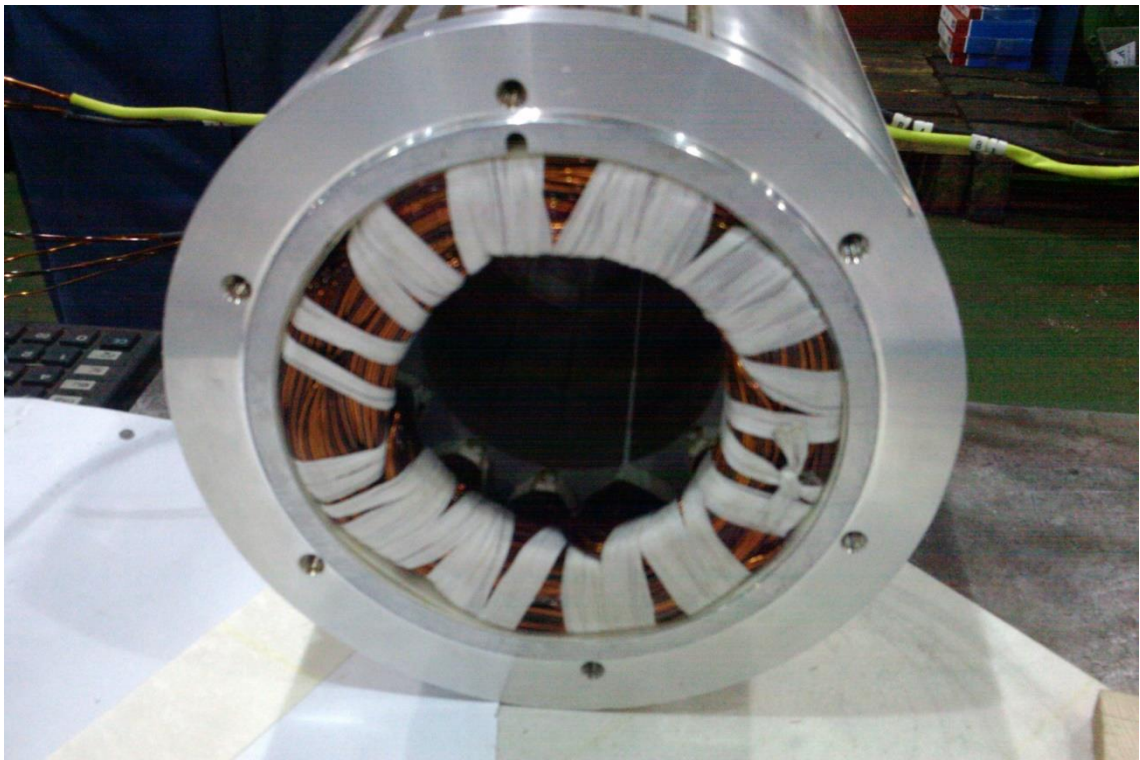


Figure 4-3: Showing wound stator with large end windings.

From subsequent discussion with the armature winders, it was acknowledged that it would have been possible to shorten the motor end windings, however this would have increased the time to wind the machine. Equally, in this motor, which has a

comparatively large slot area, the cross-sectional area of the full coil was also large making its manipulation more difficult than for the previously constructed machine. It was decided, however, not to rewind the machine as removing the now varnished copper would have been time consuming and potentially damaged the stator laminations. The effects of this increase in winding resistance on the motor are reported in section 4.2.

The motor's slots were insulated using a 0.5mm Nomex slot liner. Windings were secured in the motor slots using a 2mm glass fibre-board slot wedge. The completed machine was varnished to protect it further. Windings were terminated individually to a termination ring (see Figure 4-4) to allow flexibility to connect phases in series and parallel and also to allow tracing of any faults. Windings were checked with 2000V phase-to-phase and phase-to-earth tests and were confirmed to have no shorts.



Figure 4-4: Finished motor showing winding termination ring.

4.1.4 Rotor Support Structure and Shaft Design

The rotor is constructed of three distinct elements. At its core is the rotor shaft which transmits rotor torque from the machine. Mounted onto the shaft is the rotor support

which provides support to the ten rotor segments. This, as has been discussed in Chapter 3, must be non-magnetic in order to create a magnetic open circuit between rotor segments. Finally, the rotor segments themselves are formed of electrical steel laminations; they provide the rotor saliency which allows motor torque to be generated.

The rotor shaft was manufactured from 304 austenitic (non-magnetic) stainless steel. A non-magnetic steel was used to prevent any risk of flux linking from the rotor segments to the shaft. This effect was modelled in 2D FE and it was found that a magnetic shaft would increase unaligned inductance in the order of 5%, reducing torque capability.

It was decided to manufacture the rotor support from 6082(T6) aluminium; the key feature of material used for this component is that it be non-magnetic. This is critical as the support structure effectively forms the unaligned airgap for the machine and therefore must have a relative permeability as close to 1 as possible. Whilst a non-magnetic stainless steel could also be used, aluminium also has the benefit of being easy to machine and having low mass, therefore reducing rotor inertia. The rotor support was designed in line with the previously proven approach used by [91]. This design relies on the ability of the low volume EDM wire erosion process to cut complex and precision axial slots; an alternative solution would therefore need to be found for volume production. These slots were cut such that they could accept a key cut into each rotor segment base. A 0.05mm clearance between rotor laminations and rotor support was allowed for.

Both the shaft outer diameter and rotor support inner diameter were keyed in order to lock the rotor support to the shaft. Two radially opposed keys were used in order to retain rotor balance as far as possible.

The rotor shaft was fitted to the rotor segment support and held in place by an end cap, bolted to one end of the support. Construction then involved the manipulation of each of the 423 rotor segment rings into place on the ring (see Figure 4-5). The rotor support was 20mm longer than the final stack lamination length, allowing space for the loose laminations prior to compression. When all the laminations had been fitted they were compressed and clamped in place through the fitting of the second end cap.

The rotor voids were then potted with the same 2 part epoxy resin which had been used to bond the lamination sheets. This process ensured that the rotor segments were firmly

supported in place whilst the rotor was machined to final size. The rotor was then turned on the lathe to achieve the final rotor outer diameter (see Figure 4-6).



Figure 4-5: Showing construction of rotor with lamination rings being fitted to slotted, aluminium rotor support.



Figure 4-6: Completed rotor after machining to final outer diameter. This figure also shows how the rotor was balanced by fitting additional washers to the end-cap bolts.

Bearings were then fitted (60052-RS bearings were used, based on previous experience) and the rotor balanced. Balancing was undertaken to G2.5 using a rotor balancing machine. Due to difficulties found previously with rotor balancing through either the addition of putty or the removal of material, balance was in this design achieved through the addition of washers to the bolts holding the end caps to the rotor core. This was found to be a successful process.

The rotor bearings were supported in the final motor by the stator endcaps. These end caps, again manufactured from 6082(T6), were bolted to the stator housing.

4.1.5 12-16 Motor Design Parameters

Following detailed design and construction, Table 4-1 shows the resulting parameters of the 12-16 Segmental Rotor SRM.

Table 4-1: 12-16 Segmental Rotor SRM Design Parameters

Characteristic	Value
Topology	Inner rotor, Segmental Rotor SRM
Stator Teeth	12
Rotor Segments	16
Stator Outer Diameter	150mm
Stack Length	150mm
Lamination Material	M270-35 (Tata Cogent Steel)
Airgap Length	0.3mm
Rotor Outer Diameter	86.4mm
Rotor Support Outer Diameter	73.8mm
Motor Cooling	Air cooled, stator housing finned
Winding turns per coil (phase)	50 (100)
Winding Configuration	Double layer, fully pitched.
Winding layup	Pre-wound, 3 strand (2 x 1mm & 1 x 1.5mm)
Fill Factor	0.415
Winding resistance (20°C)	0.38Ω

Appendix 2 contains dimensioned drawings of the stator laminations, rotor laminations and assembled rotor.

4.2 12-16 Motor Testing and Model Validation

The motor was tested statically only, as at this stage an asymmetric half bridge converter was not available at the university to allow dynamic testing.

A number of static tests were undertaken as follows:

- A pulse test to allow the development of the motor Flux linkage / current characteristic;
- A static torque test, in order to develop the motor static torque characteristic;
- DC injection of current into the motor in order to characterise the motor's thermal performance.

The details of these tests are provided in the following sections.

4.2.1 Pulse Test

A pulse generator was constructed (see Figure 4-7) in order to test the dynamic current response of the motor to a pulsed voltage. A view of the constructed pulse generator can be found in Figure 4-8.

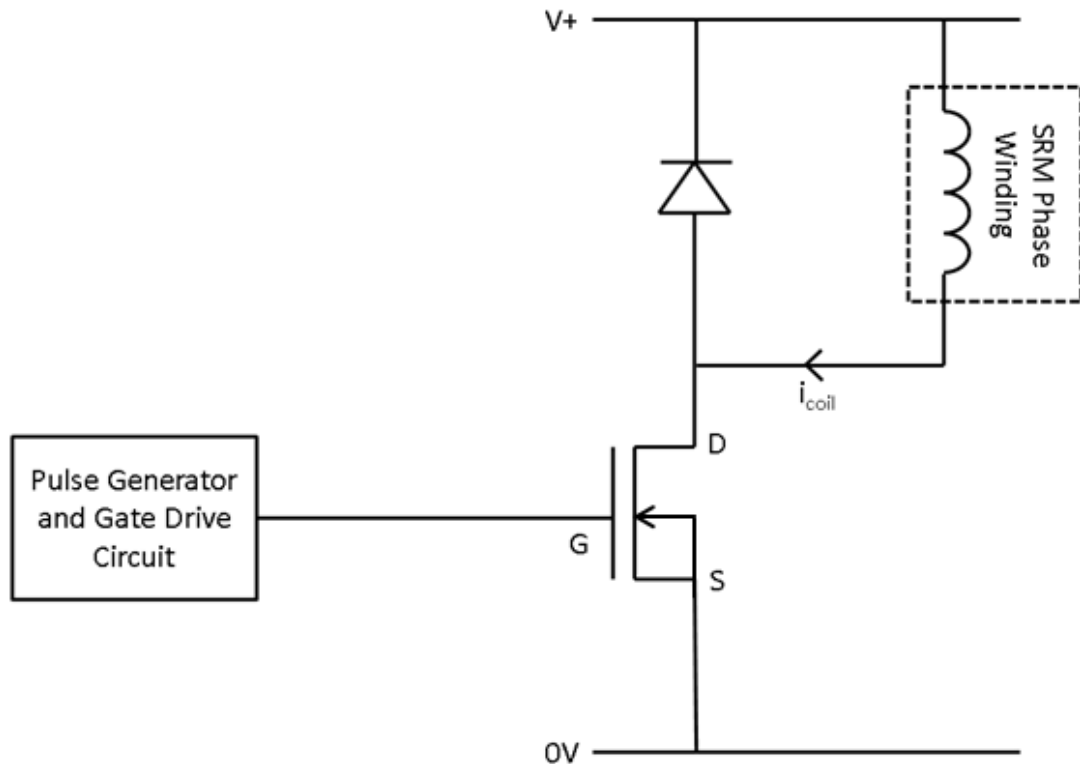


Figure 4-7: Pulse Generator schematic



Figure 4-8: Implemented Pulse Generator

This system generates a series of voltage pulses across the coils of one motor phase and can be used to derive motor flux for any given phase current and angle, $\psi(I, \theta)$. In order to allow accurate measurement of rotor angle, the rotor shaft was held by a rotary table. This rotary table allowed the rotor angle to be precisely advanced during the test while ensuring that it is held at the correct angle whilst voltage pulses are applied.

Rotor angles were advanced in 1 degree increments for this 16 segment rotor therefore meaning that 23 increments would be needed to sample a complete, 22.5deg mechanical segment of the machine. For each angle, pulse duty cycle and frequency are adjusted such that the maximum allowable motor current is achieved (in this case 93.2A(pk) / 65.9A(rms) which equates to an RMS current density of 20A/mm²) and several pulse cycles of voltage and current response are recorded.

In accordance with the technique described in [34], flux can then be calculated from the following expression:

$$\psi(I, \theta) = \int_0^T (V(t) - I(t) \cdot R) dt \quad (4-1)$$

where $\psi(I, \theta)$ is the flux linkage at a given rotor angle (θ) and instantaneous current ($I(t)$). $V(t)$ is the instantaneous phase voltage and R the phase resistance. T is the integration period bounded by the rise time of the current pulse.

In order to calculate the instantaneous flux, any experimental offsets are removed from the measured data and, in order to remove measurement noise, a moving average of the data taken. R was first estimated to be 0.38Ω , as measured during motor construction and adjusted to take into account the effect of winding temperature increases due to the excitation of the phase winding.

If flux linkage per phase is then plotted against phase current for various angles of θ then the characteristic shown in Figure 4-9 results.

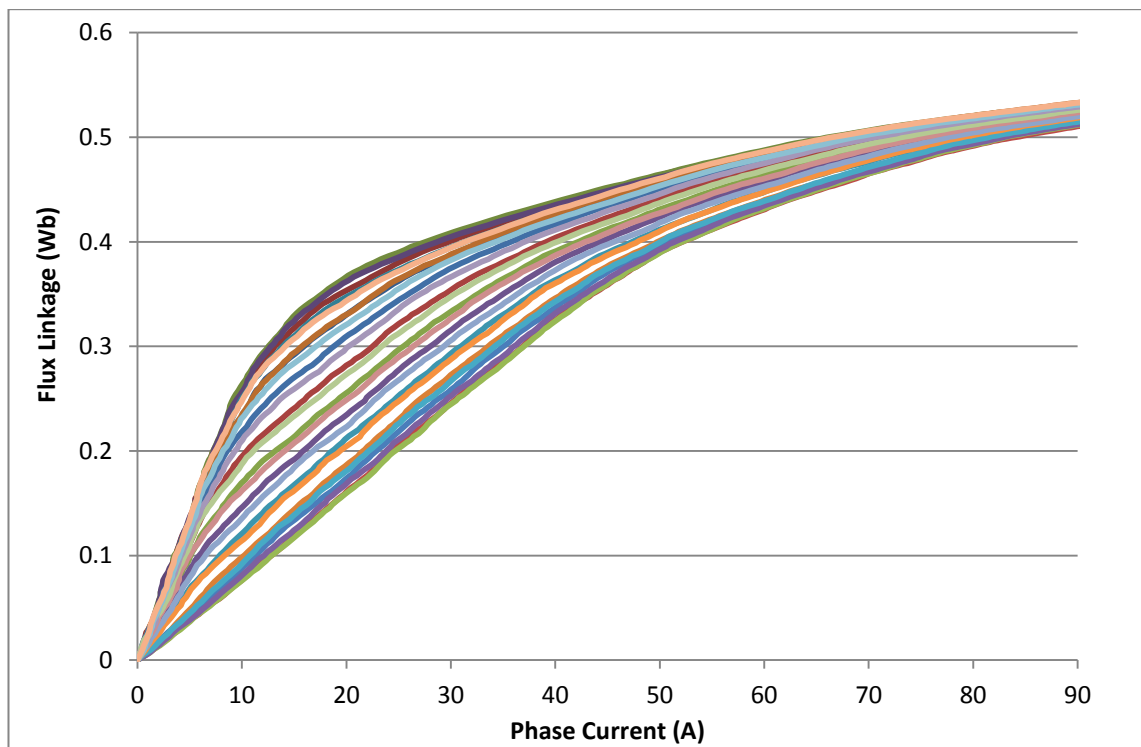


Figure 4-9: Experimentally measured Flux Linkage per Phase versus Phase Current and Rotor Angle for the 12-16 Segmental Rotor SRM.

With the maximum phase current of 95A equating to $\sim 20\text{A/mm}^2$, this characteristic shows that the motor is very heavily saturated at that operating point, however at 10A/mm^2 , the optimisation point, the motor is less saturated with additional phase current still resulting in additional torque.

If this graph is now compared to the flux linkage / current characteristic, derived from Finite Element Modelling, then it can be seen that there are differences. In particular the unaligned inductance is found to be higher than predicted by circa 10%. The aligned inductance is also slightly higher, but by a lesser degree. This difference is likely to be due to modelling having been undertaken using 2D FE analysis techniques, which do not take into account the impact of end-winding leakage flux on the inductance of the machine. Evidence for this is that the effect is shown to be more pronounced in unaligned rotor position than in the aligned position. Were the cause, for example, due to variations between the modelled and real B-H characteristics of the material then the effect would be less evident in the unaligned position, where the magnetic circuit is dominated by the large unaligned airgap, than in the aligned position, where the magnetic circuit is influenced more by the core material used in motor construction.

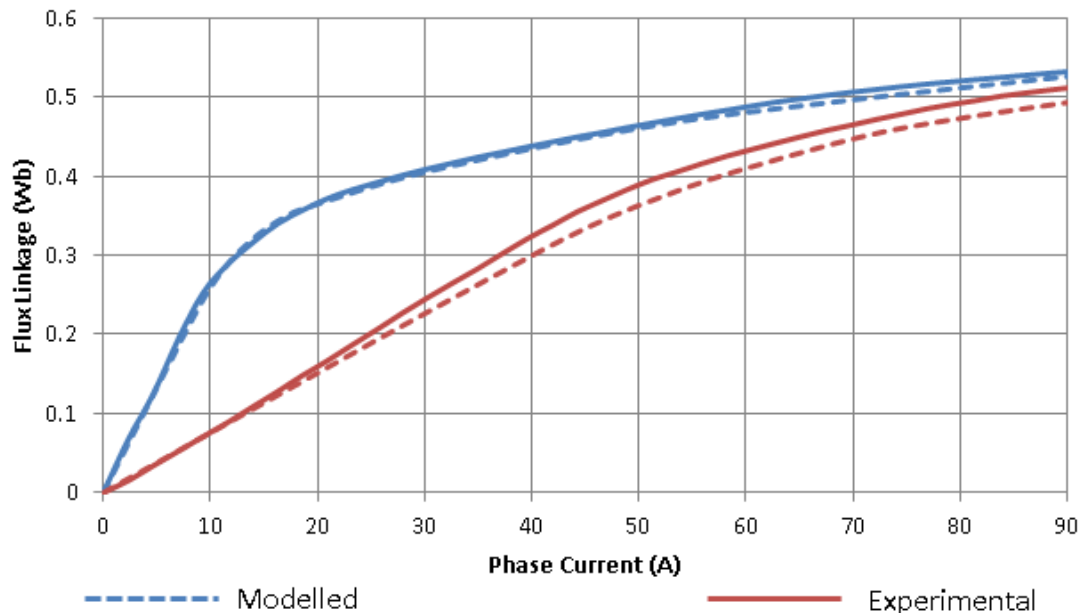


Figure 4-10: Comparing experimental and modelled Flux per Phase data for 12-16 Segmental Rotor SRM in the aligned and unaligned positions over a range of Phase Currents (peak).

It is then also possible to calculate the torque from this data, with torque being directly proportional to the co-energy, which is represented by the area between the unaligned and aligned flux characteristics. The resulting torque comparison between the modelled and constructed motors is shown in Figure 4-11, with perfect current control being assumed (0deg advance angle, 180deg conduction and a perfect square wave current

profile). The figure clearly shows the impact of flux leakage in the end-windings, with little impact on motor torque below 30A(pk) (6.5A/mm^2) but then increasing significantly so that torque is reduced by 10% at 90A(pk) (or 19.5A/mm^2).

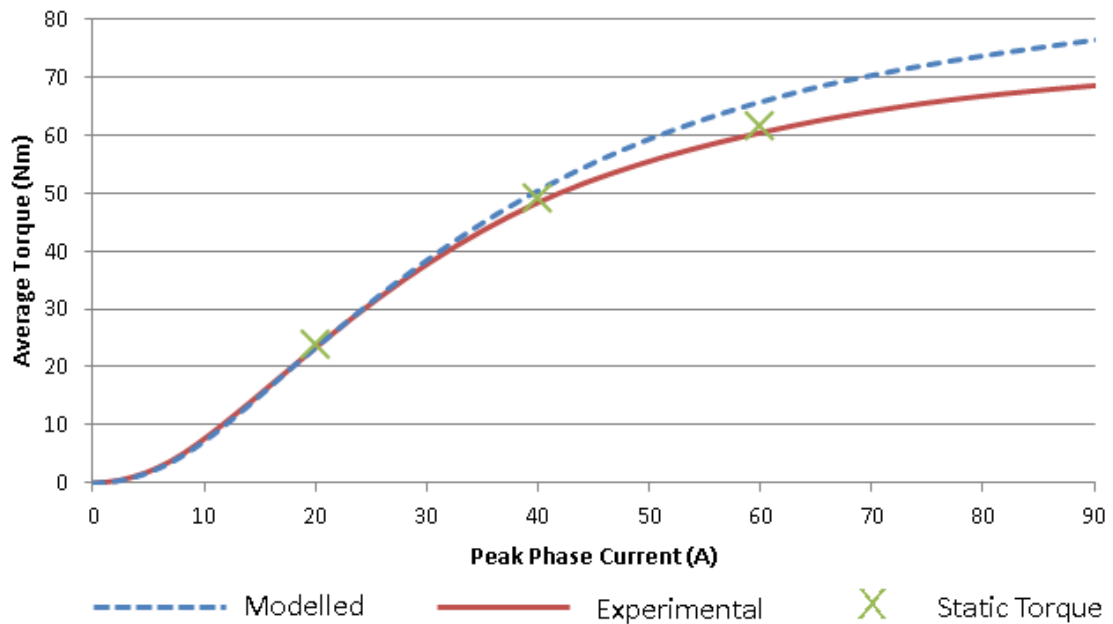


Figure 4-11: Comparing experimental and modelled Torque data for 12-16 Segmental Rotor SRM over a range of Phase Currents (peak), assuming perfect current control (experimental results derived from measured flux linkage curves). Static Torque data points are calculated from the experimental data presented in Section 4.2.2.

4.2.2 Static Torque Test

Again using the rotary table, a static torque test was undertaken. A 100Nm torque transducer was mounted between rotary table and motor. Again an angular increment of 1 degree was used for this test, with a DC source being used to inject current into a single motor phase. Figure 4-12 shows the resulting torque characteristic versus rotor angle. This supports the findings earlier, with there being a good correlation at lower levels of current, with this correlation weakening as current levels increase. Again this is likely to be due to the impact of motor end-winding flux leakage. If average motoring torque is then calculated from this static torque characteristic and compared to the torque calculated from the flux linkage data, as shown in Figure 4-11, there is strong correlation.

4.2.3 Thermal Tests

In order to confirm the performance of the 12-16 Segmental Rotor machine, a thermal test was undertaken. This test was undertaken at 5A/mm^2 as this would be expected to result in relatively moderate temperature rises, allowing the test to be run until the motor reached a steady state temperature. Iron losses were not considered.

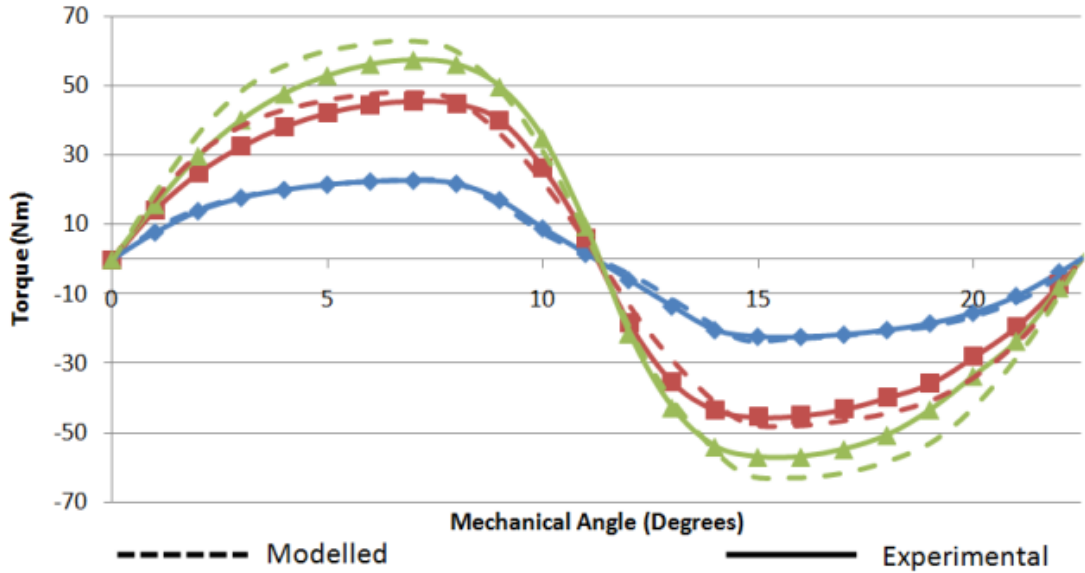


Figure 4-12: Comparison of experimental and modelled Static Torque characteristics for 12-16 Segmental Rotor SRM at a Phase Current of 20A, 40A and 60A.

K-Type thermocouples were embedded in the motor windings (buried in the centre of the slot). The three motor phases were connected in series and a DC current equating to the required current density (16.7A) injected. A fan was used to force air axially over the stator housing, leading to a convection cooling condition. The temperature rise in the thermocouples was then sampled at 10s intervals until a steady state condition was reached. Figure 4-13 demonstrates the results of this test.

A simple thermal model was then constructed, assuming that the temperature rise in the windings was the resultant of two separate thermal masses. Firstly the thermal mass of the windings themselves and secondly the thermal mass of the complete motor housing. This thermal model is characterised by the following equation, where $T(t)$ is the temperature rise in respect to time:

$$T(t) = T_{coil}(1 - e^{-\frac{t}{\tau_{coil}}}) + T_{case}(1 - e^{-\frac{t}{\tau_{case}}}) \quad (4-2)$$

Where T_{coil} is the maximum temperature rise due to the coil thermal mass and T_{case} the maximum temperature rise due to the thermal mass of the case; τ_{coil} and τ_{case} are the thermal time constants for the coil and case respectively. Table 4-2 summarises the results of a curve fit of equation (4-2) onto the experimental data.

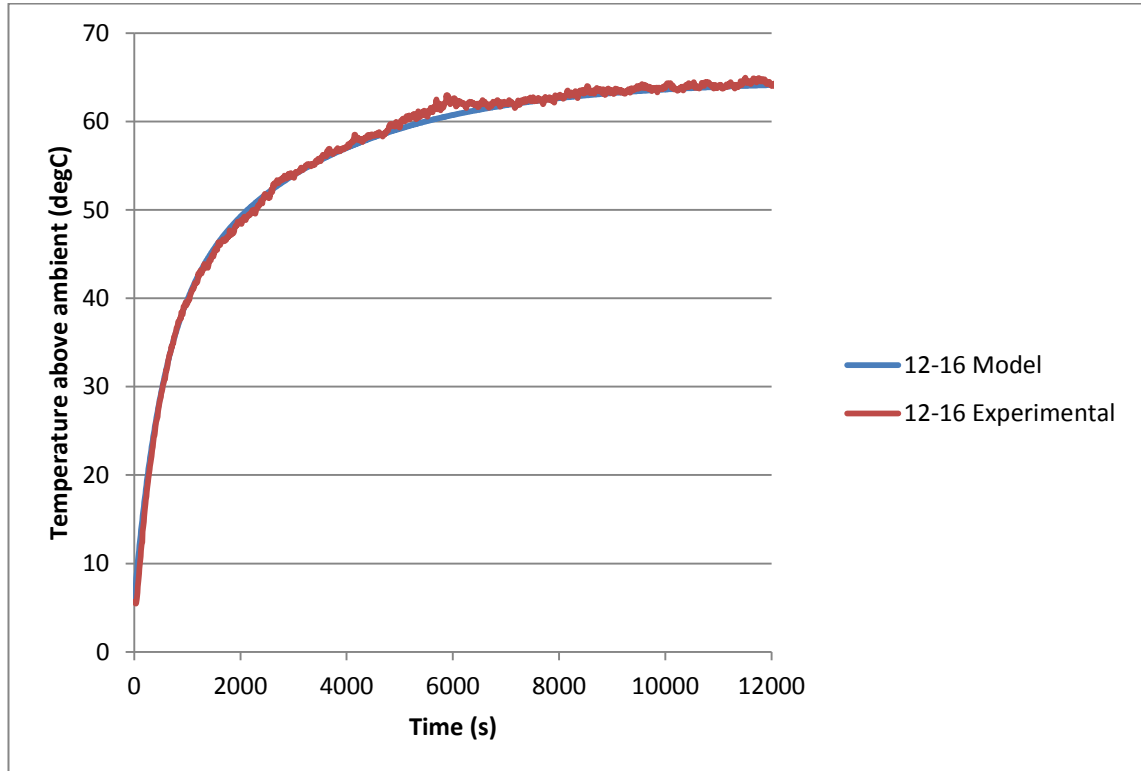


Figure 4-13: Results of a thermal test for the 12-16 machine with $5A/mm^2$.

Table 4-2: Coefficients from curve fit with 12-16 thermal test experimental data for $5A/mm^2$.

Coefficient	Value
T_{coil}	$30^{\circ}C$
τ_{coil}	$500s^{-1}$
T_{case}	$29^{\circ}C$
τ_{case}	$3000s^{-1}$

If it is assumed that the ratio between T_{coil} and T_{case} remains constant for all values of $T(t)$ then some predictions can be made about the limits of the continuous performance of the motor. Assuming that the motor winding temperature rise should be limited to no more than $100^{\circ}C$ over ambient and that peak winding temperature is proportional to

winding loss, it can therefore be calculated that a maximum copper loss of about 700W would be acceptable (at low speeds, therefore assuming that iron losses may be disregarded). For a winding temperature of 100°C over ambient, this would equate to a current of 20.6A(rms) and thus a current density of 6.2A/mm² (assumed the achieved fill factor of 0.415). This in turn, from the data presented in section 4.2.1, would equate to a peak current of 29.1A continuous torque of 37Nm, assuming convection cooling and low speed operation.

4.3 Conclusions

The construction of the 12-16 Segmental Rotor SRM provided partial validation of the modelling presented in Chapter 3. Up to about 6.5A/mm² (or 40Nm) the electromagnetic performance of the constructed motor matched predictions well; however over this level the constructed motor's performance was reduced due to the effects of end-winding leakage.

This leads to the conclusion that whilst 2D FE is a valid tool for the optimisation of this class of machines, care must be taken at higher current densities to make some allowance for 3D effects.

The winding resistance of the constructed machine was found to be some 30% higher than had been predicted; this was due to the introduction of very long end-windings during the process of construction. It is thought that these windings could have been shortened somewhat, however it is likely that they would remain longer than had been predicted. This impacts the performance of this machine significantly, increasing losses and therefore reducing its thermal capability. Thermal modelling has shown that the motor will produce a steady-state torque density of 9.3kNm per m³ for a convection cooled machine. However in conclusion, this shows that machines with fully pitched windings are not the optimum solution. As a result, a focus on motors with single tooth windings will reduce end-winding losses, whilst also simplifying manufacture.

In terms of motor construction, the method of using rotor segment lamination rings was successful and, in particular, where such a large number of rotor segments are employed, this process does reduce manufacturing effort in low volumes. The balancing of the rotor using washers bolted into the rotor end caps was also successful and will be applied to future motor designs.

PART 2: DYNAMIC PERFORMANCE
OPTIMISATION AND COMPRESSED ALUMINIUM
WINDINGS

Chapter 5. Dynamic Optimisation of Outer Rotor Brushless PM Machine for use in a Solar Powered Aircraft

At its core this project is focused on the development of the Segmental Rotor SRM for use in electric vehicles, however this chapter explores instead the development of an Outer Rotor Brushless Permanent Magnet Machine for use in a solar powered aircraft application. Whilst this represents a divergence from the central focus of the project, the development of this motor in two specific areas informed the further development of the Segmental Rotor SRM discussed further later in this thesis.

The first common link between the Outer Rotor Permanent Magnet and Segmental Rotor SRM machines is that both must be efficient and lightweight and therefore share common optimisation goals. Indeed the optimisation of this Outer Rotor Brushless PM machine very much formed, both in terms of approach and timeline, a mid-point between the static optimisation described in Chapter 3 and the more complex optimisation to be described in Chapter 7. The second link relates to the use of compressed aluminium windings and will be discussed in Chapter 6.

This chapter will therefore describe the process of optimisation that was applied to this Outer Rotor PM machine, the validation of this process and also seek to develop links to the optimisation of Segmental Rotor SRMs.

It should be noted that the work described in this chapter was funded by QinetiQ, a leading UK aerospace developer, and formed part of a larger contract. As such, and at the request of the funder, details of aspects of the design specification have been omitted from this thesis.

5.1 Requirements for Electrical Machines for Solar Powered Aircraft

The development of the perpetual, solar powered aircraft has over recent years become a reality, with both the UK's QinetiQ Zephyr [93] and Swiss Solar Impulse [94] aircraft demonstrating the technology's feasibility.

Zephyr, which incorporates motors and drives developed at Newcastle University [95] (see Figure 5-1), currently holds the world record for the longest autonomous flight for any aircraft. It is this motor which has formed the basis for the development of a new 6kW motor for a much larger solar powered aircraft which is discussed in this chapter.

The developed motor is required to offer extremely high efficiency during the aircraft's 'cruise' phase, with a very challenging mass requirement in order to assist in the maintenance of very low aircraft weight. These requirements are contradictory as generally a larger motor will have better efficiency and a smaller motor lower mass. The motor is also required to provide an extensive overload capability in order to support aircraft take-off, whilst being able to operate reliably at altitudes of up to 60,000ft and temperatures as low as -70°C and for up to 5 years continuously.

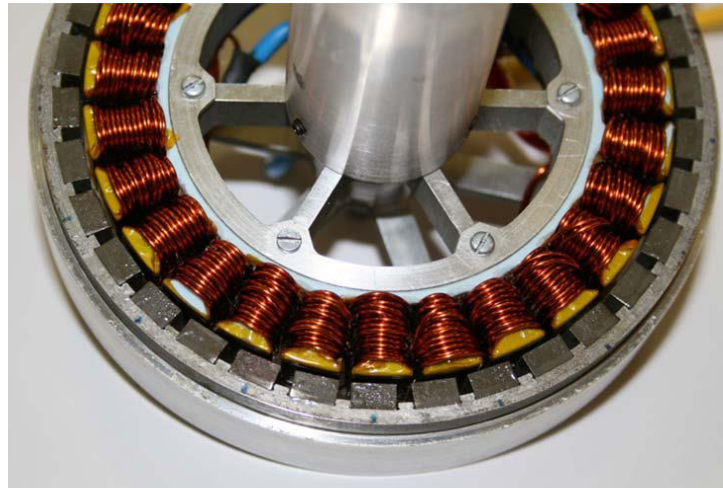


Figure 5-1: Zephyr demonstrator motor with outer rotor and single tooth wound inner stator

5.2 6kW Outer Rotor PM Motor Design

5.2.1 Basic Motor Design

For this new motor, based on the findings of the Zephyr project, a large diameter outer rotor Permanent Magnet Surface Mount design was once more selected. The university's previous work [95] had shown that this design offered the optimum balance of low mass and low losses. A permanent magnet machine intrinsically offers the lowest losses for a small machine of this type, whilst an outer rotor design maximises the airgap diameter for a given active mass. Based on a simplistic analysis, large diameter rotors can be shown to require a lower magnetising field strength and therefore electrical loading to produce the same torque. Therefore a large diameter and as short an axial length as practical can be shown to offer the potential for low copper losses. In order to reduce iron losses a very low loss, 6.5% silicon steel (10JNEX900 from JFE steel) was again to be used, as was also the case with Zephyr.

The specification for this electrical machine required that it would operate at a number of specific torque speed points, the most important of which was the ‘Cruise’ condition. In this condition the motor would be operating at medium speed and circa one third power (exact details are not provided due to confidentiality). This represented the operating point at which the motor must be at its most efficient, being able to sustain aircraft flight for many hours with minimal losses. Therefore it was this operating point which would form the basis for the optimisation of the electrical machine.

5.2.2 Pre-Optimisation Study

Prior to motor optimisation, a number of studies were undertaken to confirm the most suitable materials to be used during the optimisation process. Table 5-1 compares the materials used in the original Zephyr motor with those which it was decided would be most suitable for this larger machine.

Table 5-1: A Comparison of materials used by Zephyr and proposed for use as the starting point for optimization of the new Motor.

Component	Zephyr Materials	Proposed Motor Materials
Stator Laminations	JFE Steel 10JNEX900 (0.1mm laminations)	JFE Steel 10JNEX900 (0.1mm laminations)
Rotor Coreback	Mild Steel (un-laminated)	JFE Steel 10JNEX900 (0.1mm laminations)
Magnet	Sintered 32/31 NdFeB (B(r) = 1.17T)	Arnold Magnetics Bonded NDFeB BNP-12 (B(r) = 0.73T)
Copper	5.77e7 S/m copper (33% fill factor target)	5.77e7 S/m copper (44% fill factor target)

Retained from Zephyr was the use of the JFE Steel 10JNEX900. This material had been demonstrated to have extremely low losses during the Zephyr design process. It has a 0.1mm lamination thickness and has specified losses of less than 14W/kg at a flux density of 1T and a frequency of 1kHz. This material has a very high silicon content; from discussions with both Tata Steel and JFE Steel, generally 3% is the limit of alloyed silicon content. However JFE steel had developed a process which allows the diffusion of much higher levels (6.5%) of silicon, which is an optimum in terms of

minimising losses. According to Tata Steel, silicon content must generally be reduced where lamination thickness drop below 0.3mm; this is to reduce the brittleness of the material and so improve mechanical handling. For example Tata Steel NO10 and NO20 grades both have lower silicon content than NO27. However at 6.5% silicon, JFE claim that brittleness is naturally reduced and in fact it was not found to be a particular concern during prototyping. Drawbacks of this material, however, are its high cost and the general difficulty of working with such thin material, despite its reasonable pliability.

Since the development of Zephyr, a number of more advanced transient finite element methods had become available which also suggested changes to other motor materials.

The use of 10JNEX900 in the rotor coreback was shown to reduce total machine iron losses by approximately 35% (10 Watts). Generally speaking the flux densities in surface mounted permanent magnet rotors are assumed to be in effect static, allowing the use of mild steel. However for a machine such as this, where losses are very low, the increase in cost and complexity from using a laminated coreback material was acceptable if losses were reduced.

During the period when this motor was being developed, there was concern over the timescales for the availability of sintered NdFeB magnets. As a result other magnetic materials were considered, including both SmCo and bonded NdFeB. Detailed transient modelling studies showed that despite the lower remanence of bonded NdFeB magnets, their very high bulk resistivity meant that overall motor losses were reduced in the order of 0.2% (4W). With the motor airgap decreased from 2mm to 0.6mm to compensate for the weaker magnetic material, a small increase was noted in copper losses (1W) but this was offset both by the elimination of 90% of eddy current loss in the magnets (2W) and also a reduction in iron losses due to the still lower airgap flux density.

It was also considered that the 0.33 fill factor which had been achieved with Zephyr was conservative for a larger machine. As a result the slot fill factor was estimated, through the use of an aluminium mockup of a single section of the stator (see Figure 5-2). This was wound with two differing diameter copper wires, expected to be representative, and an average fill factor of 0.45 was achieved. This was considerably better than the 0.33

which have been achieved with the Zephyr prototypes and this higher number was therefore used as the basis of the winding loss calculations.

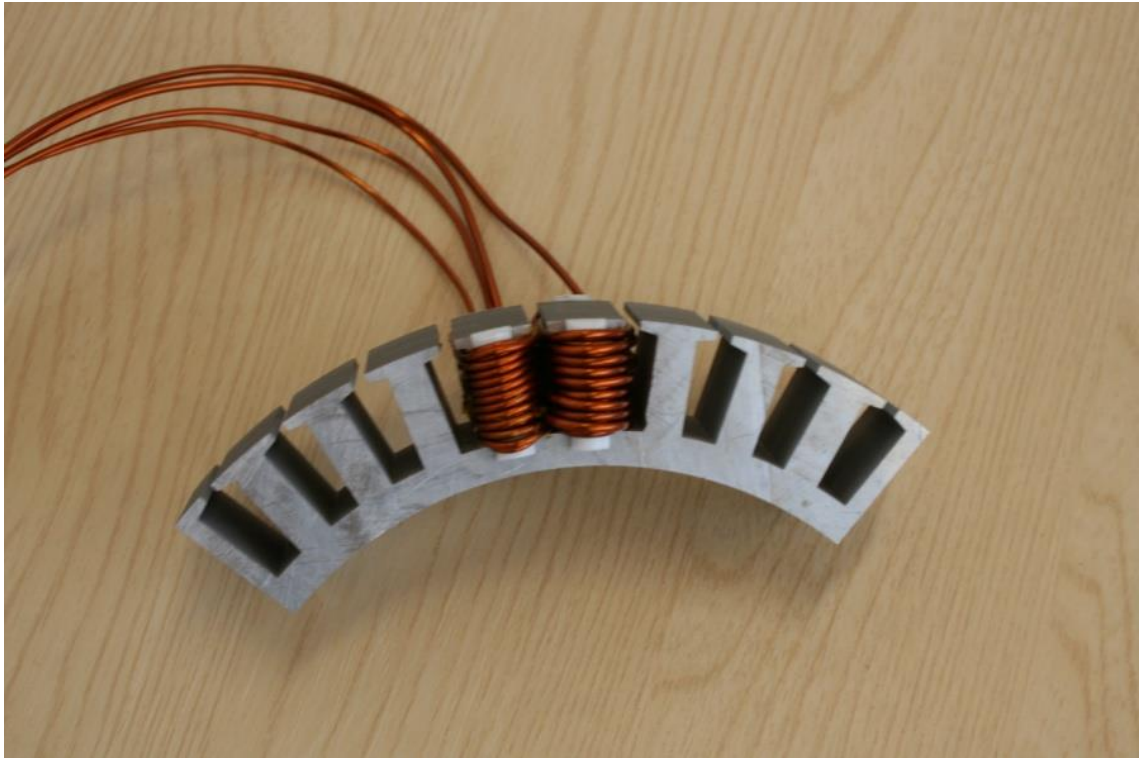


Figure 5-2: Winding prototype used to estimate winding fill factor.

5.3 Optimisation Objective Function

In this case, an optimisation objective function was supplied by QinetiQ. This function took into account two key criteria for the use of this motor on the solar powered aircraft. Firstly that the motor must be as efficient as possible and secondly, somewhat at odds with the first requirement, that it must also be as lightweight as possible. Therefore this objective function sought to find a balance between these two contradictory requirements.

In order to achieve this a method was needed of equating motor mass to motor efficiency; QinetiQ were able to do this through the use of detailed, aircraft level energy models. Motor efficiency would have a direct effect on aircraft mass; the lower the efficiency the more energy storage would be required. Equally mass would have an impact of efficiency; the more mass, the larger the work required to overcome the force of gravity.

As a result an objective function in the form shown below was developed:

$$\text{Objective Function} = \eta - k_{mass} \cdot \text{Mass} \quad (5-1)$$

where η is the efficiency of the motor in the cruise condition and k_{mass} a constant which provides a conversion between mass and efficiency; the objective being to maximise the function. The value of k_{mass} is not provided due to confidentiality.

In order to assess this objective function, it is necessary to be able to assess motor efficiency accurately at the cruise condition. For this type of machine this can be approximated by applying a sinusoidal current waveform of the correct magnitude at the correct phase angle (i.e. with peak current in the q axis) in order to maximise motor torque. However the level of motor current required in order to achieve this torque varies dependent on the precise motor geometry and therefore it is necessary to individually set the peak phase current for each optimisation candidate.

An optimisation approach was needed which would allow the correct phase current to be selected, providing the correct level of torque in order to allow a meaningful calculation of the objective function.

5.3.1 Sources of Loss

The following sources of loss were considered as part of the calculation of efficiency:

- **Copper Losses;** related to the conductivity, cross-sectional area and length of the conductor material, these losses can perhaps be primarily minimised by increasing the fill factor. For this study an ambient temperature of -50°C can be assumed, based on in-flight measurements of coils in the preceding Zephyr aircraft. Winding resistance is calculated by a custom script within the Infolytica MagNet tool, which takes into account both winding cross sectional area and estimates end winding length; both based on the variable geometrical parameters within the finite element model (for example slot area or tooth width). These losses can be calculated as part of a transient motor model run;
- **Iron Losses;** built from hysteresis, eddy current and anomalous losses, in this study these losses are estimated based on Infolytica's internal iron loss calculation algorithms. Losses in both stator and rotor iron are taken into account. Infolytica MagNet calculates iron losses via post-processing of transient finite element results; this considers eddy current and anomalous losses

in the frequency domain, whereas hysteresis losses, in order to take into account the effect of minor hysteresis loops, are considered in the time domain. This aligns with Newcastle University's previously developed best practice [75]. In addition the decision was also taken to apply a 'build factor' of 1.6, developed by Hargreaves [88], which takes into account the effect of manufacturing on constructed motors. Whilst Hargreaves work was based on larger machines, it was nevertheless considered a good starting point for this project;

- **Magnet Losses;** eddy currents may be induced in the magnets used in permanent magnets machines. These eddy current losses are directly calculated as ohmic losses by the FE toolset;
- **AC Winding Losses;** two sets of AC winding losses are possible. Firstly proximity losses due to the effect of magnets passing the stator slot openings. This creates space harmonics in the airgap field which in turn induce eddy currents in the windings. Secondly the winding can also self-induce eddy currents, as the MMF in the windings varies so does the coil flux. This flux will fringe across the slot opening, creating a time varying field which, if of high enough frequency, will induce eddy currents in the motor windings. These eddy currents can be very large, however they can be mitigated by reducing the diameter of the motor winding wire. Work by Hall [96] has provided a methodology for these calculations, however this cannot readily be undertaken as part of a standard transient analysis, requiring special and detailed FE models to be constructed. Therefore it is assumed that these losses can be minimised by reducing coil diameter as part of the detailed design process and as such they are disregarded;
- **Friction and Windage;** friction and windage losses are disregarded at this stage as both are difficult to estimate in the Cruise condition. Windage losses at the low air pressures found at high altitudes will, in any case, be likely to be low. Friction losses are dominated by the bearings; special, custom bearings are needed for this application and therefore their development and loss reduction was part of a separate activity.

5.4 Optimisation Approach

A fully dynamic, transient approach was applied to the optimisation of this electrical machine; a schematic outlining this process can be found in Figure 5-3. As with Chapter

3, this process was based on the use of the evolutionary optimiser included in Infolytica's OptiNet tool.

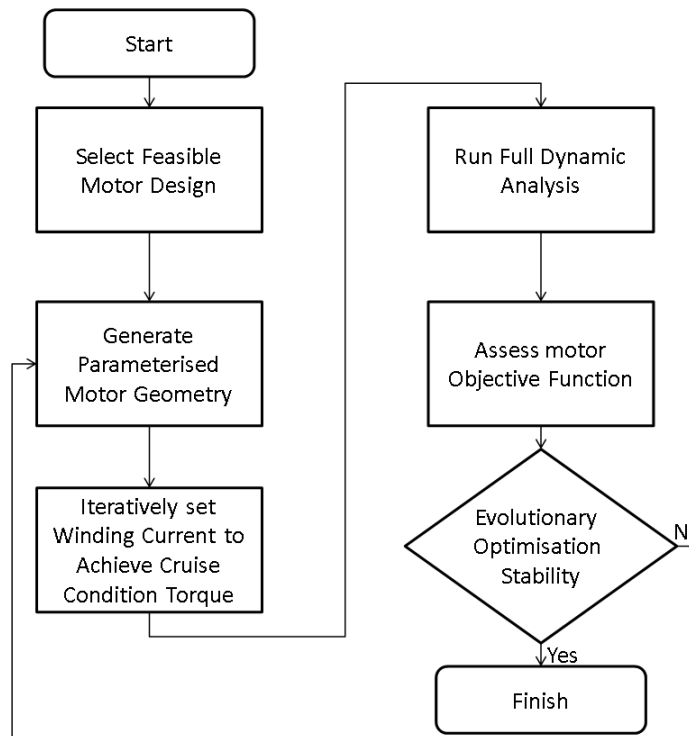


Figure 5-3: Optimisation Processed applied to the Outer Rotor PM Machine.

Firstly, a feasible motor design, scaled up from the outer rotor design used in the Zephyr aircraft, was selected. Several slot / pole combinations were considered, with a single combination forming the basis of each optimiser run (see Section 5.4.1 for more details). A Visual Basic script was then used to set up a fully parameterised model of this motor in the finite element software, where all motor dimensions could be varied continuously iteration by iteration by the optimiser and no limit was placed on motor diameter or length (more details in Section 5.4.2). For each optimiser iteration, a second iterative process was then used to set the winding current in order to achieve the Cruise condition torque within +5%/-0% (see section 5.4.3). A full dynamic, transient analysis of the motor was then run in order to allow the calculation of motor copper and iron losses (Section 5.4.4). Finally the objective function was assessed and the evolutionary algorithm allowed to continue until it has stabilised. This process was run several (three or more) times for each slot pole combination in order to eliminate outlier solutions.

5.4.1 Feasible Motor Design Selection

The Zephyr motor design was used as the basis of the development of this new, larger electrical machine. The machine was scaled, based on parametric calculations, in order to meet the higher torque and power requirements.

A physical design change was however introduced; the pole and slot number combination was varied in order make finite element modelling of the machine less computationally demanding. The original Zephyr motor was designed with 27 stator teeth and 34 rotor poles. In this configuration the slot and pole numbers share no common integer divisor; such a configuration is desirable in that it reduces torque ripple and cogging torque to a minimum. This configuration however has two disadvantages. It carries a risk of unbalanced magnetic pull, which whilst not a major concern in the smaller Zephyr machine, would represent a greater risk to the durability of the new machine (particularly with this new machine expected to have an operational life of many years). Secondly, the design also forces the finite element modelling of a complete, 360 degree motor, which is computationally expensive. Therefore in both cases it was considered better to trade off some of the low torque ripple / cogging torque characteristics, by allowing a sensible common divisor, eliminating the risk of unbalanced magnetic pull and allowing the motor to be modelled as a fractional section.

As a result, and based initially on engineering judgement, a basic slot pole combinations of 9.x Stator Slots / 10.x Rotor Poles (x being a positive integer) was chosen. Figure 5-4 shows the fractional FE model of one example, a 36 slot 40 pole machine. As machines with low numbers of poles require deep corebacks and therefore tend to be large and heavy, these were discounted. Equally machines with very high slot/pole numbers may become impractical to manufacture and so again these were discounted. As a result the following combinations of slots / poles were optimised: 27/30, 36/40 and 45/50. Based on these results it was also later decided to assess a 36/32 and 54/36 machine in order to see if reducing the number of poles would result in an improvement in efficiency due to reduction of iron loss from the reduction in electrical frequency.

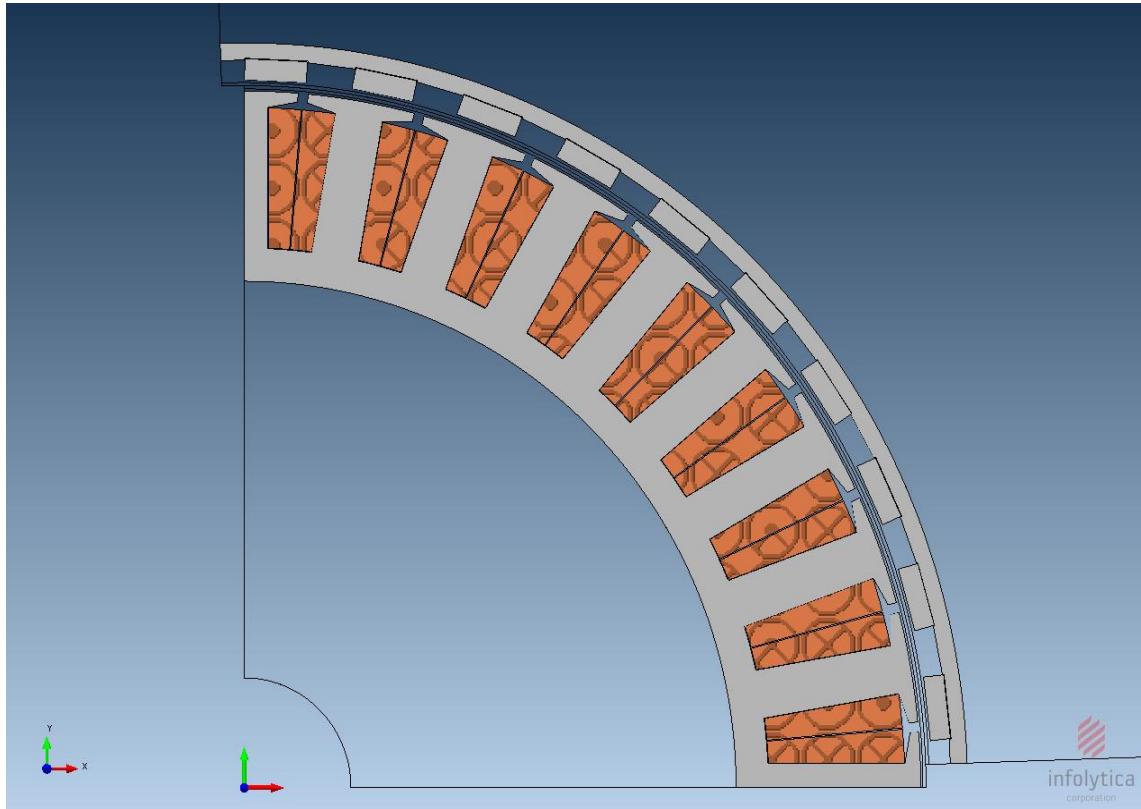


Figure 5-4: An example, fractional model of a 36/40 outer rotor permanent magnet motor.

5.4.2 Parameterised Motor Geometry

A Visual Basic script was developed which allowed the rapid generation of differing motor slot and pole geometries. These models are parameterised, allowing all aspects of the motor geometry to be varied continuously. In particular external motor dimensions (outer diameter, inner diameter and stack length) were allowed to vary with only very broad limits being placed on them; overall motor size would be limited instead by the objective function, which would seek to minimise mass. Inner motor dimensions (such as those relating to airgap, corebacks, motor teeth and magnets) were allowed to vary within set limits unless such variation would result in impossible geometries, for example where features overlapped one another.

For each iteration, the optimiser arbitrarily set motor dimensions within these bounds, in accordance with its internal evolutionary algorithm.

5.4.3 Iterative Winding Current Search Algorithm

In order to allow the valid comparison between each motor geometry, it is essential that this comparison is undertaken at the correct torque and speed. Selection of the speed is

trivial; however selection of the correct torque requires the selection of the correct level of phase current. For a permanent magnet machine it may be assumed that a sinusoidal current input be applied, with the peak being applied in the q axis. However, in order to set the level of peak torque it is therefore necessary to derive the peak value of current.

For this optimisation an iterative process to set the level of phase current was implemented. In this process, an arbitrary number of turns (10) is selected and an initial level of peak phase current, estimated based on the following equations (taken from basic machine theory and assuming unity power factor):

$$A = \frac{T}{\sqrt{2} \cdot B_{gmax} \cdot \pi \cdot \left(\frac{D_{ag}}{2}\right)^2 \cdot l} \quad (5-2)$$

where A is the RMS electrical loading of the machine required to achieve a Torque, T , with magnetic loading, B_{gmax} , airgap diameter, D_{ag} and length l ; and therefore:

$$I_{pk} = \sqrt{2} \frac{\pi \cdot D_{ag} \cdot A_{rms}}{6 \cdot N} \quad (5-3)$$

where I_{pk} is the initial peak phase current (assuming as sinusoidal distribution) and N the number of series turns per phase.

An iterative script, written in Visual Basic, is then run. This script first runs a transient with motion solve in 2D FE, assuming sinusoidal current input and the calculated peak current, in order to calculate average torque. A small number of steps per cycle (15) are used to provide this first estimate and the solver is run over two electrical cycles, with the first discarded to exclude settling transients. If the average torque from this solution is within +5%/-0% of the required Cruise torque, then the process completes. If not the script extrapolates the initial current value (assuming that the relationship between current and torque is linear) with the aim of achieving the correct torque. If successful the process completes or otherwise iterates again until a solution is found. As generally there is indeed a linear relationship between current and torque, the search is generally found to settle after one or two iterations.

5.4.4 Full Transient Solution and Objective Function Calculation

Once the required phase current has been set, a full transient with motion solution is undertaken. Over three electrical cycles and with 30 steps per cycle, this is a more

accurate solution and is used to calculate RMS phase currents, average motor torque, iron losses and magnet eddy current losses.

Phase resistance, including the end windings, is calculated manually by reference to the tooth and slot geometries; the phase resistance is calculated at -50°C as this is the ambient temperature which has been recorded in phase windings during the Cruise condition on the Zephyr aircraft.

Iron losses are taken from the FE and multiplied by a build factor of 1.6 [88], as was also the case in Chapter 3. Finally eddy current losses in the bonded magnets are calculated, based on ohmic loss information available in the finite element tool. Total machine efficiency can then be calculated.

Finally motor mass is estimated, again parametrically based on the known motor dimensions and material densities. Mass is calculated separately for rotor and stator iron, magnets, windings and for both stator and motor supporting structures. From these results the objective function can then be calculated.

5.5 Optimisation Results

Figure 5-5 shows the results of the initial optimisation process; the figure presents each optimisation run as a point on a scatter chart with the x axis representing efficiency and y axis mass. An iso-line is also shown; this represents the continuum of possible combinations of efficiency and mass that would produce an objective function equal to the best achieved.

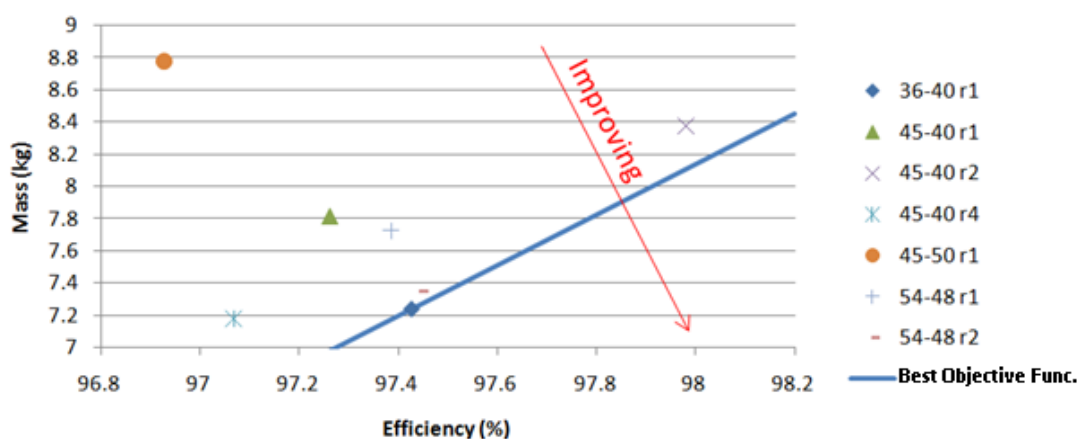


Figure 5-5: Results of the initial optimization runs; the chart compares the results of the optimisation of machines with different slot and pole combinations. Blue line is the iso-line for the best objective function achieved.

For this initial optimization, the range of masses between the differing designs was about 1.6kg (18%) whilst the range of efficiencies was lower, at less than 1%.

Whilst only a small number of optimisation runs were undertaken at this stage, it was concluded that the 36 slot, 40 pole machine would provide a good basis for further design work. Whilst the 54 slot, 48 pole offered similar levels of performance, that machine would have smaller physical features than the 36 slot machine, potentially making manufacture more difficult; particularly when considering the use of the very thin 0.1mm 10JNEX900 material.

Based on these initial findings, further optimisation runs were undertaken with the 36 slot / 40 pole design (see Figure 5-6). Figure 5-7 provides a flux plot of each of the four machines operating in the Cruise condition.

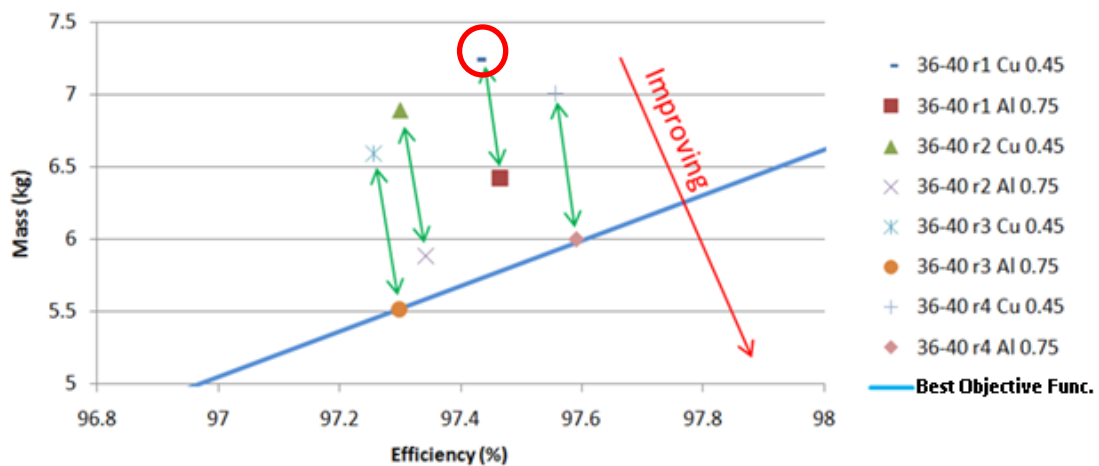


Figure 5-6: Results of the final optimisation runs; considering only 36 slot, 40 pole machines, with both 45% copper and 75% compressed aluminium windings. The green arrows link the objective functions of motors with the same geometry but with either copper or aluminum windings. Blue line is the isoline for the best Objective Function achieved. The red circle indicates the previous, best design taken from Figure 5-5.

These later optimisation runs considered three winding configurations. Firstly the continued use of 0.45 fill factor copper windings and secondly also considered were 0.75 fill factor compressed aluminium windings. These windings are the subject of Chapter 6, however in summary this assessment showed that they would reduce motor mass by circa 15% whilst increasing efficiency marginally. Also considered at this

stage, but not shown in Figure 5-6, were compressed copper windings. Calculation showed that in a machine with this aspect ratio (large diameter, short length) they would not be as advantageous. Whilst losses would be improved by about 30%, overall motor mass would increase by about 15%, which was considered unacceptable. As Chapter 6 deals with compressed aluminium windings, the remainder of this chapter will focus only on the 0.45 fill factor copper wound machines.

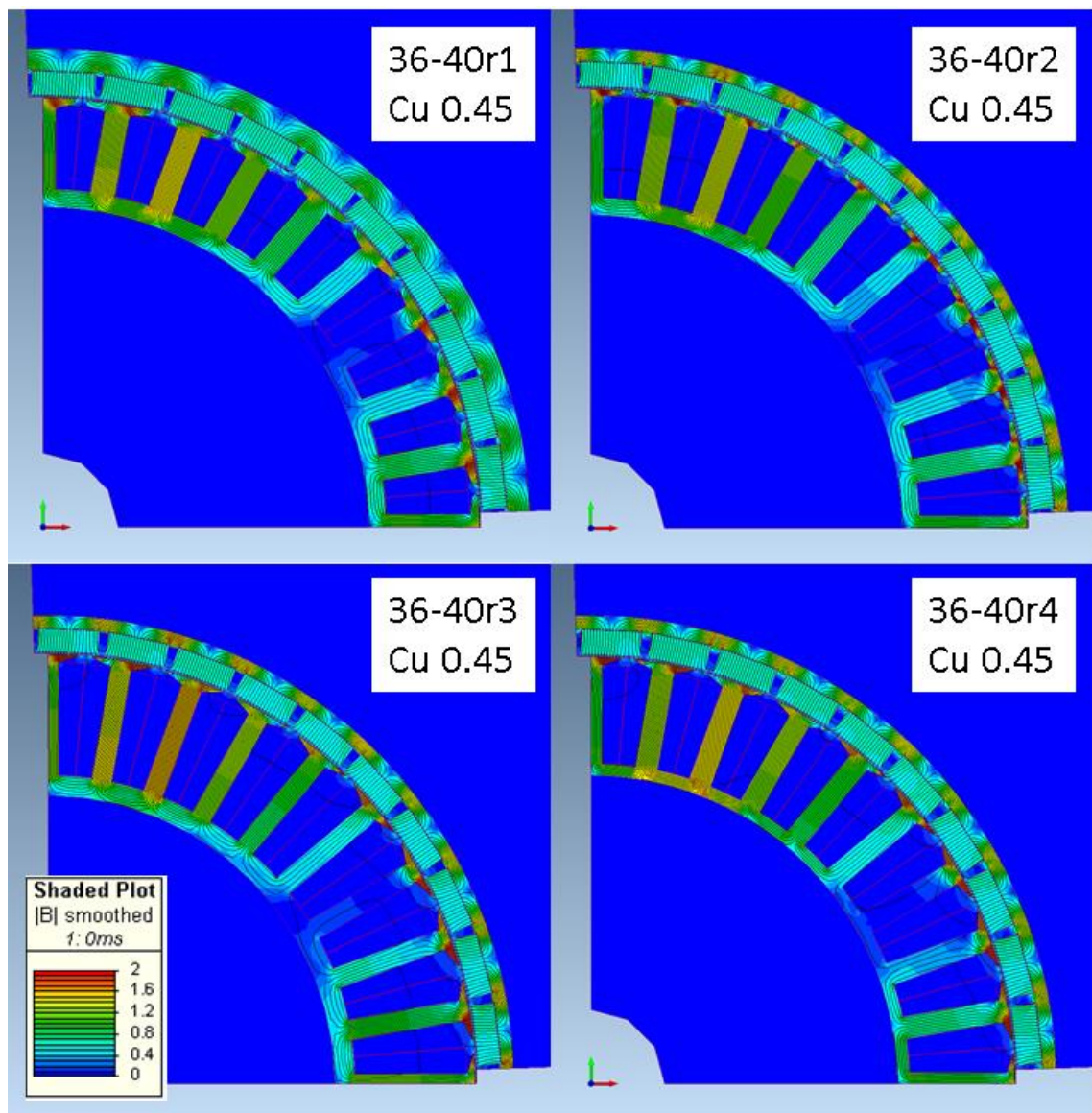


Figure 5-7: Flux plot showing the 35 slot, 40 pole motors operating in the Cruise condition.

From an inspection of Figure 5-6, it was found the range of masses was 0.7kg and the range of efficiencies just 0.3%. This is a far smaller range than for the initial optimisation run and consistent with only the 36 slot / 40 pole configuration being considered. This indicates that for a single slot and pole combination the solution

surface is actually very flat, offering little variation in performance between different optimisation runs.

Table 5-2 compares the dimensions of the four 36 slot / 40 pole machines whilst Table 5-3 compares their performance, in the Cruise condition. Table 5-4 compares the maximum current and copper loss during the ‘Take-Off’ (maximum torque) condition.

Table 5-2: Comparing 36 slot, 40 pole motor dimensions for four optimisation runs.

Parameter	36-40r1 Cu 0.45	36-40r2 Cu 0.45	36-40r3 Cu 0.45	36-40r4 Cu 0.45	Range
Rotor OD	251.6mm	252.1mm	246.0mm	245.7mm	3%
Stator OD	225.4mm	230.2mm	225.5mm	223.8mm	3%
Stator ID	167.9mm	164.3mm	151.2mm	161.8mm	10%
Stack Length	25.1mm	22.8mm	21.1mm	26.1mm	19%
Airgap Length	0.5mm	0.7mm	0.6mm	0.6mm	29%
Tooth Width	6.6mm	6.4mm	5.4mm	5.9mm	18%
Slot Depth	21.6mm	26.8mm	29.7mm	25.8mm	27%
Stator Coreback Depth	4.7mm	4.7mm	5.3mm	3.2mm	40%
Rotor Coreback Depth	5.7mm	3.3mm	3.0mm	3.3mm	47%
Toothtip Gap	1.5mm	1.7mm	1.8mm	1.7mm	17%
Magnet Depth	6.7mm	6.8mm	6.4mm	6.9mm	7%
Magnet Arc	16.8mm	17.1mm	16.3mm	16.0mm	6%

Table 5-3: Comparing 36 slot, 40 pole data in the Cruise condition.

Parameter	36-40r1 Cu 0.45	36-40r2 Cu 0.45	36-40r3 Cu 0.45	36-40r4 Cu 0.45	Range
Power	1815.2W	1835.4W	1822.6W	1837.4W	1%
Peak Current	28.5A	34.3A	37.8A	29.2A	25%
Copper Loss	33.1W	37.1W	38.0W	30.0W	21%
Iron Loss	14.9W	13.5W	13.2W	15.8W	16%
Magnet Loss	0.3W	0.3W	0.3W	0.3W	0%
Total Loss	48.2W	50.9W	51.4W	46.0W	11%
Efficiency	97.4%	97.3%	97.3%	97.6%	0%
Mass (estimated)	7.24kg	6.89kg	6.59kg	7.01kg	9%

Table 5-4: Table comparing the Take-Off (maximum torque) copper losses between the differing optimised 36 slot, 40 pole motors.

Parameter	36-40r1	36-40r2	36-40r3	36-40r4	Range
	Cu 0.45	Cu 0.45	Cu 0.45	Cu 0.45	
Power	3475.3W	3455.7W	3446.4W	3494.9W	1%
Peak Current	109.5A	130.5A	192.2A	107.0A	44%
Copper Loss	695.1W	738.6W	1348.5W	540.5W	60%

These tables, along with Figure 5-7, show that there are many similarities between the machines, as well as a number of key differences. There is very little variation between the outer diameter of the stator and rotor in each case, defining the overall diameter of the motor and its airgap diameter respectively. However stack length, which would therefore define the volume of the machine, is far more variable. The most significant differences however are between coreback depths. Magnet dimensions show little variation.

In terms of motor performance, it is the stack length which appears to have the biggest impact. The longer machines ('36-40r1 Cu 0.45' and '36-40r4 Cu 0.45') are heavier but require less current as they are operating further from saturation; this effect can also be seen in Figure 5.7 when in particular '36-40r3 Cu 0.45', the lightest machine, is already quite heavily saturated. This is shown even more clearly in Table 5-4 where the shorter machines have much higher copper losses than the longer machines.

Whilst '36-40r3 Cu 0.45' was marginally the best machine in terms of objective function (objective functions are not shown due to confidentiality), it was this high level of saturation which prevented it achieving the level of overload torque required within the current limits of the converter. As a result '36-40r4 Cu 0.45' was selected for further development.

5.6 Detailed Design and Construction of Optimised Motor

Once the '36-40r4 Cu 0.45' design had been selected it was then necessary to undertake a level of detailed design work in order to make this basic design suitable for construction.

5.6.1 Mechanical Design

The mechanical design of the stator and rotor supporting structures was undertaken by QinetiQ and is not detailed here. Changes were made to the stator and rotor lamination structures in order to improve their manufacturability.

The stator lamination design was modified in order to increase the thickness of the stator coreback; there were three reasons for this change. Firstly a thicker coreback was needed to support the proposed use of compressed aluminium windings (see Chapter 6 for more details). Secondly the coreback was an area of relatively high magnetic saturation, when compared to the other optimised designs; a thickening would therefore be expected to reduce both copper and iron losses, though mass would increase. Finally the 3mm stator coreback was considered to be mechanically marginal; there was a concern that over long periods of operation it could be prone to fatigue failures, though no work was undertaken to confirm this. In order to address these issues, whilst also creating a ‘key’ to the stator support structure, a ‘castellated’ coreback design was developed as seen in Figure 5-8. This design would reduce mass by 120g when compared to a continuous 6mm coreback with additional locating lugs, though being still 140g heavier than the baseline design.

The stator lamination design was also slightly modified to add 0.2mm fillets to all internal corners; this was required both to reduce stress in these areas but also to enable the manufacture of the stator and rotor laminations using the EDM wire erosion process. The rotor laminations were modified in order to provide a ‘cut-in’ such that the magnets could be easily located (see Figure 5-9) and additional locating lugs added.

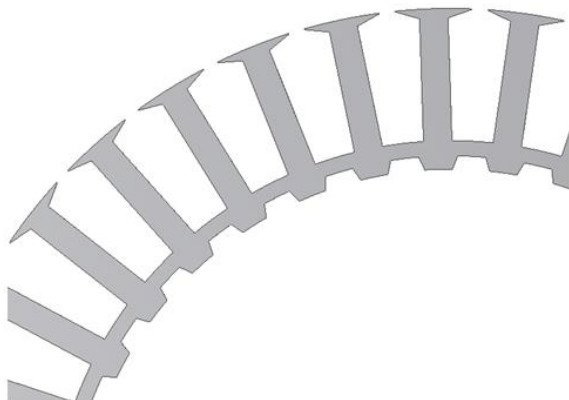


Figure 5-8: Showing castellated stator coreback design.

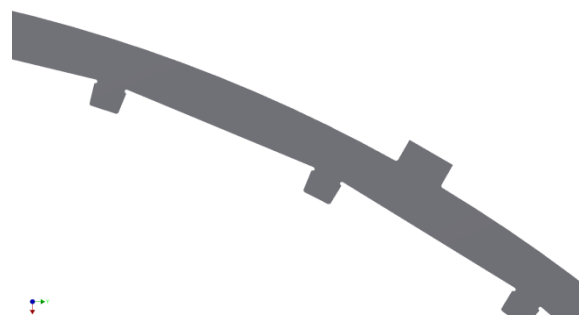


Figure 5-9: Showing Rotor Coreback Design with cut-outs to aid magnet location.

5.6.2 Winding Design

The number of turns per phase was set based on the maximum operating speed of the motor. A star connection was selected as it would avoid the risk of circulating currents around the delta connection and the risk of increased losses. The winding configuration shown in Figure 5-10 was developed featuring a combination of series and parallel interconnections between motor phases. Whilst this design carried some inherent risk of circulating currents between parallel coil groups, this was offset by other advantages.

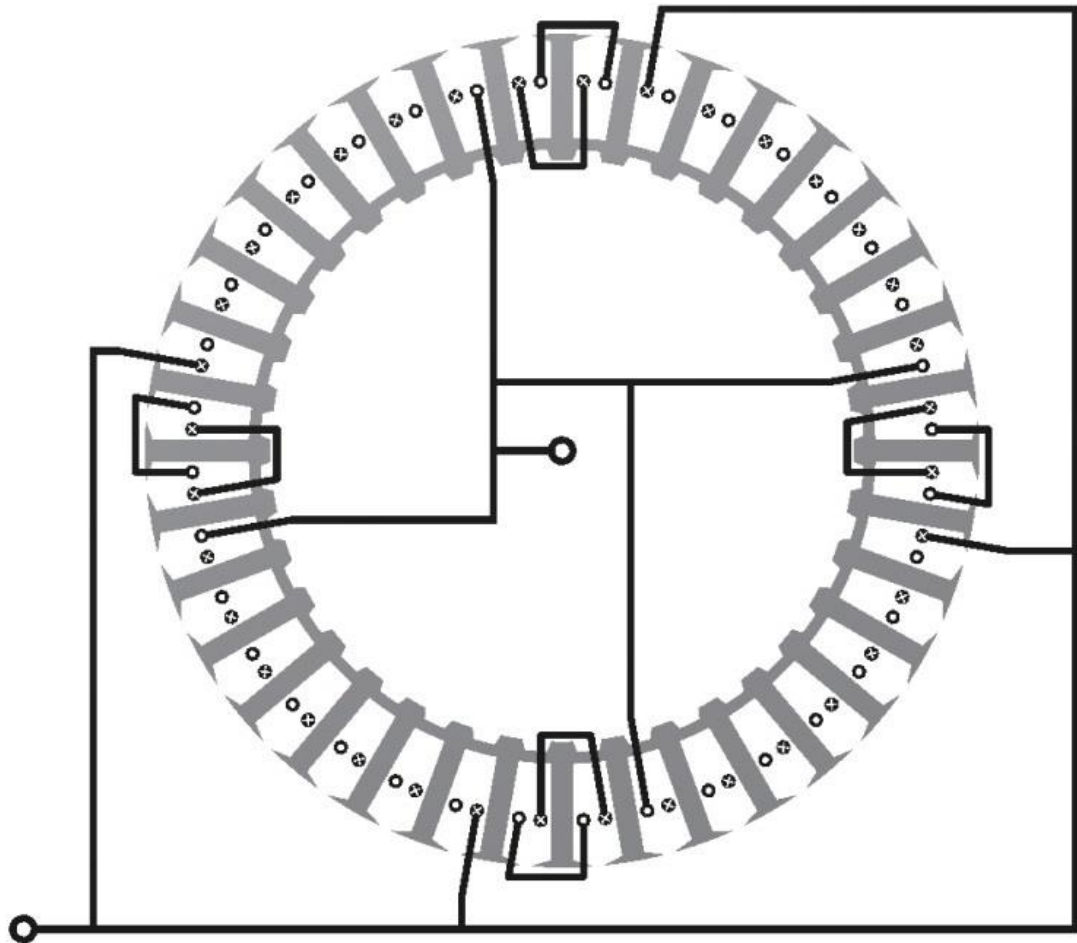


Figure 5-10: Showing the motor winding configuration for a single phase.

As discussed earlier in Section 5.3.1, modelling based on [96] had shown that, in order to limit AC losses in the coils at the normal operating range of the motor, conductors with a diameter of less than 1.4mm would be required. The chosen configuration, which featured 69 turns per coil, would allow the use of 1.06mm conductors for the copper wound machine with a fill factor of 0.43, close to the 0.45 target. It would also, with the same number of turns, allow the use of 1.4mm windings in the aluminium wound

machine (Chapter 6). This would also enable the use of single strand coils on both machines which would simplify motor winding whilst also enabling ready comparison between the two.

Table 5-5: '36-40r4 Cu 0.45' motor windings configuration.

Parameter	Value
Winding Configuration	4 sets of three adjacent series coils per phase, Star connected
Winding Wire	1.06mm, grade 2, class H copper wire (Essex U155), single strand per coil
Slot Liner	0.3mm Nomex
Number of Turns	69 per coil (equiv 208 per phase)
Fill Factor	0.43
Phase Resistance	0.100 ohms
Phase Inductance	0.335mH
Back EMF	0.142V/rpm

5.6.3 Impact of Detailed Design on Motor Performance

Following these changes, the motor was remodelled and performance found to degrade slightly as shown in Table 5-6 (For Take Off) and Table 5-7 (for Cruise Condition). The most significant impact was from the increase in motor mass, due to the new stator coreback design. However the slight reduction in fill factor also increased copper loss, though this was to an extent offset by the reduction in saturation in the coreback. Iron losses remained largely static, with the increase in iron mass offset by the decrease in coreback saturation. Peak current is significantly reduced due to the increase in turns to 208 per phase (equivalent) from 120 turns per phase, set arbitrarily during optimisation.

Table 5-6: 36 pole, 40 slot motor performance in Take-Off condition pre and post detailed design modifications.

Parameter	36-40r4 Cu 0.45 As optimised	36-40r4 Cu 0.43 Post modifications
Power	3494.9W	3494.9W
Peak Current	107.0A	62.0A
Copper Loss	552.7W	564.5W

Table 5-7: 36 pole, 40 slot motor performance in Cruise condition pre and post detailed design modifications.

Parameter	36-40r4 Cu 0.45 As optimised	36-40r4 Cu 0.43 Post modifications
Power	1837.4W	1837.5W
Peak Current	29.2A	16.9A
Copper Loss	30.0W	30.6W
Iron Loss	15.8W	15.9W
Magnet Loss	0.3W	0.3W
Total Loss	46.0W	46.7W
Efficiency	97.6%	97.5%
Mass (estimated)	7.01kg	7.28kg
Objective Function	83.75	83.57

Figure 5-11 shows the prototype motor, resulting from the optimisation and detailed design process, following its construction.

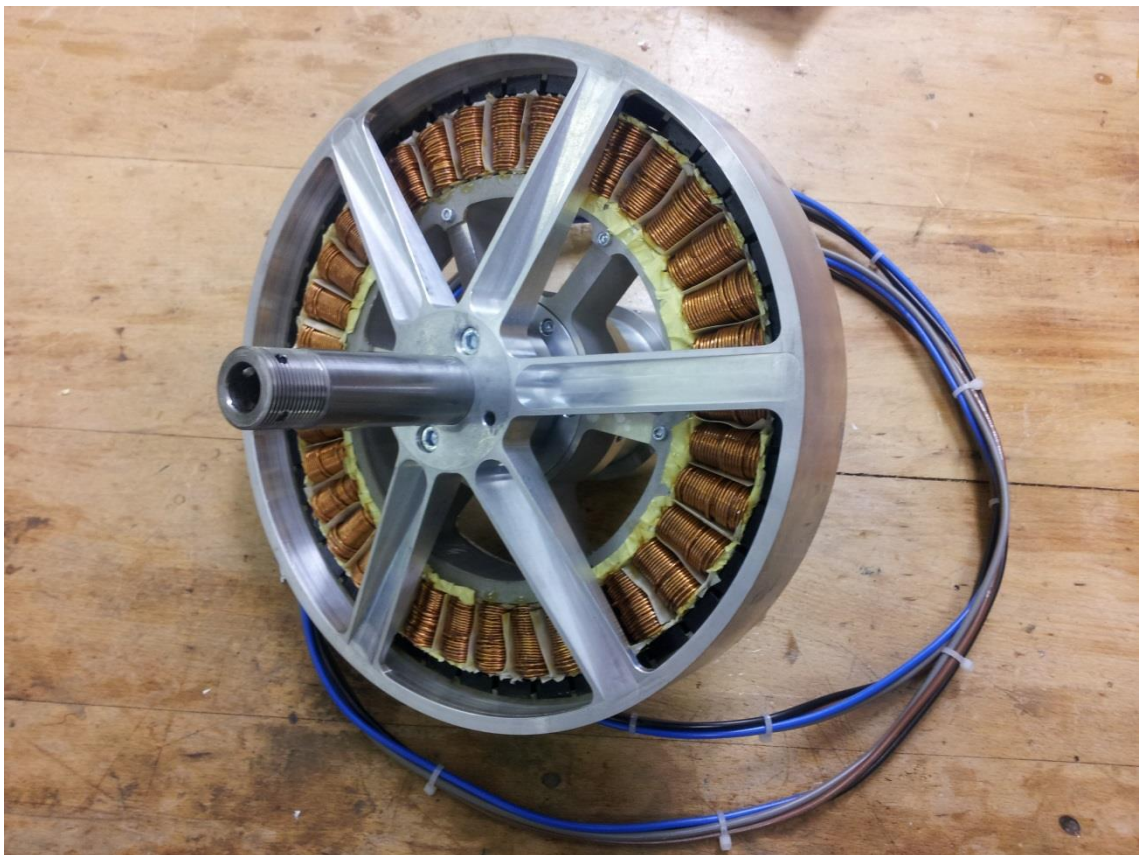


Figure 5-11: Constructed 36 slot, 40 pole motor.

5.7 Prototype Test and Validation of Optimisation Findings

A set of tests were undertaken to validate the design of this motor, as follows:

- 1) Confirmation of the physical mass and winding resistance of the motor;
- 2) Back EMF test to confirm induced voltage due to the motor magnets;
- 3) Confirmation of full motor efficiency through dynamo testing;
- 4) Run-down tests in order to allow the breakdown of the sources of motor loss.

5.8 Motor Mass and Winding Resistance;

Motor mass was measured and found to be 6.90kg compared to the predicted 7.28kg (6% lower than expected) and phase resistance 107mΩ compared to a predicted 100mΩ (7% increase over prediction)

As will be seen in Chapter 6, an almost identical aluminium wound machine was constructed and found to weigh almost exactly the predicted mass (though as items such as fasteners, cables, interconnections and liners had not been included in the estimates; this meant that predictions has slightly overestimated motor mass). Winding resistance for this aluminium machine had also been found to be within 1% of prediction. These results lead to the assumption that the reduction in mass and increase in resistance must be connected and related in some way to the motor's copper windings. Based on this comparison with the Aluminium wound machine, it was possible to calculate that a single copper coil would have a mass of 44.6g.

Analysis was therefore undertaken in an attempt to identify the root cause of the difference in mass. This analysis considered the two simple equations that follow:

$$M = l_w \cdot A_w \cdot \rho \quad (5-4)$$

where M is the winding mass for a winding with length l_w , cross sectional area A_w and mass density ρ .

$$R = \frac{l_w}{A_w \cdot \sigma} \quad (5-5)$$

where R is the winding resistance for a winding length l_w , cross sectional area A_w and conductivity σ .

As M and R are known from measurements and given that ρ and σ are constants for copper, it is therefore possible to calculate the values of l_w and A_w with only a single, unique solution being possible, as shown in Figure 5-12.

Therefore the diameter of the copper coil must be circa 1.01mm, however this was significantly less than the 1.06mm specification for the purchased conductor. Unused conductor was therefore measured and confirmed to meet the 1.06mm specification. It was therefore assumed that the conductor must have been stretched during winding, reducing cross sectional area, as indeed a significant force had been applied to the conductors in order to achieve the 0.43 fill factor. In order to confirm this an experiment was devised where similar forces were applied to a length of conductor and its extension measured. When put under tension consistent with the motor being hand-wound, the conductor was found to stretch in the order of 10%; as volume must be conserved, this would therefore equate to a decrease in diameter of 5%, consistent with the observation of the copper wound coils.

Overall this change in resistance and mass would lead to a slight increase in objective function to 8.71 from 8.57.

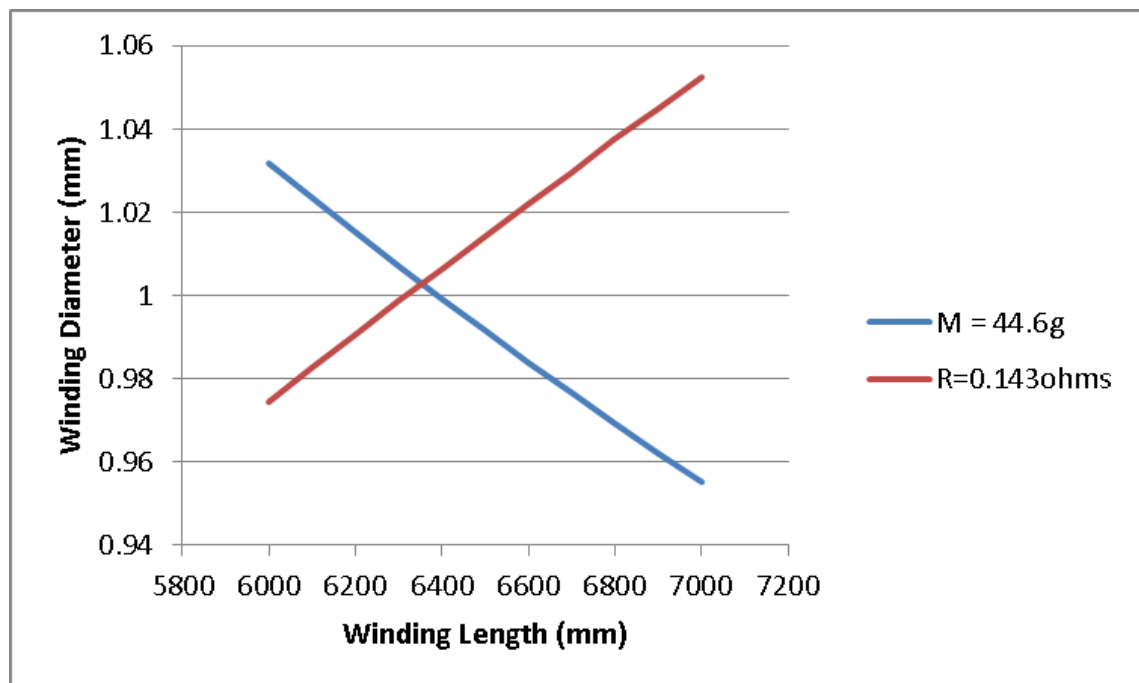


Figure 5-12: Showing relationship between Winding Mass and Resistance for a Copper Coil. The intersection indicates the only possible solution of winding diameter and length which reflects the experimental observations.

5.8.1 Back EMF Test

The motor was run up to speed, with the windings open circuit, in order to confirm back EMF versus modelling assumptions.

The no load, back EMF constant was found to be 0.130V/rpm. This was 9% lower than the predicted 0.142V/rpm; this is consistent with the results of 3D modelling² which showed that the motor flux would be expected fall due to 3D fringing effects.

5.8.2 Dynamo based Motor Efficiency Test

The motor was then installed in a dynamometer in order to test full motor efficiency (see Figure 5-13). It is important to note that for this experimental setup the total system measurement error was calculated to be no better than $\pm 2.2\%$ in terms of efficiency; the biggest sources of error being in the measurement of torque and phase angle between voltage and current.

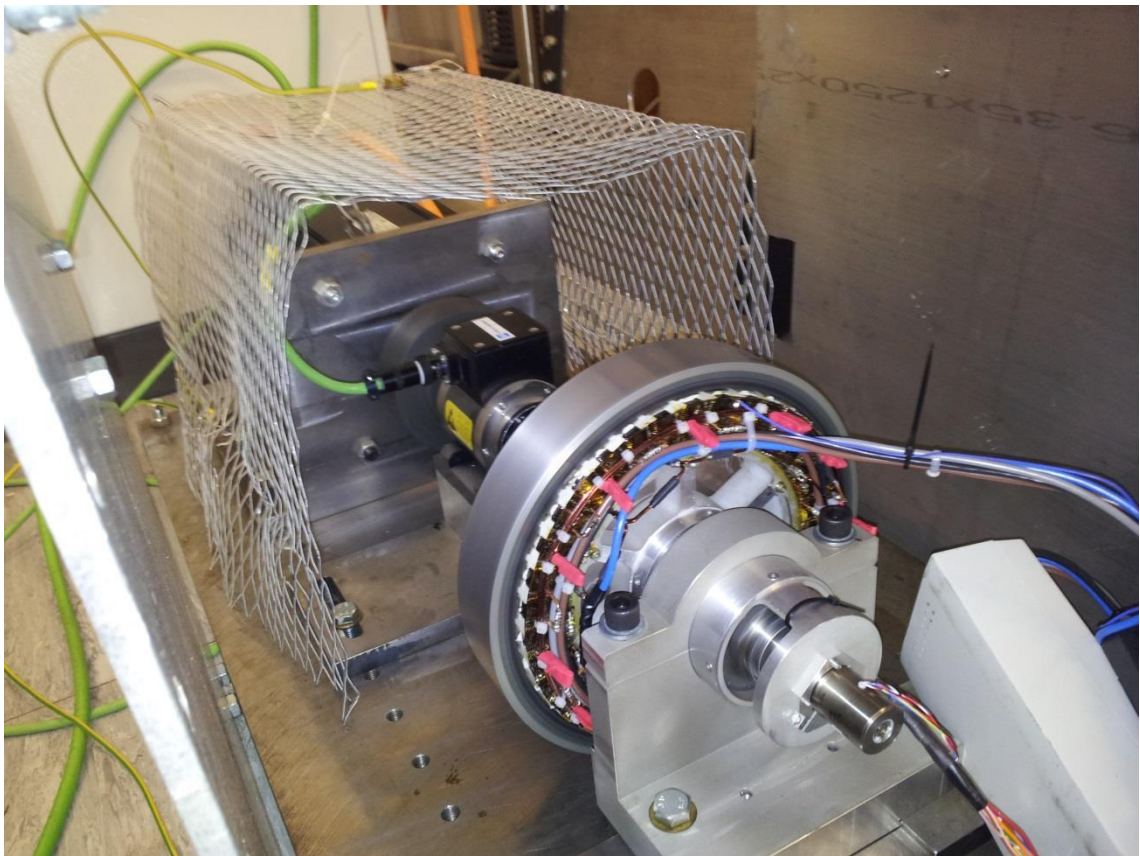


Figure 5-13: Motor installed on dynamo test rig

² Undertaken by a colleague, Dr Glynn Atkinson.

This testing showed that, with an ambient temperature of 20°C, total motor losses were 95.6W which equated to a nominal efficiency of $94.8\% \pm 2.2\%$. However, at this stage, these losses were not comparable with those calculated during the optimisation process as they included friction and windage and were at ambient temperature, some 70°C above the specified temperature. As a result it was necessary to undertake run-down tests in order to separate the differing sources of loss.

It was also possible to generate a comparison between motor phase current and motor torque as shown in Figure 5-14. The constructed motor was found, for magnetisation levels below saturation, to have 10% lower torque than predicted (consistent with the lower back EMF figure). However it was also clear that the motor was saturating far earlier than had been predicted and that as a result the levels of peak torque predicted were unlikely to be achievable within supply current limits or acceptable current densities. It was concluded that this fall-off in torque density was likely to be attributed to worse than expected material properties, with the 10JNEX900 saturating earlier than had been indicated in datasheets. As is later discussed in Chapter 10, this effect has also been observed with other motors operating in saturation. However the problem would be simply resolved by increasing the stack length of the machine by up to 30% in order to increase torque, though this would clearly effect motor mass and therefore the objective function.

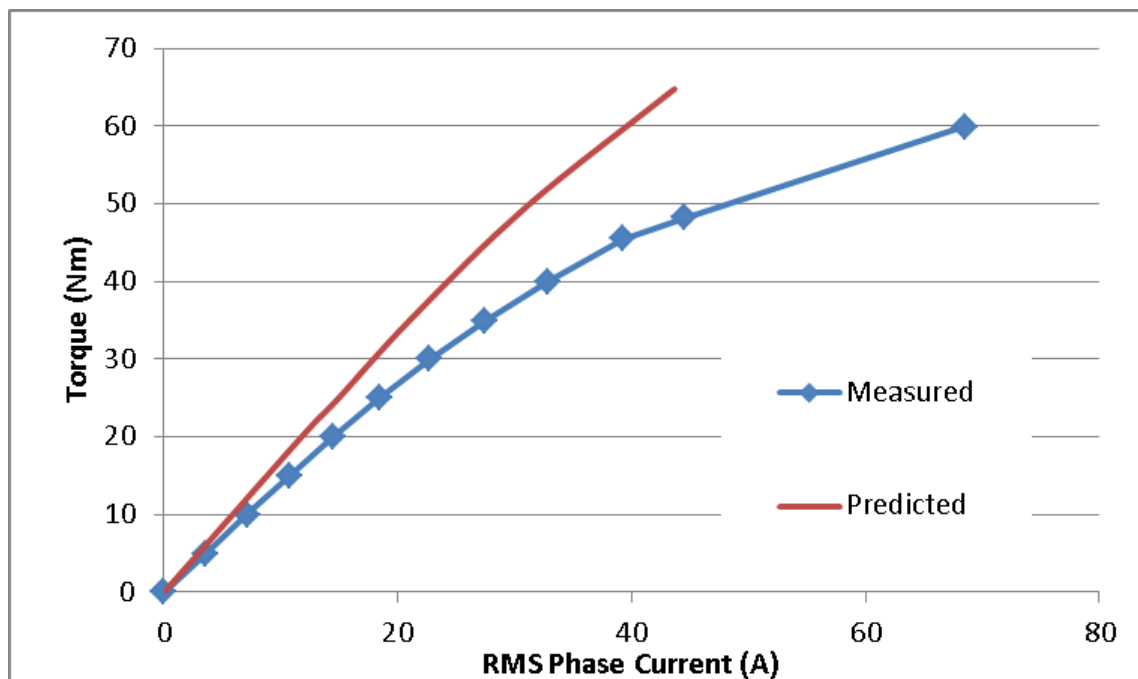


Figure 5-14: Measured Torque per RMS Amps versus Prediction

5.8.3 Run-Down Tests

Run-down tests are a method of accurately measuring no load losses. These tests involve spinning the motor up to a known speed and then allowing it to naturally slow. Given that the moment of inertia of the rotor can be calculated from the motor solid model (0.019 kg.m^2), the rate of change of speed provides a measure of the forces acting to decelerate the rotor and these forces can then be equated to losses.

Two sets of tests were undertaken, firstly to calculate friction and windage losses and then iron losses, separated into hysteresis and eddy current components. These tests are explained in detail in Appendix 3.

Figure 5-15 shows the results of friction and windage test, using a dummy stator, where the friction constant (T_f) was found to be 0.023 Nm and the windage coefficient (k_w) to be $0.00115 \text{ Nm/rad.s}^{-1}$; these coefficients therefore allowing calculation of the friction and windage losses at cruise speed.

From the results of the second test (see Figure 5-16), then $k_h.B^\beta$ was calculated as 0.11 Nm and $k_e.B^2$ as being, over this range of operating speeds, effectively zero.

If it is further assumed that the peak flux density in the motor iron will remain relatively constant between no-load and the cruise condition, then it is possible to generate an assessment of the total motor losses as found in Table 5-8.

Table 5-8 shows that the objective function of the copper wound motor is lower than predicted. This is due to the increase in winding resistance, coupled with the requirement for a higher rms current than predicted, increasing copper losses.

Calculated iron losses are however likely to be somewhat optimistic, they assume that the motor B field at the cruise condition is of the same intensity as that field at no-load, whereas it would in reality be higher. Iron losses from the rundown test are therefore likely to be understated, affecting the estimation of losses at -50°C by increasing the proportion of copper loss (as a proportion of total loss) which can therefore be scaled down to the lower temperature. It is therefore likely that the comparison at 20°C provides a better measure of the relative efficiencies.

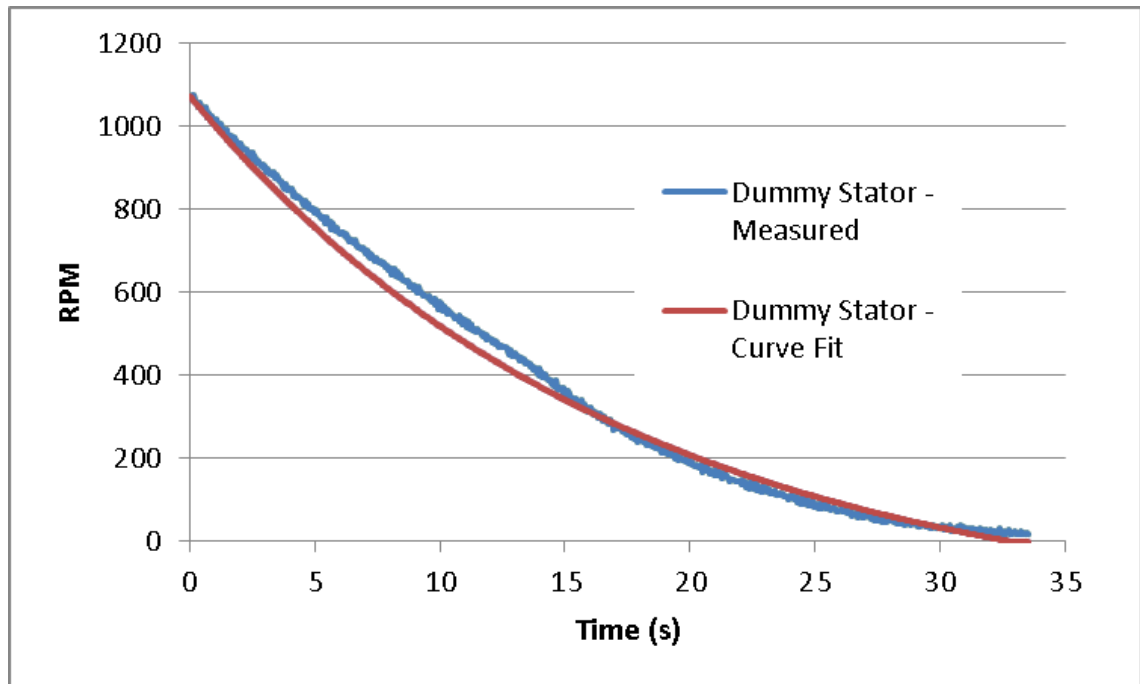


Figure 5-15: Measured and Curve Fit Speed vs Time data for Rotor Rundown Test with Dummy Stator Fitted.

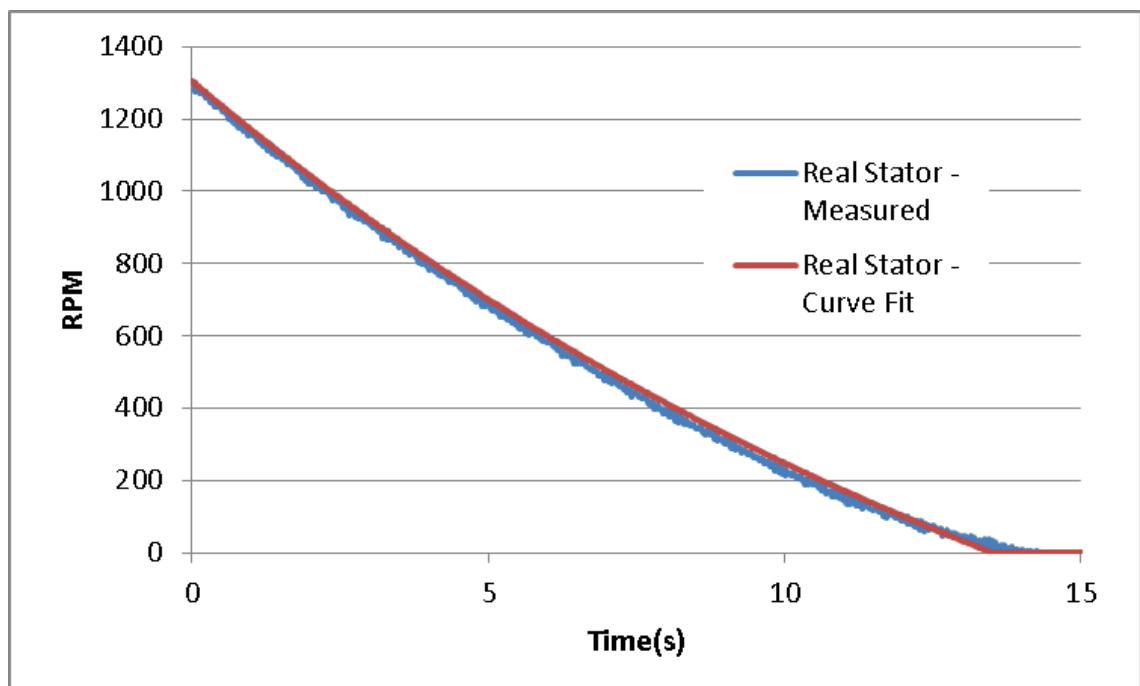


Figure 5-16: Measured and Curve Fit Speed vs Time data for Rotor Rundown Test with Real Stator Fitted.

Table 5-8: Table comparing test results in the Cruise Condition with the prediction from optimization (please note that speed and torque data is not made available at the request of the client).

Parameter	Test Value	Predicted Value
Mechanical Power	1834.6W	1837.5W
Total Loss from Dynamo Test	104.0W	-
Test Efficiency	94.6% (+/-2.2%)	-
Friction Loss from Rundown Test	2.1W	-
Windage Loss from Rundown Test	9.5W	-
Hysteresis Loss from Rundown Test	9.9W	-
Eddy Current Loss from Rundown Test	0W	-
Total Iron Loss	9.9W	15.9W
Copper Loss (20°C)	82.5W	58.4W
Copper plus Iron Loss (20°C)	92.4W	74.3W
Electromagnetic Efficiency (20°C)	95.2% (+/-2.2%)	96.1%
Copper Loss (-50°C)	54.1W	30.6W
Copper plus Iron Loss (-50°C)	69.1W	46.5W
Electromagnetic Efficiency (-50°C)	96.4% (+/-2.2%)	97.5%
Motor Mass	6.90kg	7.28kg
Objective Function	82.78	83.57

5.9 Conclusions

This chapter has discussed the optimisation of an electrical machine, of a different type and for a very different application, than forms the basis of this doctoral project.

However the development of the dynamic optimisation process discussed in this chapter provided a number of stepping stones to the development of the more complex optimisation process which will be described in Chapter 7. The use of a dynamic, transient finite element model approach in order to allow the calculation of iron losses was demonstrated to be effective. Also of great value was the idea of constructing an objective function which limits motor size based on a mass penalty function; this is as valid in an automotive setting as for an aircraft.

Some strengths and weaknesses of these computational optimisation processes have also been demonstrated. The process has worked well and, from the analysis in Section 5.5, it has produced solutions which appear to represent a flat solution surface, with little variation between motor performance. This is an indication of a robust process.

However the process has shown to be weaker when considering critical performance characteristics outside of the Cruise condition. The motors developed through optimisation, both during initial model based analysis and then during prototype validation, have failed to produce the required overload torque. The design which offered the best objective function was found to magnetically saturate and was therefore unable to provide adequate torque to support aircraft take-off. The prototyped design was then found to saturate too early during testing.

The reasons for these two instances are different, but both provide lessons for the optimisation of segmental rotor SRMs. In particular, as was also highlighted in Chapter 4, the early saturation of electrical steels in real test, compared to modelled predictions, is of concern. Equally the impact of 3D effects on optimisation is also again highlighted; these effects ideally need to be taken into consideration as part of any future optimisation.

Chapter 6. Application of Outer Rotor Brushless PM Machine with Compressed Aluminium Windings in solar powered aircraft

This chapter explores the use of compressed aluminium windings for use in a variant of the outer rotor permanent magnet machine, developed in Chapter 5. It explores how these very high fill factor ($> 75\%$) compressed aluminium windings can be implemented and compares them to a more conventional winding approach. For an aerospace application, such as that described in this chapter, the advantages will be shown to be primarily centred on the reduction in winding mass, however advantages will also be shown in terms of loss (versus a conventionally copper wound machine with a fill factor of 45%) and thermally. These are attributes which are also found to be of benefit to automotive traction motors, as will be seen in Chapter 8.

Interest in the use of compressed aluminium windings first arose in conjunction with the development of the 80kW Segmental Rotor SRM (developed later in this thesis), where advantages were considered to be low cost (aluminium is 10% of the price of copper per unit volume), recyclability (as advised by clients Tata Steel) and, to a lesser extent, low mass (though it was seen as a potentially useful way of increasing torque per unit mass capability of the Segmental Rotor SRM). That it is the motor for this solar powered aircraft which was first built using this technology, was due to the commercial pressures of the solar powered aircraft contract. However as can be seen in this chapter, the experience gained in terms of understanding this technology and its manufacturing techniques has been invaluable in the development of the Segmental Rotor SRM discussed in Chapter 7 onwards.

This chapter is based on a journal paper [97] which has been published in IEEE Transactions on Energy Conversion³.

It should be noted that the work described in this chapter was funded by QinetiQ, a leading UK aerospace developer, and formed part of a larger contract. As such, and at the request of the funder, details of the end user and aspects of the design specification have been omitted from this thesis.

³ This footnote acknowledges the contribution of Chris Spargo, who co-wrote the referenced paper. Whilst the work described is the work of the author, some of the text reused from the paper, in particular in Sections 6.2, 0 and 6.5.4 must be properly attributed to Chris.

6.1 Aluminium as a Conductor

Aluminium has been widely used for many years as a conducting material, both in applications such as power distribution and in low cost electrical machines. However copper has tended to maintain a dominant position in the development of higher performance motors, due primarily to its high electrical conductivity. It is clear that aluminium has potential advantages over copper including its low mass density, important in applications where motor mass is a significant consideration, and its high thermal heat capacity, important in overload conditions. Also of interest is the relatively low cost of aluminium, about one twelfth of the cost per unit volume of copper [98]. From the perspective of sustainability, the recycling of aluminium wound electrical machines is more straightforward than for copper wound; aluminium can be recycled with steel, whereas copper is both a considerable contaminant in the steel recycling process whilst being extremely difficult to separate from a motor's steel core without a significant dismantling processes [99].

The above factors are of great interest to electrical machine designers. High thermal heat capacity may be important where there is a desire to operate motors in short term overload conditions. Low mass is important in the design of 'mobile' electrical motors for use in applications ranging from electric vehicles to the 'More Electric Aircraft'. Low cost is always of interest and recyclability is of concern to all designers, perhaps particularly driven by initiatives such as the European End of Vehicle Life Directive which requires manufacturers to increasingly recycle a larger percentage of a vehicle at end of life [100].

Clearly there are also challenges associated with the use of aluminium for stator windings. Firstly its low electrical conductivity compared to copper may make it less volume efficient, increasing the size of windings and therefore indirectly the mass of a motor, perhaps outweighing its benefits. The reliable and safe termination of aluminium cables has also caused concern amongst consumers, particularly in the US [101]. Finally, concerns exist over the high temperature performance of aluminium conductors and particularly their ability to maintain their shape at temperatures above 150°C. These issues must be addressed in order to fulfil the material's promise as an electrical conductor in high performance electrical machines.

This chapter proposes the use of a very high fill factor ($\approx 75\%$), compressed aluminium coil for use in an extremely demanding application, that of providing propulsion for a solar powered aircraft. The use of such aluminium coils has enabled the design and construction of a machine with lower mass and reduced winding losses when compared to an electromagnetically equivalent machine with conventionally wound copper windings. The paper investigates mitigations for the issues discussed above, as well as the techniques which may be applied to manufacturing a motor with such high fill factor windings. The chapter compares the performance of two prototype machines; that already presented in Chapter 5 and an otherwise identical, aluminium wound motor.

6.2 Solar Plane Motor Requirements and Constraints

As was discussed in Chapter 5, the motor developed to power a solar powered aircraft is required to offer extremely high efficiency during the aircraft's 'cruise' phase, with a very challenging mass requirement in order to assist in the maintenance of very low aircraft weight. These requirements are contradictory, as generally a larger motor will have better efficiency and a smaller motor, lower mass. The motor is also required to provide an extensive overload capability in order to support aircraft take-off, whilst being able to operate reliably at altitudes of up to 60,000ft, temperatures as low as minus 70°C and for up to 5 years continuously. Chapter 5 discussed the development of an outer rotor, Brushless Permanent Magnet machine using conventional copper windings which had been optimised in order to achieve this requirement. For reference, a summary of the design parameters of this machine is provided in Table 6-1.

Table 6-1: Outer Rotor Brushless Permanent Magnet Motor Design Parameters

Parameter	Value
Topology	Outer Rotor, surface mount permanent magnet motor
Slots / Poles	36 / 40
Airgap diameter	223.8mm
Stack Length	25.8mm
Airgap Length	0.6mm
Rated Power / Torque	6kW / 60Nm

6.3 Selection of Compressed Aluminium Windings

Also introduced in Chapter 5 was that the use of compressed aluminium coils had been explored as an alternative. During optimisation different motor designs were compared, based on the calculation of an objective function. To recap this was:

$$\text{Objective Function} = \eta - k_{\text{mass}} \cdot \text{Mass} \quad (6-1)$$

where η is the efficiency of the motor in the cruise condition and k_{mass} a constant which provides a conversion between mass and efficiency; the objective being to maximise the function. The value of k_{mass} is not provided due to confidentiality.

Figure 5-6 shows a comparison between the best optimised solutions, which made use of conventional copper windings, with those that instead were to use compressed aluminium with a fill factor of 0.75.

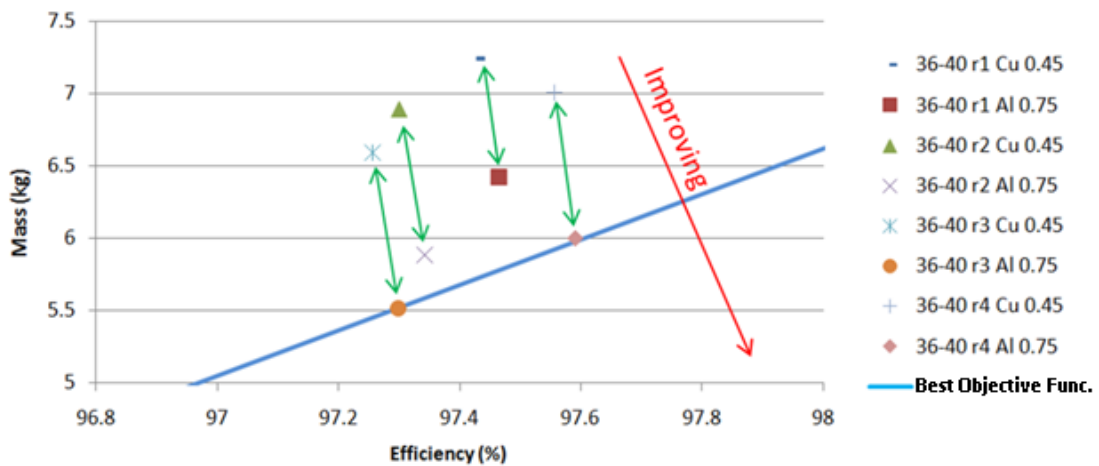


Figure 6-1: Results of the final optimisation runs; considering only 36 slot, 40 pole machines, with both 45% copper wound and 75% compressed aluminium windings. The green arrows link the objective functions of motors with the same geometry but with either copper or aluminium windings. Blue line is the iseline for the best Objective Function achieved.

The reasons for the predicted improvements, due to the use of these compressed aluminium windings, can be understood by comparing the properties of copper and aluminium. Firstly the ohmic winding loss in an electrical machine for a given phase MMF is calculated as;

$$P_w = \frac{n.m.MMF_s^2.l_{av}}{\sigma.S_{FF}.A_{slot}} \quad (6-2)$$

where m is the number of phases, n is the number of coils per phase, l_{av} is the average turn length in a coil, σ is the winding material electric conductivity, S_{FF} is the slot fill factor, A_{slot} is the slot area and MMF_s is the coil rms MMF given by;

$$MMF_s = N_{coil} \cdot I_{ph} \quad (6-3)$$

Where, in turn, N_{coil} is the number of turns per phase and I_{ph} is the phase current, assuming the phase coils are in series.

Clearly for a single motor geometry then the number of phases, number of coils per phase and the slot area are fixed. If it is assumed that the average turn length is also fixed, then the material conductivity and the slot fill-factor become the remaining variables. Assuming that a fixed MMF is required in order to produce the desired motor torque, then it is these variables which will set the level of winding loss in the motor.

For weight reduction purposes, the mass density of copper (ρ_{Cu}) is 8940 kg/m³ and for aluminium (ρ_{Al}) it is 2700 kg/m³, if we then take the mass ratio, correcting for the fill factors;

$$\partial_{mass} = \frac{m_{Al}}{m_{Cu}} = \frac{\rho_{Al}S_{FF}^{Al}}{\rho_{Cu}S_{FF}^{Cu}} \cong 0.302 \frac{S_{FF}^{Al}}{S_{FF}^{Cu}} \quad (6-4)$$

Therefore for the same fill factor, replacing copper with aluminium results in a reduction in the mass of the windings by 70%. However the lower conductivity of aluminium also needs to be considered and so it is also necessary to take into account the electrical conductivity ratio for the two materials and so similarly to (6-4);

$$\partial_{\sigma} = \frac{R_{Al}}{R_{Cu}} = \frac{\sigma_{Cu}S_{FF}^{Cu}}{\sigma_{Al}S_{FF}^{Al}} \cong 1.638 \frac{S_{FF}^{Cu}}{S_{FF}^{Al}} \quad (6-5)$$

as the electrical conductivity of copper (σ_{Cu}) is 58.0×10⁶ S/m and for aluminium (σ_{Al}) it is 35.4×10⁶ S/m, both at 20°C. As a result, for the same fill factor, mass is reduced but at the expense of increased winding loss due to the reduced conductivity. It is therefore

possible to trade off mass reduction for equivalent winding loss by setting $\partial_\sigma = 1$, which forces the loss, P_w to meet the constraint;

$$P_w^{Al} = P_w^{Cu} \quad (6-6)$$

Assuming initially a copper wound machine with a fill factor of 0.40, the required fill factor for the aluminium wound machine to meet the loss criteria can be calculated. The calculated value of the fill factor using (6-5) is 0.64, which then can be substituted into (6-3) to obtain the resulting mass reduction value; this is found to be 52% based on a 0.64 fill factor in the aluminium based machine. This fill factor is on the limit of what can be achieved with conventional bobbin winding techniques.

However, if a fill factor of greater than 0.40 is achievable with copper windings, as is the case in Chapter 5 where 0.43 was achieved, then this would push the aluminium fill factor for the same loss over what can be achieved by conventional means. As a result it was decided to investigate the compression of windings, previously explored by other researchers at Newcastle University [76], in order to increase the winding fill factor beyond 0.64. [76] considered that copper windings could be pre-compressed under high pressure in order to achieve a fill factor of up to 0.80. The application of this process to aluminium windings could therefore lead to reductions in winding mass whilst matching or even reducing the winding resistance when compared to conventional copper windings; this therefore supports the findings in Figure 5-6.

From Chapter 5, an achievable fill factor of 0.45 is the limit of what was possible for this type of motor with copper single tooth windings. Therefore a compressed aluminium winding with a fill factor as high as 0.72 (with 0.75 being targeted) would be required in order to match the former's winding resistance. Assuming a fill factor of 0.75, the use of aluminium windings would therefore theoretically bring the winding mass down from 2.03kg to 1.02kg, a 50% winding mass reduction, which equates to around a 15% predicted overall weight reduction for the same output torque and loss.

6.4 Winding Configuration Selection

As was discussed in Chapter 5, in order to stay within converter maximum voltage and current limits, the motor would require windings with 208 turns per phase. As the design had 12 coils per phase, this would lead to a need for circa 17 turns per coil, each having a diameter of 2mm or greater, assuming single strand conductor is used.

However this would not be acceptable. The assessment of AC losses in the coils (see Chapter 5 for details) indicated that the maximum acceptable wire diameter would be lower than 2mm, at circa 1.5mm. One alternative was to consider the use, as is common, of a multi-stranded coil, however this had not been previously attempted with compressed coils and was considered risky due to the project timescales. It was therefore instead decided that the windings would be configured as four parallel sets of three series coils as was discussed in Chapter 5. This allowed the number of turns per coil to be increased to 69, which with a 0.75 fill factor equates to a single strand diameter of approximately 1.4mm, acceptable in terms of predicted AC winding losses.

The prototype motor, constructed with compressed aluminium windings, would therefore utilise 1.4mm diameter, grade 2 class H aluminium wire and achieve a fill factor of .75. These winding configurations of copper and aluminium wound machines are compared in Table 6-2.

Table 6-2: Winding data for Copper and Aluminium Wound Motors (predicted).

Parameter	Cu Windings	Al Windings
Winding Configuration	4 sets of three adjacent series coils per phase, Star connected	4 sets of three adjacent series coils per phase, Star connected
Number of Turns	69 per coil (208 per phase)	69 per coil (208 per phase)
Winding Material	Grade 2, Class H Copper	Grade 2, Class H Aluminium
Conductor Diameter	1.06mm	1.4mm
Fill Factor (Slot)	0.43	0.75
Phase Resistance	0.100ohms	0.090ohms
Phase Inductance	0.335mH	0.335mH
Motor Mass	7.28kg	6.26kg

6.5 Compressed Aluminium Coil Considerations

6.5.1 Coil Manufacture

In order to reliably achieve the required fill factor it is necessary to compress the motor windings before assembling them into the motor. As had been previously applied to

copper windings, this was achieved through the use of a specially manufactured bobbin, punch and die set (Figure 6-2).



Figure 6-2: Compressed winding die (left) suitable for compaction of 6 coils simultaneously. Compressed coil fitted to bobbin, pictured with punch above (right).

The tool pieces are designed such that, when the bobbin and punch are fitted into the die, a void forming the final shape of the coil, minus any predicted material ‘spring-back’, remains. ‘Spring-back’ is governed by elastic recovery of the material and is influenced by its tensile and yield strengths, with aluminium and copper having different responses as will be seen. An essential element in achieving a high fill factor is to ensure that the windings are laid-up on the bobbin such that they are distributed evenly and in the relative position in which they will occupy once the coil is pressed. If this approach is not followed then some parts of the cross sectional area of the pressed coil may have a very high winding density where other areas are less dense, reducing total coil fill factor. It is also important that the position of the coil terminations in the bobbin wound coil is considered, as it is also critical that they are located in a position which will allow them to be accessed once assembled with the completed machine.

The coils are wound onto the bobbin and wrapped with a thin (0.03mm) Kapton tape in order to hold them in place and to provide a level of abrasion protection at the outside surface of the coil. The bobbin is inserted into the die and then the punch fitted in place. Using, in this case, a 15 tonne workshop press, a uniformly increasing pressure is then

applied to the punch until it pressed flat with the top surface of the die. For copper windings this has been found previously to require pressure in the order of 400MPa. However using aluminium the required pressure was reduced, totalling only 250MPa. This is thought to be due to the higher malleability of the aluminium conductor compared to the copper, allowing a lower pressure to be used in forming the coil. This effect is also seen when the pressure is removed from the punch. With copper coils there is a spring-back in the order of 2-3%, whereas with aluminium this is less pronounced, moving only 0.5-1%. This reduced spring-back is to be expected as pure aluminium has a lower Young's modulus than copper (70GPa versus 130GPa), which would result in a lower material elasticity, coupled to having a lower yield strength (20MPa versus 33MPa), providing a greater tendency to retain the deformation due to the coil compression.

The pressed coil is then removed from the die, the Kapton tape removed and the terminations exposed (Figure 6-3). The figure shows clearly how the compression of the coils has led to a close hexagonal packing of the coil's conductors, removing air voids completely.

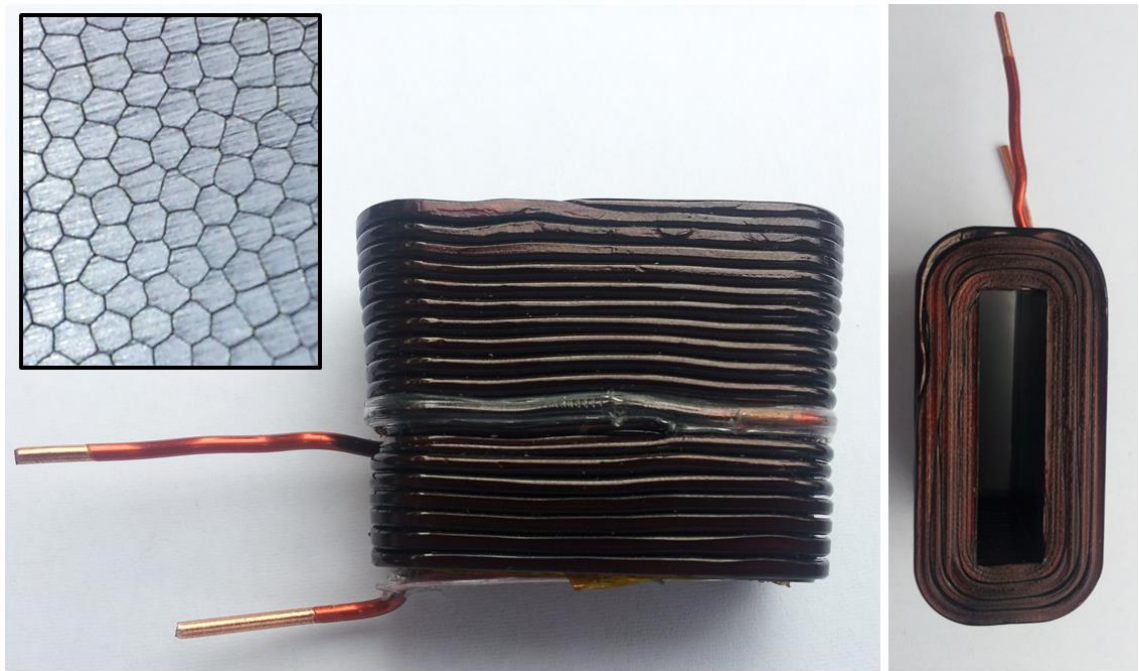


Figure 6-3: Compressed coil showing copper interconnecting leads. Inset shows the level of compression achieved at 250MPa (~2x magnification).

6.5.2 Stator Design for Compressed Coils

A stator design is required which allows the pressed coil to be fitted to the stator tooth. Whilst several designs were considered for this machine, the most successful in terms of minimising motor losses was the so called ‘keyed tooth’ design. This design attached the stator tooth to stator coreback through the use of a tapered, precision fit ‘key’ (see Figure 6-4 and Figure 6-5). This would allow the coil to be assembled first with the tooth, which could then in turn be fitted into the stator coreback.

The rationale for the selection of this method is that previous research has shown that compressive stress in motor laminations increases iron loss [102], whilst reducing permeability [103], therefore also increasing winding losses. As a result there is a need to avoid any mechanism that builds compressive stress into the tooth root. The use of a precision fit taper met this requirement and it was possible to manufacture this tapered key and keyway to the tolerances required ($\pm 0.02\text{mm}$) through the use of an Electrical Discharge Machining (EDM), wire erosion machine. For the low manufacturing volumes and throughput required for the construction of the solar powered aircraft motors, this was considered to be an appropriate manufacturing process.

A one degree taper angle was selected as this allowed a good, consistent fit whilst maintaining sensible diameters for the keyway at each end; avoiding the need for very small and fragile features. As can be seen in Figure 6-4, a castellated coreback design was selected for the prototype; this increased the available area for keyway opening whilst also providing a mechanical interface with the rotor support structure without significant increase in total motor mass.

The use of a keyed tooth had a further benefit of reducing the radius of the single piece stator from circa 225mm to circa 170mm for the keyed coreback (minus separate teeth). This design allowed all stator teeth to be cut from the centre of the stator lamination blank, reducing scrap by more than 50%; a significant saving where such a high cost material was used.

The coil was insulated from the tooth using 0.2mm Nomex slot liner, cut from sheets printed with a cutting template. The tooth was then gently slid into the stator coreback, with the final 1 to 2 mm requiring a gentle tap with an aluminium drift.

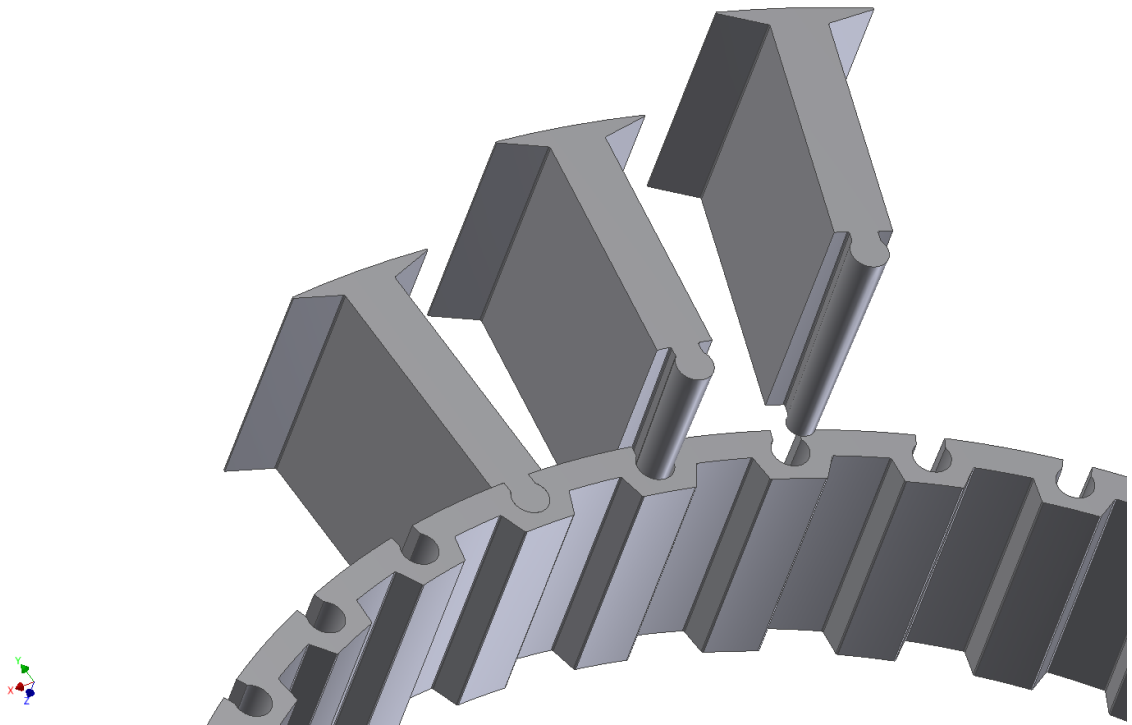


Figure 6-4: Showing the keyed tooth stator coreback, which is castellated, and tooth concept which enables the use of compressed windings.

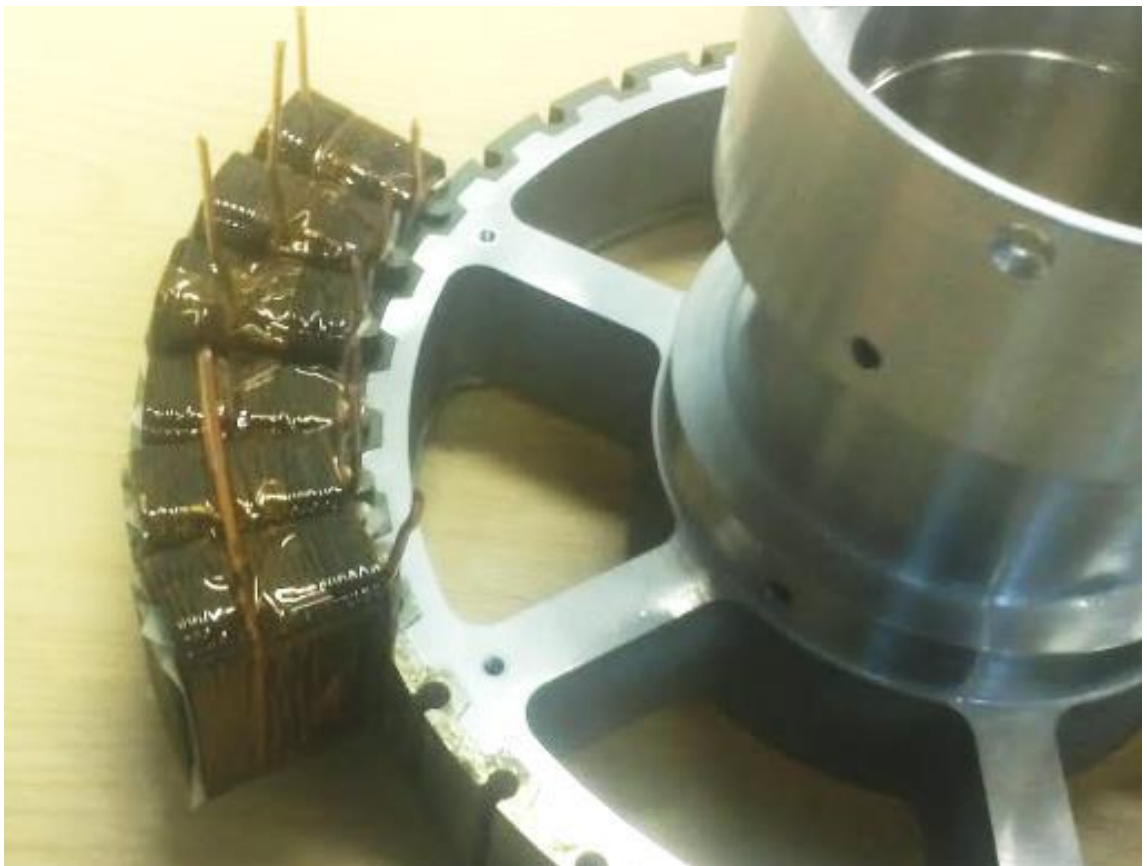


Figure 6-5: Aluminium wound motor during construction showing six coils, assembled with their keyed teeth, attached to the motor.

One further benefit was identified. Whilst additional tooling was required to allow for the manufacture of the compressed coils, once this had been perfected the time to wind the machine was greatly reduced and the process deskilled when compared to manual winding with closely fitting end windings. The conventional machine took a skilled operative in the region of 6 working days to wind, whilst the aluminium coils were made and fitted by a less experienced operative in less than 2 working days. However, it is noted that, compared to the use of bobbin wound coils, compression would add an additional process step.

6.5.3 Coil Termination

One of the concerns associated with the use of aluminium conductors is how to achieve a low resistance and high reliability joint. Direct soldering of aluminium to copper is not possible and therefore a crimped joint is generally used. However aluminium's tendency to form an insulating oxide layer raises concerns about the long term reliability of anything but the most airtight bond. This is of particular concern for an aerospace application, where reliability is essential, ruling out the use of crimped connections in this case.

As a result, after a survey of the numerous available options, the process of cold pressure welding [104] was identified as a strong candidate. This process, undertaken at room temperature, mechanically forces same diameter conductors of aluminium and copper into each other. This process is reported to result in removal of impurities from the surface of each material and the formation of a molecular level bond between the two conductors (see Figure 6-6).

In the prototype machine the aluminium coil stub leads were therefore cold pressure welded to copper flying leads which could then be soldered into the final winding configuration.

However, in order to ensure the reliability of this connection, it was necessary to undertake two key experimental validations, to confirm the bond's mechanical strength and also its thermal 'strength'; that the bond would not fail prematurely under high current loadings and before either of the parent materials.

Firstly the mechanical strength of aluminium to copper joint was tested using a tensile test machine. It was found that well-made joints were stronger than the Cu parent

material, with the Cu failing first. It was also found that the good preparation of joints was essential and that, in particular, it was necessary to remove a length of enamel from the joint and ensure that it was grease free prior to cold pressure welding. Failure to carry out these steps would result in bond failure.



Figure 6-6: Showing (left) cold pressure welded joint between 1.4mm copper and 1.4mm aluminium enamelled wires. (Right) demonstrates the mechanical integrity of the joint.

Secondly an electrical heating test was performed. This test had the objective of identifying whether the bonding process would result in high electrical resistance at the joint, which could cause excessive heating, leading to a potential failure. The tests, carried out at an RMS current more than twice motor rating, showed that the aluminium wire would fail first and repeatably, some way from the bond. It was therefore concluded that a significant contact resistance did not arise and the join was not likely to fail thermally under load.

6.5.4 Coil Thermal Performance

In regard to the thermal performance of the coil, it has been stated in [2] that the effective thermal conductivity of the winding in the slot can be calculated by evaluating (assuming homogenization of impregnation and conductor insulation):

$$\lambda_{eq} = \lambda_{air} \frac{(1+S_{FF})\lambda_{al} + (1-S_{FF})\lambda_{air}}{(1-S_{FF})\lambda_{al} + (1+S_{FF})\lambda_{air}} \quad (6-7)$$

where λ_{air} is the thermal conductivity of the air and λ_{al} is the thermal conductivity of the aluminium. In this equation the thermal conductivity of the wires insulating enamel is disregarded. The rationale for this is firstly that the enamel coating is very thin; for example a grade 2, 1mm diameter wire typically has a maximum thickness of less than 0.032mm [105]. Secondly the thermal conductivity of the enamel coating is very high compared to air; bulk polymers, such as polyurethane and polyesterimide, have thermal conductivities in the range of 0.1-0.3W/m/K [106] versus 0.024W/m/K for air. Both factors mean that the relative impact of the enamel on the overall coil's conductivity will be small when compared to that of air.

If a further comparison is made between the properties of aluminium and copper, in terms of thermal conductivity:

$$\partial_k = \frac{\lambda_{Al}}{\lambda_{Cu}} \cong 0.593 \quad (6-8)$$

The assumed thermal conductivities are 387.7 W/m/K, 230 W/m/K and 0.024 W/m/K for copper, aluminium and air respectively. Calculated for the same fill factor, even with the decreased thermal conductivity, the winding effective thermal conductivity is only slightly lower; this is due to the dominant factors being the fill factor and the very low thermal conductivity of air. However, taking into account the increased fill factor, the equivalent thermal conductivity of the compressed aluminium winding is found to be a factor of 2.65 greater than that of the low fill factor copper winding. The amount of air between conductors is significantly reduced at this fill factor leading to improved thermal properties.

In order to confirm these calculations, a thermal test was undertaken on both copper and aluminium wound motors. A DC current of 14A per phase (equivalent to the motor operating at a torque of 20Nm) was injected into both machines, representing a common operating condition, and the winding temperatures monitored over time. This test resulted in the copper wound machine reaching a steady state temperature of 53°C above ambient, whilst the aluminium machine saw a much lower increase of only 40°C over ambient (Figure 6-7). Some of this difference may be attributed to the lower electrical resistance of the compressed aluminium windings, when compared to the

tested copper windings (see Section 6.6). However it is clear that the increased thermal conductivity of the aluminium coil will have contributed to the lower winding temperature.

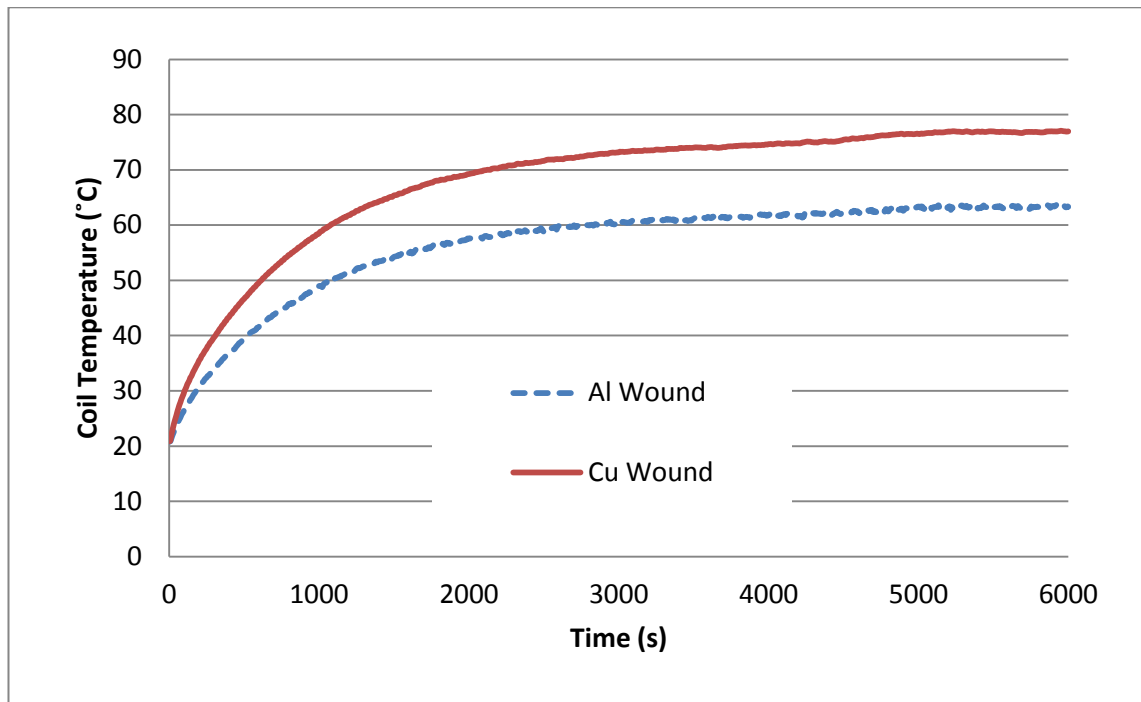


Figure 6-7: Motor coil temperature versus time for Copper and Aluminium stator coils under the same test conditions ($14A_{rms}$ per phase, equivalent to 20Nm motor torque).

6.5.5 Coil Reliability

There was considerable concern about the impact of compression on the integrity and longevity of the coils.

In order to confirm the integrity of the coil a number of tests were undertaken, both before and after coil assembly with the prototype motor. Standard high voltage breakdown tests were undertaken to identify shorts between coils and the motor core as well as between adjacent coils. High voltage surge tests were also undertaken on all coils, using specially developed hardware, to confirm winding inductance and therefore that that no turn to turn shorts were present. These were then further confirmed through use of a commercially available surge tester which tested the fully assembled machines at voltages of up to 2.5kV.

Whilst these tests did find faults, these were not associated with the compression of the coils but instead due to damage to the slot liner between coil and coreback which had been caused during the fitting of the keyed tooth. Where these manufacturing failures

were found, it was a fast and straightforward task to repair; taking no more than 10 minutes to remove the tooth and coil, change the coil and then reassemble.

Whether there is any impact on the durability of motor windings has yet to be conclusively proven, however indications from the testing of this machine and others previously manufactured with compressed copper windings have been positive. Further work is planned in this area.

6.6 Prototype Motor Validation

A prototype motor was constructed using compressed aluminium windings along with the keyed tooth stator design, this motor is shown in Figure 6-8. This was compared with the copper wound motor constructed and tested in Chapter 5.

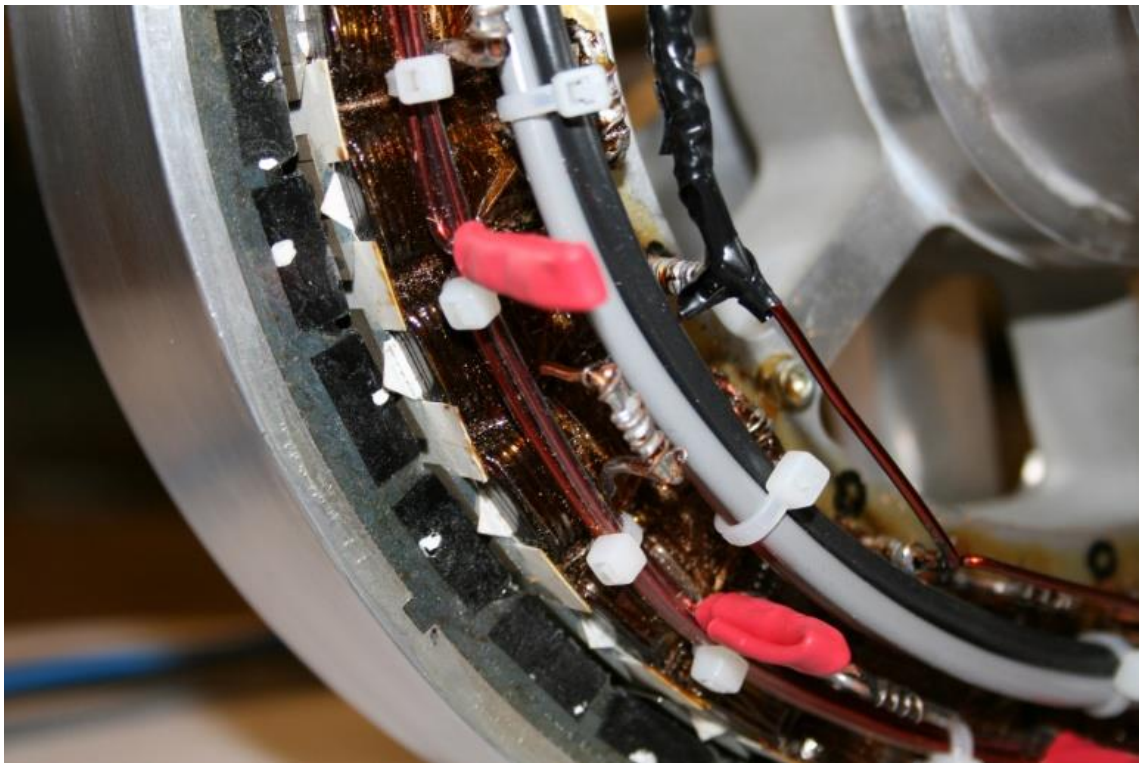


Figure 6-8: Rear view of the constructed prototype motor with aluminium compressed windings.

Motor phase resistance was measured with the aluminium coils having, due to its very high fill factor, lower resistance than that for the conventional machine with phase resistance at $89\text{m}\Omega$ (99% of the predicted resistance in Table 6-2) compared to $107\text{m}\Omega$ (107% of the predicted resistance) for the conventional machine (both at 20°C); this equated to a 17% reduction in winding resistance for the aluminium wound machine.

The two constructed motors were weighed, with the compressed winding machine being found to have a mass of 6.28kg whereas the copper machine's mass was 620g higher at 6.90kg, with the 9% mass saving being attributable to the use of aluminium coils. However, this saving is lower than the 1020g (16%) predicted in Table 6-2.

In order to identify the cause of these differences from prediction, a standalone, compressed aluminium coil was weighed and found to have a mass of 27.4g, within 1% of the predicted mass of 27.0g. It was not possible to weigh a fully representative copper coil without removing it from the machine, however the difference between the stator masses led to the conclusion that each copper coil had a mass of 17.2g greater than each aluminium coil, at 44.6g, as was fully explained in Chapter 5 (section 5.8).

A number of comparative tests were then undertaken to confirm that the motors performed consistently magnetically, as well as to compare losses.

To test the magnetic performance of the two machines, firstly the back EMF was measured. Both machines were found to be within 1% of each other, with each having back EMF constants of about 7.7rpm/V; this suggested that the use of the keyed tooth assembly method was having no effect on this aspect of the motor's performance.

A test was then also undertaken to assess motor torque versus RMS phase current, i.e. the torque per ampere constant of the machine (Figure 6-9). Here again the performance of the two machines was extremely consistent.

These two tests therefore demonstrated the effectiveness of the keyed tooth stator design in allowing a separable tooth without impacting the stator permeability. As a result it was possible to demonstrate that motor winding losses for the aluminium machine would be 17% lower than for the copper wound machine at room temperature.

Iron losses were also measured for both machines in line with the rundown test method described in Chapter 5. For the aluminium machine $k_h \cdot B^\beta$ was calculated as 0.072Nm (0.11 for the copper machine) and $k_e \cdot B^2$, as for the copper machine, being at this speed effectively zero.

This analysis showed that no load iron loss was broadly consistent for the two machines, with both generating only in the region of 10W in the Cruise condition and at no load. Again this finding validates the use of the keyed tooth coreback design.

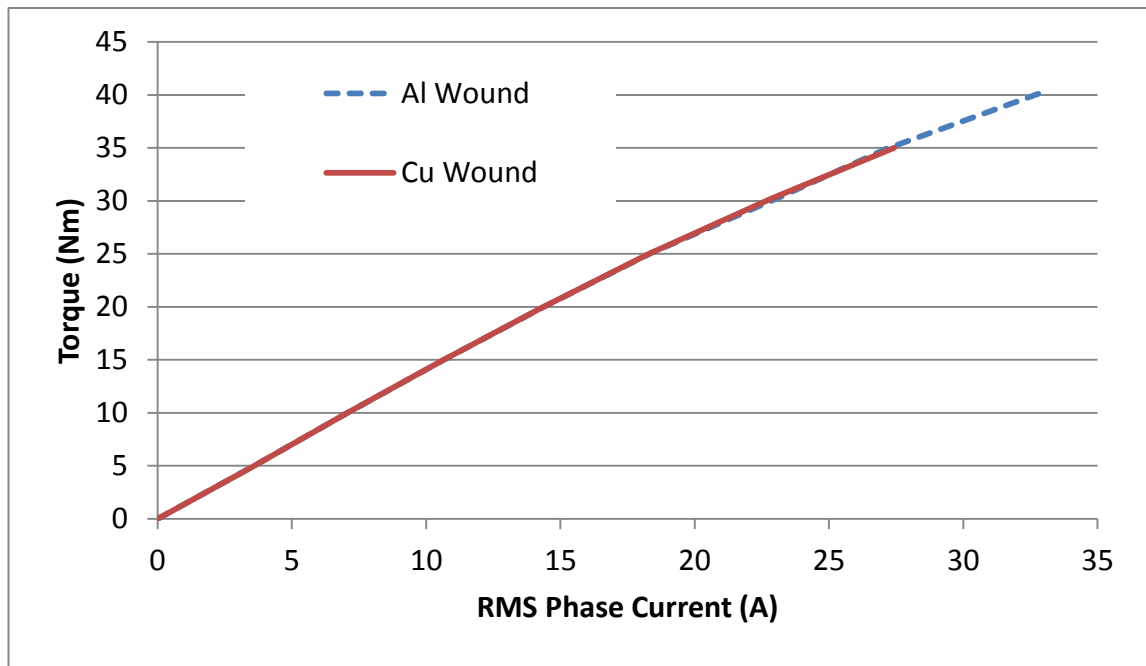


Figure 6-9: Comparison between torque versus phase current for copper and aluminium wound motors.

As a result of the above tests it is possible to construct Table 6-3 which compares the performance of the two motors.

This analysis shows that the aluminium wound motor offers a 9% reduction in mass compared to the copper wound machine, less than that predicted due to the stretching of the copper conductors, but also an 18% reduction in winding loss, larger than would have been expected, again due to the same effect. Overall performance improvements in this application are in any case considerable with a greater than 1% increase in the objective function.

The iron loss calculations in Table 6-3 must be treated with care. The difference between the iron loss values for the machines would equate to only 0.4Nm, which could simply be a result of natural variation between the friction in the two sets of motor bearings. Equally, these iron loss figures are likely, in any case, to be understated, with the no-load tests not taking into account the influence of on-load MMF on the B field within the motor.

However, for this application, the aluminium wound motor is still shown to have benefits due to its lower mass.

Table 6-3: Comparison between performance of prototype aluminium and copper wound motor (results are restated at -50°C ambient, see note).

Parameter	0.45 Copper Wound	0.75 Aluminium Wound	Delta
Coil Mass	44.6g	27.4g	-39%
Motor Mass	6.90kg	6.28kg	-9%
Phase Resistance (20°C)	107mΩ	89mΩ	-17%
Phase Resistance (-50°C)	75mΩ	65mΩ	-14%
Power (Cruise)	1834.6W	1793.5W	-
Winding loss (Cruise) ⁽¹⁾	54.1W	44.3W	-18%
Iron Loss (Cruise) ⁽²⁾	9.9W	6.7W	-34%
Tot EM Loss (Cruise) ⁽¹⁾	69.1W	50.7W	-25%
Efficiency (Cruise) ⁽¹⁾	96.4% (+/-2.2%)	97.3% (+/-2.2%)	0.8%
Objective Function ⁽¹⁾	82.78	83.92	+1.3%

Notes: 1) Losses and efficiency in this table are taken from tests in accordance with the procedure outlined in Chapter 5. Winding loss is then recalculated assuming an ambient temperature of -50°C.

2) As discussed in Chapter 5, iron losses are understated due to the use of the no-load rundown test as a basis for their calculation. These tests do not take into account the contribution to the B field due to MMF in the motor windings.

6.7 Conclusions

It is possible to use aluminium windings to facilitate mass reduction in electrical machines, whilst maintaining electromagnetic performance, increasing thermal performance and reducing cost.

It has been shown that the compressed aluminium winding has a weight advantage for the same loss, better thermal properties and the added benefit of up to an 85% cost reduction for the winding material (when compared to hand-wound copper windings with fill factors of up to 45%). This makes aluminium windings potentially a more weight, cost and thermally-efficient solution, provided high fill factors can be achieved.

Improvements may also be possible when contrasted with higher fill factor copper coils (for example bobbin wound or compressed copper coils), however these are likely to be less marked as the total motor volume with compressed copper windings will be less than with aluminium windings in order to achieve the same winding loss.

For relatively low volume manufacture it is also possible to reduce manufacturing time at the expense of some additional tooling complexity. The recyclability of the machine at end of life is also improved by the elimination of copper, a contaminant in the steel recycling process.

Experimentally determined results from two prototype machines, one with compressed aluminium windings, at 0.75 fill factor, and a ‘control’ machine built with copper windings at 0.43 fill factor, have shown it is possible to build machines using this technology. The aluminium wound machine has used a ‘keyed tooth’ stator coreback design, which has been shown to allow fitting of coils without impact to the motor’s magnetic or loss characteristics.

This chapter has therefore shown that these compressed aluminium windings have benefits to this aerospace application, however it can also be expected that these advantages will be equally significant when applied to an automotive application.

**PART 3: HYBRID OPTIMISATION OF AN 80kW
SEGMENTAL ROTOR SRM WITH COMPRESSED
ALUMINIUM WINDINGS**

Chapter 7. Hybrid (Static / Dynamic) Optimisation of Automotive Segmental Rotor SRM

The objective of this research is to develop the Segmental Rotor SRM for use as an automotive traction motor; specifically the goal has been set of developing one of these electrical machines such that it is comparable to the performance of the 80kW Interior Permanent Magnet Motor used by Nissan in the Leaf electric vehicle. This chapter builds on the work presented in Chapter 3 (static optimisation of a Segmental Rotor SRM) and Chapter 5 (dynamic optimisation of an outer rotor Brushless PM machine) to present the steps which were taken to develop an optimisation technique for an automotive, Segmental Rotor SRM.

In Chapter 3, static approaches to SRM optimisation were found to be limited in a number of ways when assessing a motor for use in an automotive traction application. Firstly they take no account of the mutual interactions between adjacent motor phases and therefore have been found to inaccurately predict dynamic motor torque. Secondly it provides no information as to the iron losses resulting from differing geometries, preventing a full optimisation for all motor losses. Finally this method does not facilitate the assessment of the dynamic performance of the motor, in terms of its torque and speed envelope, clearly critical as torque-speed curves frequently form the basis of automotive traction requirements. Equally a fully transient approach, as applied in Chapter 5, will be shown to be difficult to apply and very computationally intensive when used to optimise Segmental Rotor SRMs.

As a result a new optimisation approach is proposed, which employs a combination of static and dynamic, transient techniques. This process allows the overall performance envelope of the motor to be confirmed, whilst also allowing a detailed assessment of its efficiency at its normal operating points.

This chapter is based in part on [107] which was presented at the IEEE International Electrical Machines and Drives Conference 2013, in Chicago.

7.1 Nissan Leaf Comparator Interior Permanent Magnet Motor

To provide a valid basis for comparison for the Segmental Rotor SRM technology, the electrical machine from the Nissan Leaf was selected as a benchmark. A picture of this machine is shown in Figure 7-1 and details of its performance provided in Table 7-1.

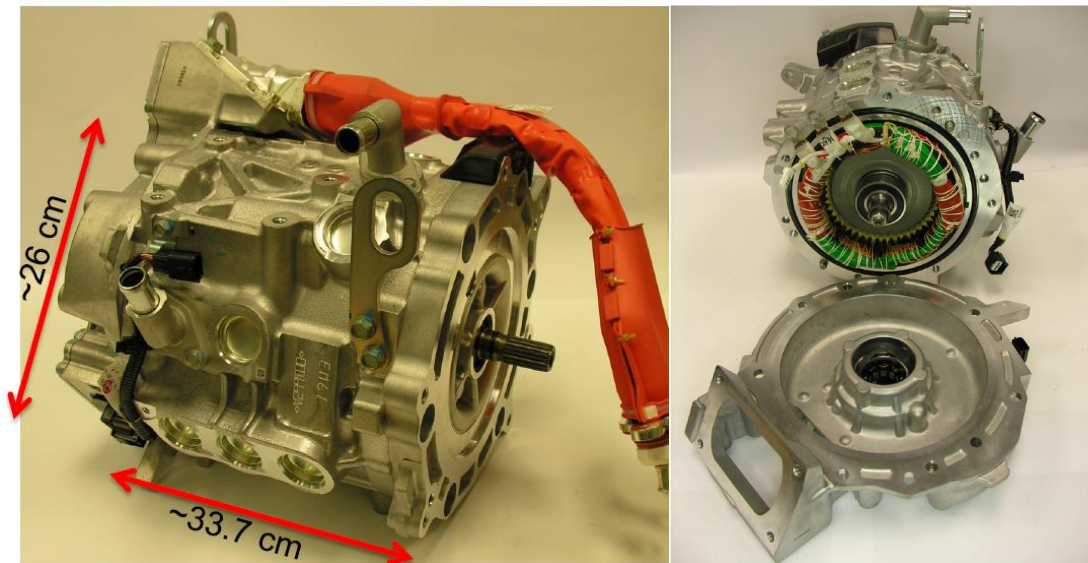


Figure 7-1: The Interior Permanent Magnet Synchronous Motor used by Nissan in the Leaf Electric Vehicle [31]

Table 7-1: Key features of the Nissan Leaf Interior Permanent Magnet Motor [9]

Feature	Nissan Leaf
Motor Type	Interior Permanent Magnet
Max Speed	10,390 rpm
Max Torque	280Nm (340Arms)
Peak Power	80kW (est. 154kVA)
DC Link Voltage and Current	400Vpk / 500Apk
Peak Motor Efficiency (estimated)	>96% (6.5krpm / 120Nm)
Motor Outer Diameter: Active / with Jacket	200.4mm / 280mm
Length: Active / with Jacket	231.5mm / 300mm
Volume: Active / with Jacket	7.3l / 18.5l
Motor Mass: Active / Complete	32.0kg / 58kg
Power Density: Mass / Volume	2.6kW/kg / 11.0MW/m ³
Torque Density: Mass / Volume	8.8Nm/kg / 38.4kNm/m ³
Mass of NdFeB Magnet	2.0kg

7.2 Basic Segmental Rotor SRM Design Selection

A single topology of Segmental Rotor SRM is considered in this chapter, comprising a machine featuring 12 stator slots, 10 rotor segments and alternately wound teeth and using compressed aluminium windings (see Figure 7-2).

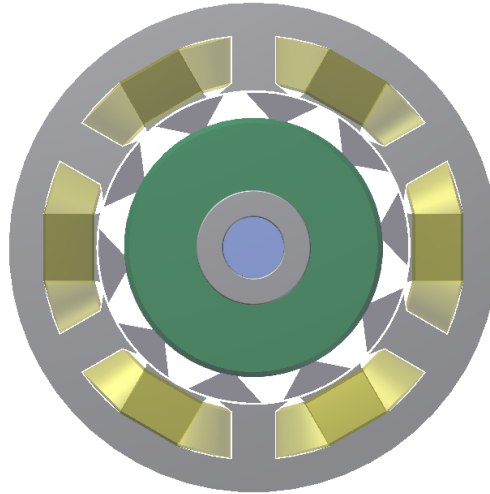


Figure 7-2: A 12-10, single tooth wound Segmental Rotor SRM.

The single tooth wound topology has been selected as this winding configuration is considered to have advantages for mass production when compared to a fully pitched design, such as the ability to use a modular stator construction. It also allows the use of compressed aluminium windings; it was decided that these windings would be used as they offer benefits in terms of cost, mass and recyclability (see Chapter 6), making them potentially ideal for use in a mass produced automotive electrical machine.

Only the 12-10 slot / segment combination is considered; with this class of machine the number of allowable stator tooth and rotor segment combinations are limited, as has previously been discussed in Chapter 3. For a 3 phase single tooth wound machine, combinations of either 6.x-5.x (indicating 6.x stator slots and 5.x rotor segments) or 6.x-7.x series, with x being a positive, even, integer number, are possible due to geometrical limitations on the rotor geometry and other factors such as unbalanced magnetic pull. In the case of a 10,500 rpm machine, rotor segment numbers are further limited by electrical frequency. A ten segment rotor, the practical minimum, already has an electrical frequency of 1.75kHz, close to the limit for a power converter of this size.

Similar to the process applied in Chapters 3 and 5, a parameterised, finite element model of the 12-10 motor is generated such that all motor dimensions may be varied

continuously. Basic design rules are applied, similarly to Chapter 3. These include some restrictions; for example, the gap between stator tooth tips be equal to the gap between rotor segments and that the rotor segment must have the same span as each stator tooth tip. No limitations are placed on motor outer diameter or length, with it being expected that the mass penalty function would limit total motor volume (see Section 7.3).

Limitations are however placed on minor motor dimensions to avoid the creation of geometries where, for example, stator slots become closed or which in other ways are impractical.

7.3 Optimisation Requirements

The optimisation of an electrical machine for use in an automotive application is a complex problem. Whilst there is a requirement that the electrical machine meet a certain torque speed envelope [108] – which defines the vehicles acceleration and maximum speed characteristics – it is equally important that the machine be optimised to operate most efficiently at the most common vehicle operating points [7]. This is illustrated by Figure 7-3.

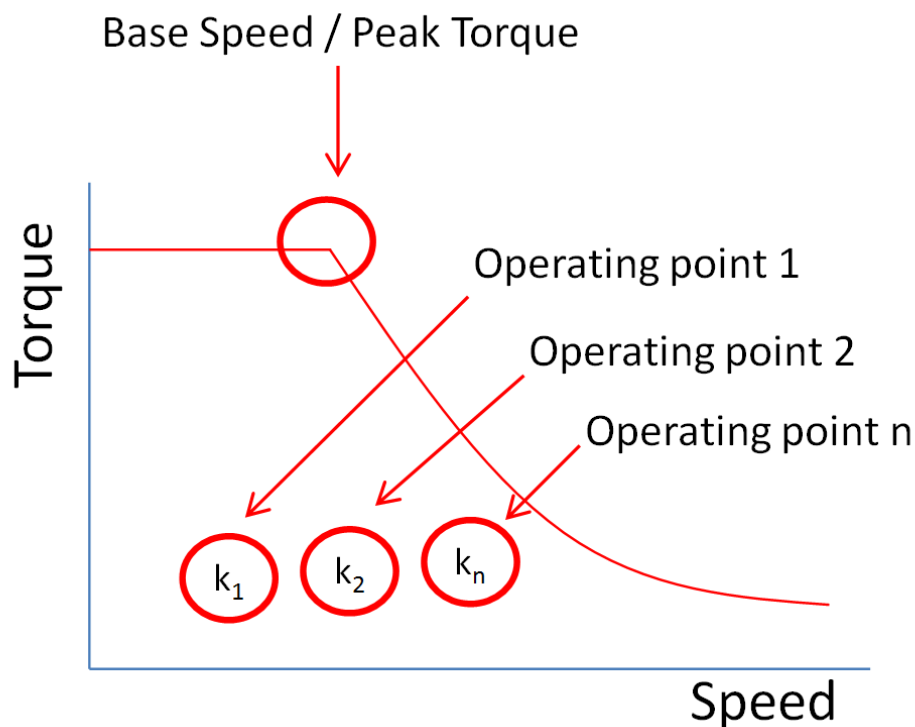


Figure 7-3: Generalised automotive traction torque speed curve showing common operating points.

Figure 7-3 shows the torque speed envelope for a single speed (i.e. without multi-ratio gearbox) electrical traction motor; this envelope is perhaps best characterised by a single point; base speed / peak torque. It may be surmised that if this single operating point can be achieved then, assuming that the peak motor speed is less than 3-4 times base speed, it will be possible to achieve this range with an SRM, a class of machine often cited as having excellent constant power ranges [34]. Achievement of the base speed / peak torque operating point may be bounded in many ways. For example it can be defined simply as the ability of the motor to achieve that operating condition, given the available supply volts and amps. It could alternatively be some measure of the thermally limited dwell time at that operating point, after which the motor will overheat, whether that be continuously or for some finite period.

In terms of the definition of common motor operating points, the automotive industry uses many drive cycles to define the normal operation of a vehicle (electric or otherwise). For example the Artemis drive cycle [109], which resulted from a European Union Research project, has been designed to define the standard drive cycles for vehicles under 'Urban', 'Rural Road' and 'Motorway' conditions. If these operating points (or indeed those arising from other drive cycles) could be converted into zones on the torque speed characteristic, then they may be plotted as shown in Figure 7-3; for example Operating Point 1 aligning with Urban, Operating Point 2 with Rural Roads and Operating Point 'n' as Motorway. The Artemis cycle also assumes that these operating points do not have equivalent importance in overall vehicle operation. As such it would be necessary to implement some method of weighting the importance of each operating point.

It is these operating points where the efficiency of the electrical machine is most critical, as it is these points where the vehicle will mainly operate. In order to assess the efficiency of these operating points it is necessary to run a dynamic simulation so that iron losses, alongside winding losses, can be assessed.

For this project, the definition of the torque speed envelope is already provided by the specification shown in Table 7-1. As peak torque is known to be 280Nm and constant power to be 80kW, it is trivial to calculate base speed to be 2,728rpm allowing the torque speed envelope to be constructed.

It is more difficult to define the common motor operating points, as Nissan do not provide these. As a result (and in order to reduce computational time during optimisation) it was decided to arbitrarily define a single operating point. It was decided to that this would relate to a pseudo urban scenario, with a speed of about 35mph selected (which with the Leaf's 7.937:1 [31] gear ratio would be equivalent to circa 3,500rpm) with a torque of about 40Nm, which would equate to just less than 15kW or 18% of peak vehicle power which was deemed reasonable. This resulted in the torque speed envelope shown in Figure 7-4.

However the expectation was that once the optimisation process had been proven then the use of this single operating point could be simply extended to cover a range of additional points. As a result the optimisation process developed is designed to be able to work with more than one operating point.

It was decided that no limitation should be placed on the size of the SRM and that there would be no requirement that it fit in the same space envelope as the Leaf's motor. Instead it was intended that the optimisation would seek to limit the active mass of the resulting motor as far as possible as part of optimisation objective function.

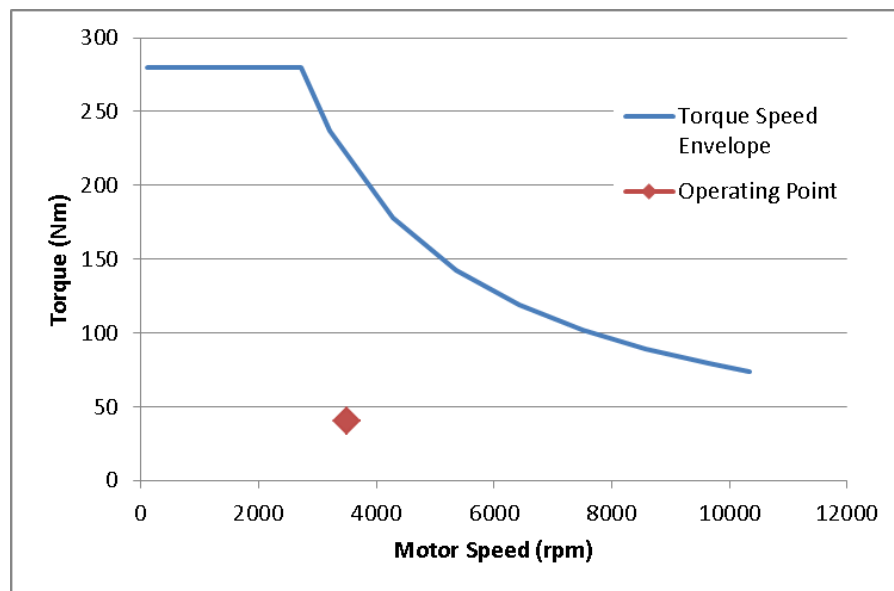


Figure 7-4: Optimisation torque speed envelop and selected optimisation operating point.

As was discussed in Chapter 5, it is essential to in some way limit the size of the motor during optimisation. A larger motor is by definition more efficient and, without

constraint, an efficiency optimised motor's size will otherwise tend to infinity. Similarly to the approach taken with the solar powered aircraft thrust motor, optimised in Chapter 5, it was decided to implement a mass limit as part of the objective function. The assumption that motor mass can be equated to motor efficiency is as valid in an electric vehicle application as for the case of a solar powered aircraft, though the level of allowable motor mass per unit efficiency is likely to be somewhat different. Unfortunately no information was available on the equivalence between mass and loss in this vehicle and so again an arbitrary selection was made, with 10kg active motor mass being assumed to be equivalent to 1% efficiency gain. Whilst 10kg per percent efficiency is a low value, it was assumed that a 10kg active mass increase would result in further cumulative gains in vehicle mass, including the impact on non-active motor components and vehicle structure, and so perhaps equate to as much as 30kg in terms of total additional vehicle mass.

As a result the optimisation objective function could be defined as in the following equation:

$$\text{Objective Function} = \frac{\sum_{i=1}^n k_i \cdot \eta_i}{n} - k_{mass} \cdot \text{Mass} \quad (7-1)$$

with n being the number of operating points to be assessed, k_i the relative weighting of the operating point i , η_i being the motor efficiency at operating point i and k_{mass} being the mass weighting factor, in this case 0.1.

Motor optimisation would therefore proceed in two parts:

1. For each geometry, firstly an assessment to ensure that the motor could achieve base speed / peak torque within the voltage and current limits of the power electronic converter, indicating that the full torque speed envelope is likely to be accessible;
2. The calculation of the objective function allowing a comparison to be made between differing candidate motor geometries.

7.4 Limitations of SRM fully Dynamic Optimisation

In Chapter 5 the process of dynamically optimising an outer rotor permanent magnet machine was described. This process employed a pre-processing script which ran a series of finite element solutions, coupled to an iterative search algorithm, to set the

sinusoidal motor input current such that the correct torque would be achieved. This input current then formed the basis of the full optimisation run, allowing the calculation of motor electrical losses (winding, iron and eddy current) such that a good comparison could be made between different motor designs. Clearly this is essential; all candidate motor geometries must run at the same torque and speed point in order for a fair comparison to be made between them.

Ideally this type of approach would also be applied to the optimisation of an SRM, however this is where the difficult, non-linear nature of SRMs becomes a limiting factor. In the case of the PM machine it was possible to assume sinusoidal current waveforms, as would be a realistic assumption across the full range of motor speeds. However with an SRM driven from an asymmetric half bridge this assumption cannot be made, as is shown in Figure 7-5.

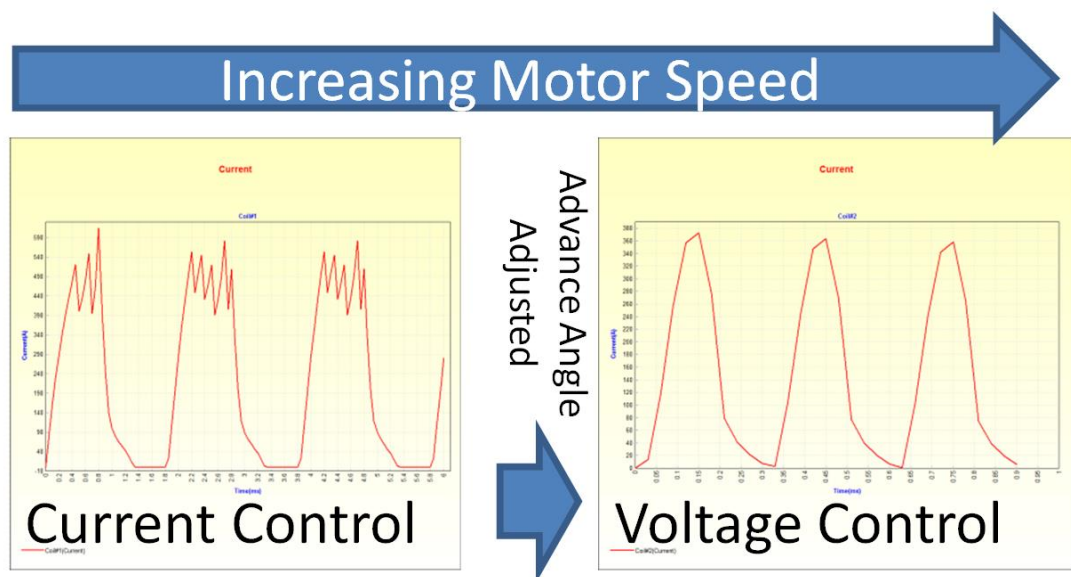


Figure 7-5: Showing SRM transition between current and voltage control modes. This demonstrates the non-sinusoidal nature of SRM current waveforms.

With SRMs, at low speed, current control is generally implemented. DC link voltage is switched in order to limit motor current to the required level. This operating mode generally results in a broadly square-wave current output. However as motor speed rises further then, due to the high reactance of the motor windings, the current becomes self-limiting and the motor enters voltage control. During the transition from current to voltage control mode, the voltage advance angle is adjusted so that the peak current is

achieved in the motor's peak torque region. This is a complex process and, due to the non-linearity of the motor, generally trial and error is used to define the peak current and advance angle for any particular operating point.

With the proposed SRM optimisation, the intention is to assess several operating points as part of a single optimisation run. This makes the use of some form of iterative assessment of the best current limit and advance angle for each operating point impractical due to computational time limitations. This problem is exacerbated by the need for highly torque dense electrical machines to operate in saturation, a condition which significantly slows the solution time for a single finite element model solution.

Confirming the impracticality of this approach, an optimisation run was undertaken using Infolytica's OptiNet and MagNet software to optimise for peak torque / base speed only. This test optimisation was undertaken according to the process flow chart in Figure 7-6.

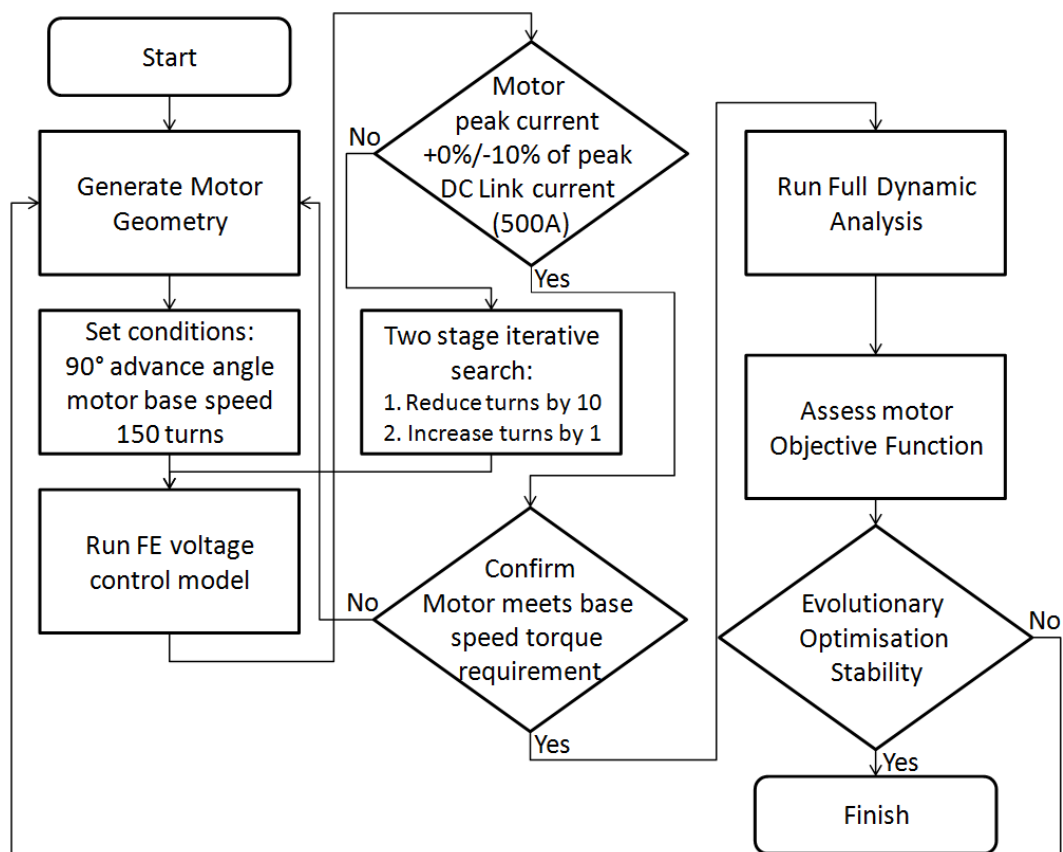


Figure 7-6: Process used to trial fully dynamic optimisation.

The principle applied was that, given a fixed advance angle of $90^\circ_{\text{(electrical)}}$ (a reasonable limit) and the motor operating under voltage control, then a way to achieve a comparison between differing motor geometries would be to set the number of winding turns so that the peak motor phase current was just below the peak allowable DC link current. If under this condition the motor design was able to achieve the desired average peak torque, then the design would be in principle acceptable.

In order to determine the number of winding turns, an initially high number of turns per coil (150) was selected and the transient with motion solver run over one and a half electrical cycles with 12 steps per cycle. The initial half cycle would be excluded from the calculation of average motor torque, eliminating settling transients. The use of 12 steps per cycle was deemed to give an acceptable accuracy in terms of the current waveforms and torque output. Should the motor current fall within $+0\%/-10\%$ of the DC Link max current, then the process would advance to the next phase. If not, a two stage iterative search would be undertaken. Firstly turns would be reduced by increments of 10, again until the phase current criteria were met. If, however, the solution overshot, then turns would be increased by increments of one, until the current criteria was met. From experimentation, it was found that the process would generally require between three and twelve iterations to achieve a solution.

Following the completion of this iterative process, should the required torque be achieved, then the process would move to a full optimisation solution at the base speed / peak torque operating point. Again this is based on a transient with motion solve, however in this case with the number of time steps per cycle increased to 30 to provide an acceptable level of accuracy to support iron loss estimation. The objective function was then calculated and the process repeated until the optimiser achieved an optimum solution.

This optimisation process took approximately 200hrs to complete, based only on a single operating point, with approximately half of the motor geometries rejected as not achieving the required base speed / peak torque. Equally, no satisfactory way was found of extending this approach to work in the current control region. However this limitation was fundamentally due the finite element toolset offering no way to operate a machine under voltage PWM driven current control and therefore could potentially be overcome if a differing toolset were used.

Therefore on both of these grounds, time and feasibility, it was not possible to apply such a fully dynamic optimisation process and so an alternative approach was required. The chosen approach would combine static finite element based estimations with a dynamic assessment of motoring losses.

7.5 Hybrid Static and Dynamic Optimisation Approach

7.5.1 Optimisation Process

The optimisation process, summarised in Figure 7-7, is a hybrid of static and transient finite element analyses. This process is fully automated through the use of Visual Basic scripts, coupled again to the Infolytica optimisation toolset.

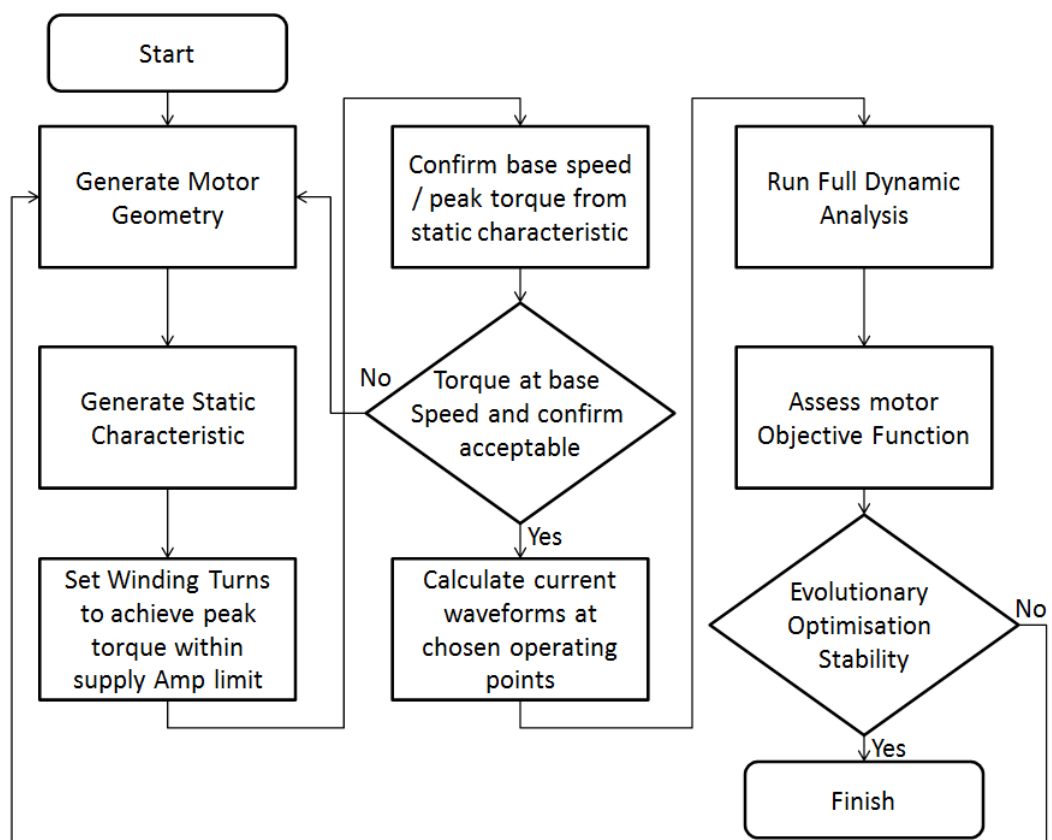


Figure 7-7: Proposed optimisation process which makes use of both static and transient finite element analysis techniques.

In order to confirm the achievement of the full torque-speed characteristic, a series of static analyses are undertaken; these was implemented through the use of a pre-processing Visual Basic script which can be found in Appendix 4. For each geometry, a static flux linkage characteristic is generated; this is used to set the number of winding

turns to allow the achievement of peak torque below base speed with the available supply current (see Section 7.5.2 for full details). The static characteristic is then also used to predict the maximum achievable torque at base speed; this prediction is based on an assessment as to whether sufficient flux can be built up in the machine, given the converter's voltage limit, in order to achieve the required mechanical power at base speed (see Section 7.5.3).

If this static analysis demonstrates that base speed / peak torque can be achieved then the optimisation proceeds to the next step. Should it not be possible to achieve the required base speed / peak torque then the geometry is rejected and a new geometry generated.

The optimisation then assesses motor efficiency and motor mass, more detail of which is provided in Section 7.5.4. In summary, current waveforms, estimated from the static data collated earlier, are generated for each operating point and a full transient with motion 2D simulation undertaken. This allows motor output power along with both winding and iron losses to be estimated, allowing calculation of motor electromagnetic efficiency. The motor mass is then estimated and the objective function for each candidate geometry calculated; these results are then used by the evolutionary algorithm (more information on which is provided in Chapter 3) to allow it to progress until an optimum solution is identified.

7.5.2 Static Prediction of Number of Turns

As has been described, static finite element calculations are used to assess each candidate geometry's ability to meet the required torque-speed characteristics. Static solutions are used as they significantly reduce solution time, when compared to a transient solution, and also because assumptions can be made which simplify the complex, non-linear behaviour of SRMs.

The first stage of this process is to set the number of winding turns so that the peak motor current from the supply is able to deliver the required average motor torque whilst operating at base speed. As has been seen in Section 7.4, for an SRM this process is generally complex, requiring a number of transient FE runs in order to set turns and advance angle. A process was therefore developed which makes a number of assumptions in order to make a quick, simplified estimate of the number of turns required using a small number of static point solutions.

In Segmental Rotor SRMs, peak motor torque is invariably produced at around the mid-point between the aligned and unaligned rotor positions; this is where the rate of change of flux linkage with rotor position is at its highest. A static solution was therefore undertaken, for various values of MMF, in this rotor position, and torque values taken from the finite element software. These provide an indication of the instantaneous peak torque value which would be achieved when the motor is running.

An estimation must then be made of how these values of peak motor torque scale to average motor torque. Figure 7-8 shows a representative characteristic, from finite element analysis, for a Segmental Rotor SRM operating at base speed under voltage control with optimised phase turns and advance angle; here average torque is 278Nm, peak torque 385Nm, minimum torque 203Nm and peak to peak torque ripple is 65%. This level of torque ripple and its asymmetry from the mean has been found to be generally representative of a Segmental Rotor SRM operating at this point in the torque speed envelope.

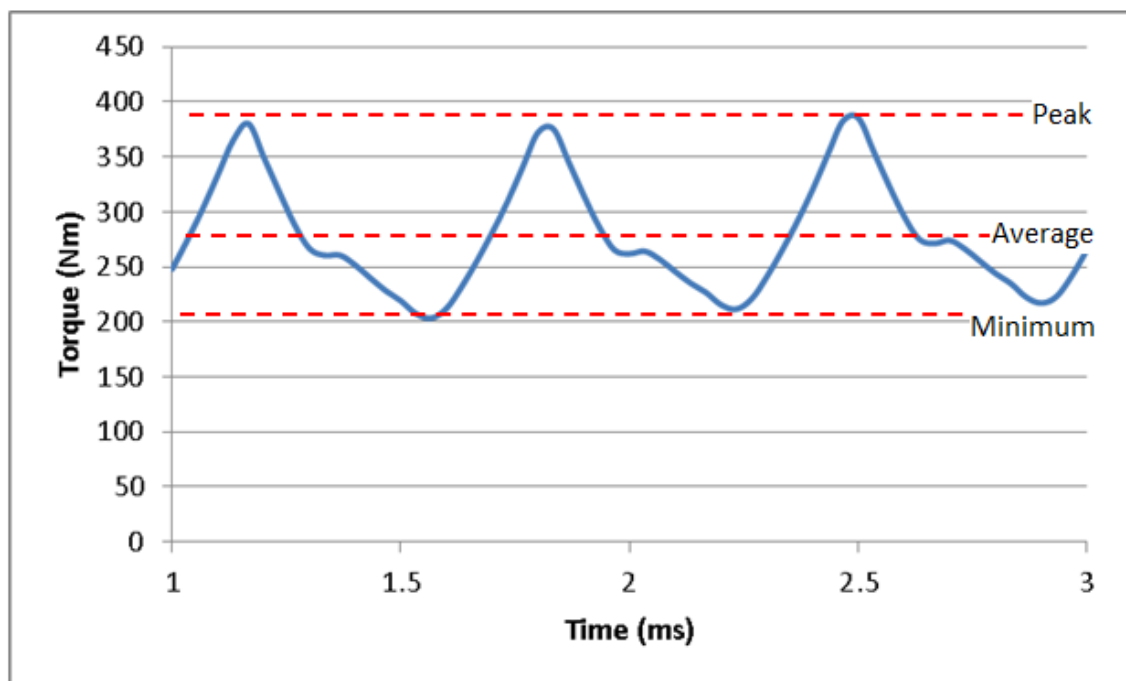


Figure 7-8: Representative torque waveform at base speed, peak torque assuming voltage control, optimised winding turns and advance angle.

This characteristic can therefore be used as the basis for estimating mean torque from peak torque for other motor geometries as follows:

$$T_{peak} = k_{offset} \cdot T_{ave} \cdot (1 + \frac{k_{ripple}}{2}) \quad (7-2)$$

where T_{peak} is the required peak motor torque assuming that T_{ave} is the desired average torque, k_{ripple} the peak to peak torque ripple as a decimal and k_{offset} is a constant specifying the asymmetry of maximum and minimum torque around the average. For the case shown in Figure 7-8, k_{ripple} would be 0.65 and k_{offset} 1.05, representative of these machines operating at this torque and speed.

As a target average torque of 280Nm is required, it can then be calculated that a peak torque of at least 390Nm will be required. In order to provide a further factor allowing for motor build effects, a scaling of 1.05 is applied to this value, resulting in a target peak torque of 410Nm.

As the peak permissible converter current is assumed to be 500A, it is then straightforward to set the turns such that they are minimised whilst still allowing a peak torque of 410Nm to be achieved for less than 500A phase current.

7.5.3 Static Prediction of Peak Torque at Base Speed

The objective of the next stage of the process is to estimate whether instantaneous peak torque (410Nm) and hence average torque (280Nm) and peak power (80kW) can be achieved within the available supply VA rating at base speed (2750rpm). This can be tested by confirming whether it is possible to achieve the required flux linkage, at the peak torque rotor position, by applying full supply volts (400V) at base speed (2750rpm).

To make this assessment, firstly the static characteristic in the peak torque position is once more calculated. Assuming the number of winding turns derived in the previous step, phase current is increased in steps between zero and 500 amps and flux linkage and torque recorded from the finite element software. In order to allow for end winding inductance in a real 3D machine, based on the results presented in Chapter 4, a fixed 15% is added to the both unaligned and peak torque flux linkages in order to simulate this effect.

This data then provides a mapping between flux linkage and motor instantaneous peak torque. As the instantaneous peak torque required to achieve the desired average

motoring torque has been estimated to be 410Nm, this can be used to identify the flux linkage that would be required in order to achieve the required average torque.

In assessing whether this flux linkage is achievable at a given speed, a conduction angle of $180^\circ_{\text{(electrical)}}$ is selected in conjunction with an advance angle of $90^\circ_{\text{(electrical)}}$ (see Figure 7-9). The conduction angle is selected as this represents the longest possible conduction period where the flux will return to zero between electrical cycles. The 90° advance angle ensures that the peak flux, built up over the conduction period, therefore aligns with the motor's peak torque position.

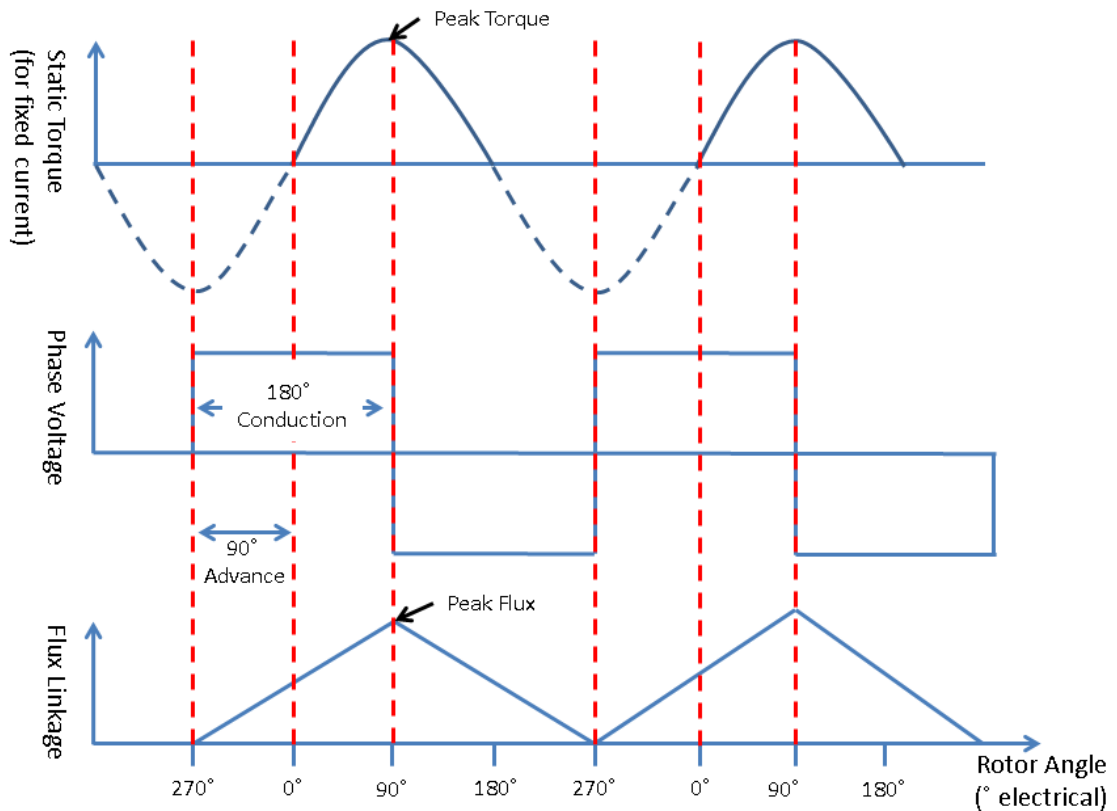


Figure 7-9: Conduction and Advance Angles selected for base speed / peak torque confirmation.

Full supply volts (in this case 400V) are applied during this conduction period. By using the simple relationship:

$$\varphi = v \cdot t \quad (7-3)$$

(where φ is the flux linkage, v the voltage applied to the phase and t the period over which that voltage is applied) it is trivial to calculate whether, at a given motor speed,

there is sufficient time for the flux linkage, and therefore phase current, to climb to the level required.

As a result, it is possible to use this analysis to confirm whether the motor could achieve base speed, peak torque by ascertaining whether it would be possible to produce sufficient flux linkage, given available DC link volts, in order to deliver the required torque.

For each optimisation run this current rise test is therefore used to either select, if peak torque can be achieved, or reject a particular geometry prior to moving onto the next stage of optimisation.

7.5.4 Dynamic Assessment of Motor Losses

Once it is established that a motor geometry is able to achieve peak torque at base speed, the next step in the optimisation process is to undertake a transient 2D finite element simulation in order to calculate losses at the selected operating points.

For SRMs, a high fidelity assessment would be onerous, requiring that, for each operating point, an optimum advance angle and conduction angle be selected and that a current control scheme be implemented. An alternative is to use a simple trapezoidal current source to approximate such a current control scheme. However it is important that a reasonable approximation of current rise and fall is made so that iron loss calculations remain realistic. In order to simplify this process, a current rise estimation approach is used to develop a representative current waveform. The demand current to achieve the necessary torque is once more estimated from the static torque assessment, considering the likely relationship between peak and average torque.

The current waveform is assumed to be centred on the peak torque position, with zero degree advance angle and that the conduction angle is 180deg. Static flux linkage / current characteristics are again used in order to provide an estimate of current rise time. Static flux linkage / current characteristics are calculated in the unaligned and aligned positions and the existing characteristic for the peak torque position reused.

These static characteristics are then used to estimate the flux linkage equating to the demanded phase current around the unaligned position, where current will rise, and around the aligned position, where it will fall. Again equation (7-3) is used as the basis of this calculation, allowing the calculation of current rise and fall times. Figure 7-10

compares the estimated current waveform for a single phase with that taken from a full, voltage PWM based ‘bang bang’ current control simulation run in the FE toolset.

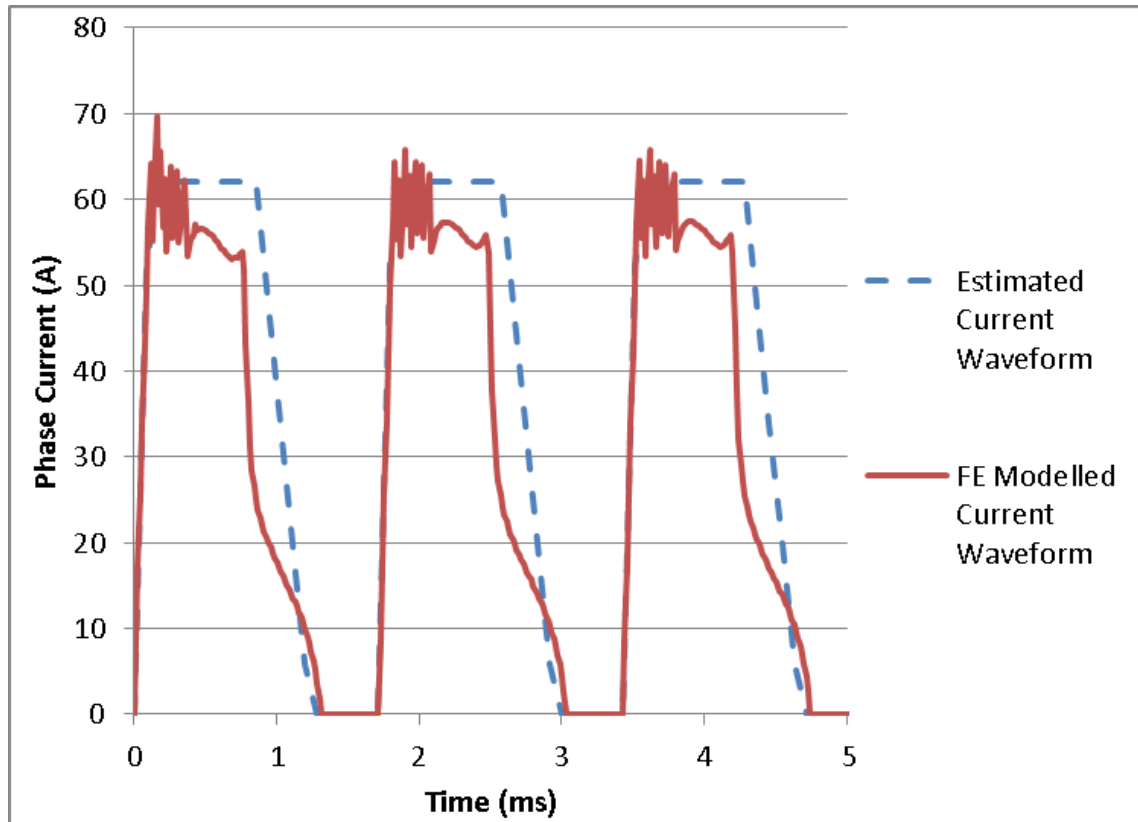


Figure 7-10: Comparing the estimated current waveform for the assessment of motor losses during optimisation and a full, ‘bang-bang’ current control waveform for the same operating point.

These waveforms are used as the basis of a transient with motion 2D finite element analysis of the motor operating at the required, 3500rpm 40Nm operating point. Winding and iron losses are estimated and motor efficiency calculated. Finally the objective function is calculated and each geometry compared.

7.6 Hybrid Optimisation Results

Table 7-2 and Figure 7-11 present the results of a series of five optimisation runs and contrast them with the performance of the IPM Motor from Nissan’s Leaf electric vehicle. Despite the simplifications applied to the optimisation approach, optimisation runs took between 5 and 15 days to converge, running on a modern server.

Table 7-2: Comparison of Segmental Rotor SRM Designs resulting from a series of five optimisation runs and the Nissan Leaf's IPM machine

	Stator OD (mm)	Stack Length (mm)	Volume (l)	Turns per Coil	Active Mass (kg)	Efficiency (%)	Objective Function
SRSRM1	241.4	151.5	6.9	21	28.4	97.5	94.66
SRSRM2	229.6	136.4	5.6	22	25.2	97.3	94.78
SRSRM3	191.0	241.9	6.9	16	30.8	97.2	94.12
SRSRM4	246.2	159.1	7.6	20	32.8	97.3	94.02
SRSRM5	250.0	155.2	7.6	22	29.5	97.5	94.55
Nissan Leaf IPM	200.4	151.5	5.7	N/A	32.0	Not Known	-

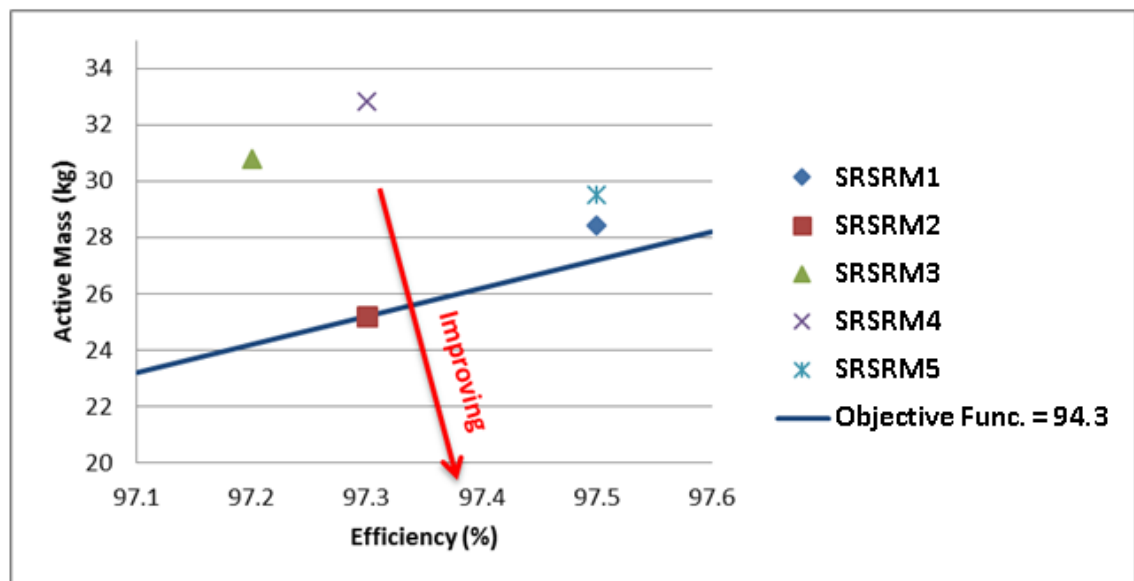


Figure 7-11: Showing optimisation results for the differencing optimisation runs. Blue line is the iso-line for the best Objective Function achieved.

In one case, SRSRM2, a motor that is both marginally volumetrically smaller and 21% lighter than the Nissan Leaf is predicted; the lower mass being due to the use of aluminium windings and the intrinsically low mass of the segmented rotor.

However, as will be seen in Chapter 8, the development of this design into a practical prototype, modified to be able to meet the mechanical requirements of operation at 10,500rpm, resulted in its performance becoming marginal when compared to the requirement to match the performance of the Nissan Leaf. In all other cases larger, but still in all but one case lower mass motors, result from the optimisation. In fact it is the largest of the resulting, optimised machines (SRSRM4) which is selected for prototype manufacture (again see Chapter 8 for full details).

It is interesting to note that whilst each optimisation run produces a similar objective function, dimensions differ significantly due to the stochastic nature of the optimisation process. This suggests that the optimisation surface is relatively flat, offering a similar objective function across a range of optimum but differing motor designs.

7.7 Finite Element based Validation of Optimisation

Despite its limitations, the SRSRM2 design still forms a valid basis upon which to validate the assumptions which underpinned the optimisation process; even with this marginal design the optimisation process must still be shown to provide valid results, based on the approach and assumptions described in Section 7.5.

Two operating points are considered; firstly base speed, peak torque, validating the current rise modelling. For the solution to be valid the current rise would need to be sufficient to allow the optimised machine to produce the required output power / torque.. The results of this analysis are summarised in Table 7-3.

Table 7-3: Comparing the results of base speed peak torque (2750rpm, 280Nm) analysis from estimates during optimisation and full 2D FE.

	Estimate from Optimisation	Results from 2D FE
Advance Angle	90 deg	75 deg
Peak Current	494.9 A	509.6 A
Time for Current to rise to Peak	933.5 μ s	927.3 μ s
Peak Torque	409.3 Nm	383.7 Nm
Average Torque	280.0 Nm	295.7 Nm

Current and torque graphs are shown in Figure 7-12 and Figure 7-13 respectively with a flux density plot of the motor being shown in Figure 7-14. Figure 7-12 and Figure 7-13 assume voltage source PWM, with a bang-bang current controller. In this case, the advance angle is adjusted to 75° in order to maximise the torque produced at this operating point; whilst the optimiser assumed a greater, 90° advance, this also took into account the 15% allowance for increase winding inductance due to 3D effects which was, as previously discussed, built into optimisation.

A higher average torque was predicted by the detailed finite element model, than that predicted during the optimisation process. This is consistent with the optimisation objective, which is to ensure that the optimised motor has a margin of performance when modelled in 2D, allowing for 3D and other build effects.

However peak torque is found to be less than predicted; this is because the combination of 75° advance angle and 180° conduction angle led to significant levels of instantaneous negative torque, as shown in Figure 7-13. Adjustment of advance and conduction angles would reduce this effect. Figure 7-13 also shows both the torque produced by a single phase (with other phases inactive) as well as the torque from the three phase operating together. This shows that the mutual interactions between phases have an impact on average torque, increasing it by the region of 15Nm (5%). However Figure 7-12 also shows how the mutual interactions between the phases have allowed the current to rise faster than where Phase B operated alone; this is due to interaction between flux generated by each phase in the unwound tooth between phases, as can be seen in Figure 7-14; this shows how interactions between phases must be considered.

The second test was to compare the results for the selected operating point (3500rpm, 40Nm) from the optimisation process with a full PWM based, bang-bang current control simulation in 2D FE. The results of this analysis are shown in Table 7-4.

The results showed reasonable correlation except in the case of iron loss, with the 2D PWM based current control simulation showing higher levels of loss. This is due to the impact of high frequency switched currents present in the waveform at PWM frequency (see Figure 7-10).

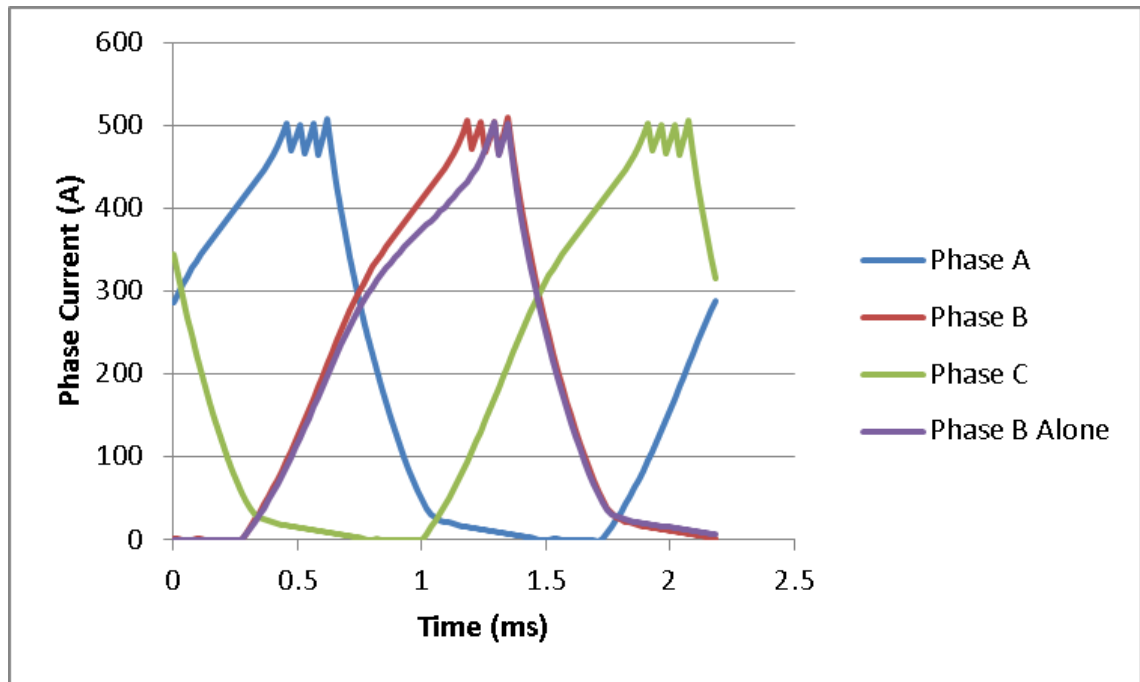


Figure 7-12: Phase current waveforms for motor at base speed / peak torque. Phases A, B and C are shown operating together. 'Phase B Alone' is operating with phases A and B inactive.

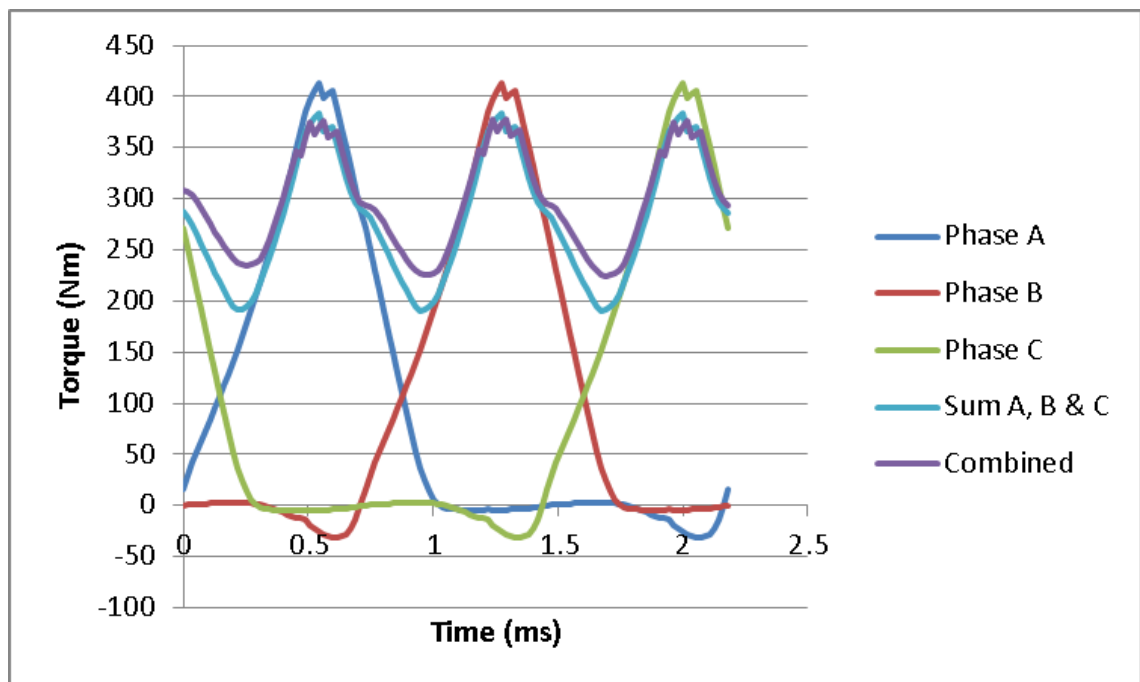


Figure 7-13: Torque characteristic for motor operating at base speed / peak torque with voltage source PWM based current control. Individual phase torque characteristics are from a finite element run where only a single phase was active. 'Sum A, B & C' is the sum of these three individual torque characteristics. 'Combined' is the torque resulting from a finite element run under the same conditions, but will all phases active.

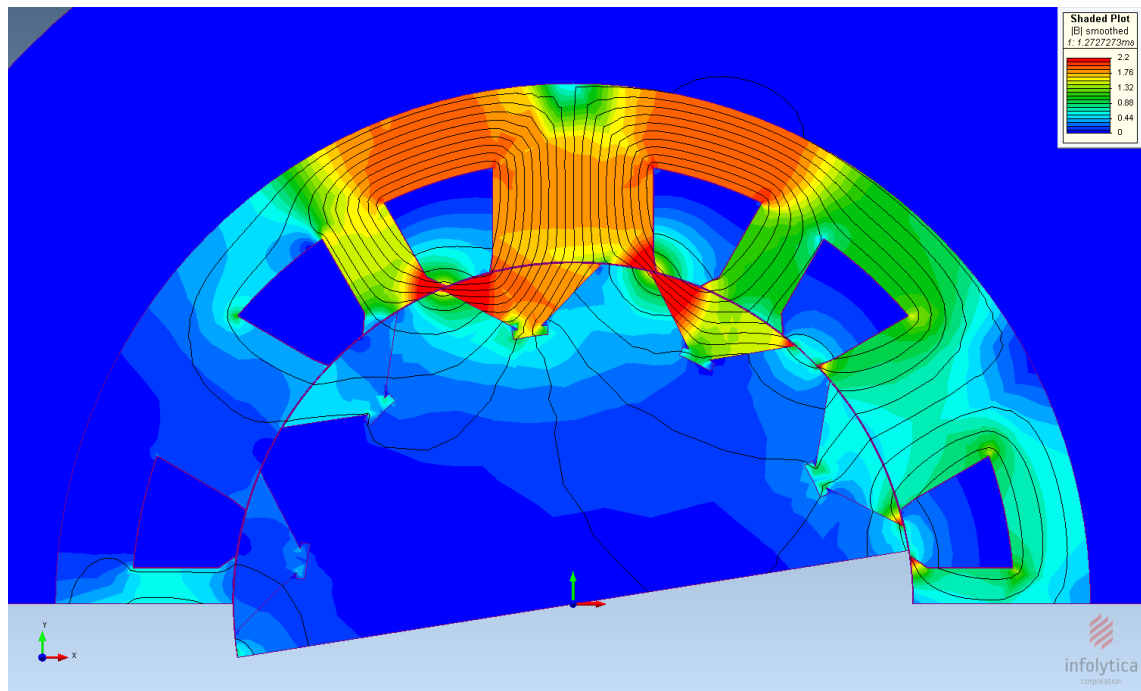


Figure 7-14: Segmental Rotor SRM R3-2, resulting from the hybrid optimisation process. Finite element plot shows motor operating at base speed peak torque.

Table 7-4: Comparing the results of analysis of motor performance at 3500rpm / 40Nm from the optimisation process and full 2D FE analysis.

	Estimate from Optimisation	Results from 2D FE
Average Torque	38.9Nm	36.6Nm
Mechanical Power	14.3kW	13.4kW
Peak Current	62.0A	65.8A
RMS Current	39.9A	38.8A
Winding Loss⁽¹⁾	168.3W	157.8W
Iron Loss	234.7W	344.1W
Total Loss	403.0W	501.8W
Efficiency	97.3%	96.4%

Notes: 1) Winding loss assumes winding temperature of 150°C

7.8 Conclusions

This chapter has shown how the combination of static and transient finite element analyses can be applied successfully to the problem of Segmental Rotor SRM optimisation. A static only approach (see Chapter 3) was not considered to be appropriate for use in the optimisation of an automotive Segmental Rotor SRM; such an approach would be not allow for the dynamic nature of the electric vehicle drive requirement or for any interactions between motor phases. A dynamic only approach (see Chapter 5) was also shown to have limitations; these were associated both with the complexities of the modelling of SRM current control and with the very large number of finite element ‘set-up’ runs which would be required to support each optimisation step.

The proposed hybrid approach makes use of static finite element runs in order to map current, flux linkage and torque so that current rise times may be calculated. This is also used as the basis for calculating simple, trapezoid current waveforms which are then in turn used as the basis of a full transient assessment of motor losses. This approach is shown to achieve a good match with the results of the 2D finite element, voltage PWM based, current controlled model runs.

The optimisation produced a single motor design (SRSRM2) which was volumetrically smaller and had a lower mass than the Nissan Leaf. Chapter 8 will however show how, through the process of detailed design, this motor is shown to have marginal performance and therefore was not selected for prototyping. The other designs resulting from optimisation are up to 30% larger, though of similar active mass, to the Nissan Leaf’s IPM motor; this is a result which is perhaps closer to what might be expected when the torque density advantages due to the inclusion of rare-earth magnets are taken into consideration.

This hybrid optimisation approach has now also been used to support commercial research into the use of these Segmental Rotor SRMs for a real automotive traction application (see Chapter 12 for more details). Whilst, at time of writing, no prototype motor has been produced, work funded by Tata Steel and involving Jaguar Land Rover has shown that by increasing the rotational speed of these machines, well above those possible for a Nissan Leaf type IPM motor, very large improvements in power density are possible.

Chapter 8. Detailed Design of Automotive Segmental Rotor SRM

Chapter 7 discussed the optimisation of an 80kW Segmental Rotor SRM, designed to match the performance of the Interior Permanent Magnet (IPM) motor fitted to the Nissan Leaf. From that optimisation a favoured design (known as SRSRM2) was selected for further development. This design had an active volume very similar to that of the Nissan Leaf's motor, but with a 20% lower active mass due to the use of aluminium windings and the lightweight rotor design.

This chapter discusses the detailed engineering undertaken in order to finalise the design of the motor for prototype construction. Firstly, modifications are made to the Volt / Ampere rating of the motor to make it more compatible with the university's dynamometers. The detailed design of the motor's rotor is then discussed, in particular in relation to the mechanical design of the fixing for the rotor segments; this section is in part based on [110], which was presented to the UK Magnetics Society in June 2013. The implications of the selected fixing method on the electromagnetic performance of the motor are then considered and it is found that these are significant, leading to the need to develop a larger motor (SRSRM4) than had previously been anticipated. An assessment is also made of the eddy currents induced in the aluminium rotor support; they are found to be large, a design modification is found and implemented.

The design of the stator is discussed. The design intent is that the prototype use very high fill factor (75%) compressed aluminium windings, building from the developments in Chapter 6. The design of the coils for use in this application is discussed, as is a new coreback design to allow the pre-compressed motor coils to be assembled into the stator core. The design of the compressed aluminium coils themselves is reviewed, as is the design of the motor housing and cooling jacket.

An assessment of the full performance envelope of the selected motor design is made, as are some predictions as to its thermal performance; these include an assessment of the degree of airgap closure due to differential thermal expansion between rotor and stator components. The final design is presented and conclusions drawn as to its success.

8.1 Limitations of University Dynamometers

In Chapter 7, the Segmental Rotor SRM was designed to operate with a DC link of 400V with a peak current of 500A. However the university's power supplies are unable to supply this level of current and therefore the decision was taken to wind the motor for use with a 600V power supply, reducing peak current to circa 350A. As a result motor turns per phase for the selected design were increased from 44 to 66.

8.2 Segmental Rotor Detailed Design

8.2.1 Limitations of Standard Segment Root Design

The Segmental Rotor SRM is designed to operate at a rotational speed of 10,390rpm. In order to ensure safe operation an overspeed condition must also be considered, in this case 20%, resulting in a maximum rotor speed of ~12,500rpm.

Analysis was undertaken considering only the ultimate tensile strength of the rotor; fatigue analysis was not considered at this stage. However as the rotor support would be made from aluminium, which will eventually fail even with lower levels of time varying stress, this would be an important consideration, perhaps defining the service life of the motor.

Efforts were made to maximise the radial distance between the airgap and the rotor support with the objective of minimising time varying flux in the rotor support and therefore the potential for eddy current losses and heating.

The rotor segment fixing design previously applied to Segmental Rotor SRMs (for example in Chapter 4) had been shown by Hall [96] to be inadequate for use in higher speed, higher power machines.

Static structural finite element modelling, using the Ansys mechanical analysis toolset, was undertaken to confirm this finding. This modelling showed that, for the design developed for this project, forces on the rotor segments and support would be well beyond the ultimate tensile strength of the base materials, making such a design unacceptable. The conditions and results of this analysis are summarised in Table 8-1 and Figure 8-1 respectively.

Advice was sought from Dr Timothy Lisle in the University's Design Unit in undertaking this analysis. Dr Lisle, who works on the accurate modelling of stress in

gear teeth, was able to provide advice as to the best approach to the modelling of the contact and stresses between the rotor segment and rotor support structure.

Table 8-1: Key conditions for the static mechanical analysis of a standard Segmental Rotor fixing.

Parameter	Value
Rotor Support:	
Material	Aluminium (6082-T6)
Ultimate Tensile Strength	310 MPa
Density	2770 kg/m ³
Youngs Modulus	71 GPa
Rotor Segment:	
Material	Electrical Steel (M270-35)
Ultimate Tensile Strength	575 MPa
Density	7650 kg/m ³
Youngs Modulus	185 GPa
Model Set-up:	
Rotational Speed	12,500 rpm
Maximum Element Size	0.25 mm
Element Size at Contact Region	0.02 mm
Symmetry Boundary Conditions	Frictionless
Contact Boundary Condition	Frictionless
Model Length	0.35mm

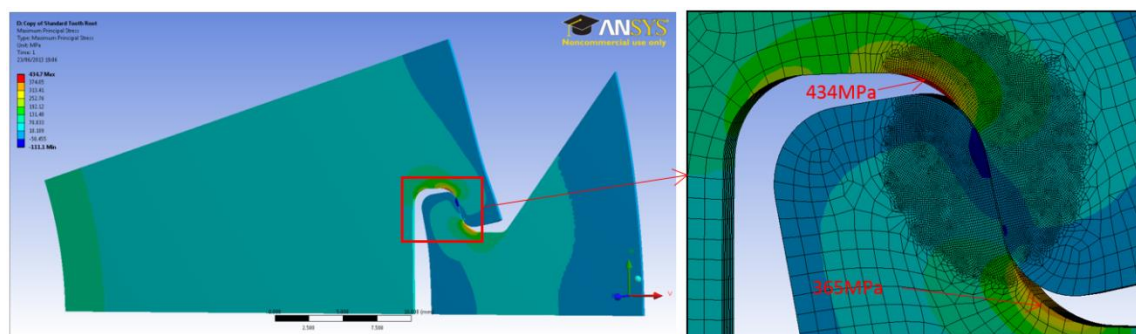


Figure 8-1: Showing Maximum Principal Stresses in a standard rotor segment root structure at 12,500rpm. Distortion is shown magnified by a factor of 100.

It was suggested that the use of von-Mises equivalent stress (which is one method of approximating material failure) would most likely be misleading and that instead the Maximum, Middle and Minimum Principal Stresses should be considered independently. Simplistically, if a 3D cube is considered, the principal stresses are a measure of the stresses applied in three dimensions parallel to the three planes of zero shear stress (see Figure 8-2).

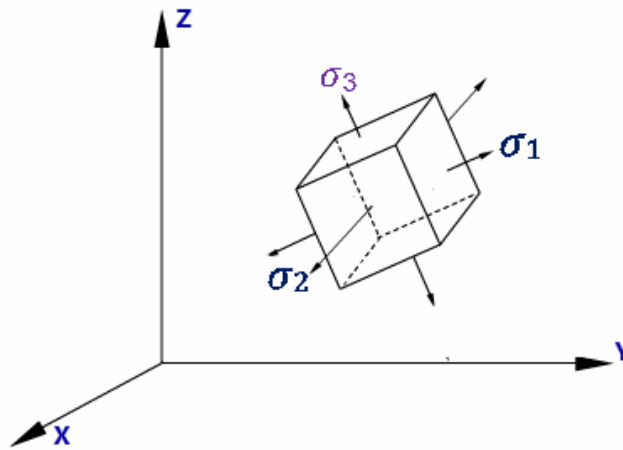


Figure 8-2: Principal stress is defined such that the shear stress on the three principal planes (the planes normal to the principal stresses, σ_1 , σ_2 and σ_3) is zero.

These three stresses are by convention named as the Maximum Principal, Medium Principal and Minimum Principal; these forces are oriented so that they are normal to the three planes of zero shear stress. The maximum principal stress has the largest tensile force and the minimum principal stress the largest compressive force. The middle principle stress represents the stress on the remaining plane.

Lisle's [111] research had shown that whilst the modelling of tensile stresses in the root of a gear could be accurately achieved with a fine mesh in the order of 100s of microns, the modelling of the compressive stresses in the compressive contact region would require a mesh of perhaps an order of magnitude smaller.

It is suggested that, in the case of a gear tooth or fir tree root, it is tensile stresses which will lead to the most immediate failure. Compressive stresses could over time lead to fatigue failure, however Design Unit experience had shown that the assessment of fatigue in a new system such as this would require experimental validation and could not be readily predicted from modelling without this. Subsequently work undertaken with Tata Steel as part of a follow-on project (see Chapter 12) also supported this

finding, with Maximum Principle Stress considered to be the design driver. As a result, for this project the Maximum Principle Stress was taken to be the main consideration when simple material failure is considered, with the Minimum Principle Force (maximum compressive force) noted for future consideration.

Based on this advice a 0.35mm axial slice of the rotor was considered; it was felt that this best reflected the use of laminated electrical steel in the rotor segments. A rotational velocity of 12,500rpm (>20% overspeed) was applied and magnetic forces on the rotor segments ignored at this stage.

M270-35A was assumed as the lamination material, with mechanical data taken from the Cogent Steel datasheet [112]. The support was assumed to be made of 6082-T6 structural aluminium, and suitable materials properties for this material were found at [113].

Two mesh densities were applied. A mesh of 0.25mm was used across the bulk of the fir tree root, with a much finer 0.01mm mesh used in the contact region, as suggested by Lisle. Frictionless supports were used on all symmetry boundaries; these boundaries allow the part to move freely tangentially to the boundary but prevent any perpendicular movement. The contact region between rotor segment and rotor support was also assumed to be frictionless.

This analysis (see Figure 8-1) clearly showed that the standard root fixing approach would not be suitable at the required operating speeds; a safety factor of just 0.71 was achieved in the rotor support, indicating that this part would fail before 12,500rpm.

8.2.2 Fir Tree Root base Rotor Segment Fixture

To overcome this problem it was decided to investigate the use of a fir tree root system. This system, commonly used to connect high speed gas turbine blades to a rotor core, has been shown to be able to provide a reliable joint even under extremely high forces [114] and has therefore been used as the basis for analysis of a suitable fir tree root for this application.

It was decided to use a fir tree root with three teeth forming the root, each tooth sharing the radial contact loads. Figure 8-3 shows the geometric parameters which were varied in the fir tree root in order to achieve a satisfactory design.

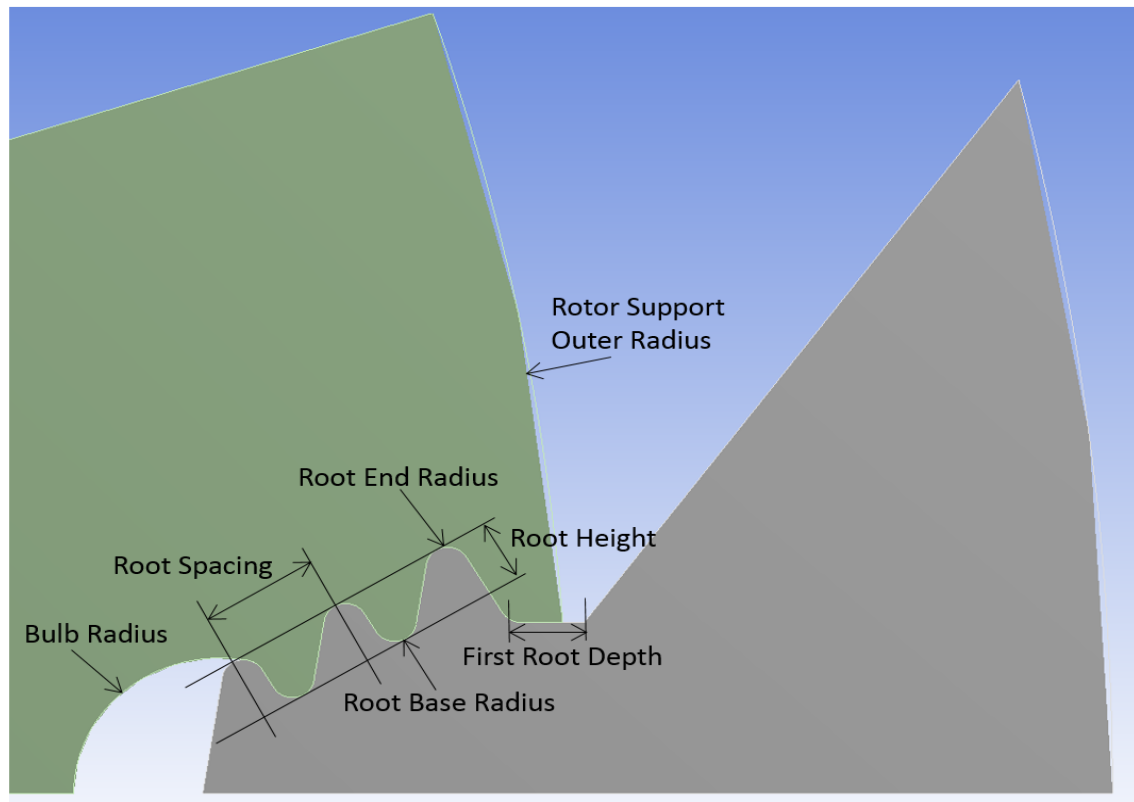


Figure 8-3: Showing the variables considered in the optimisation of the fir tree root.

A large number of manual optimisation steps were undertaken until a design was achieved which delivered a safety factor of 1.6, shown in Figure 8-4.

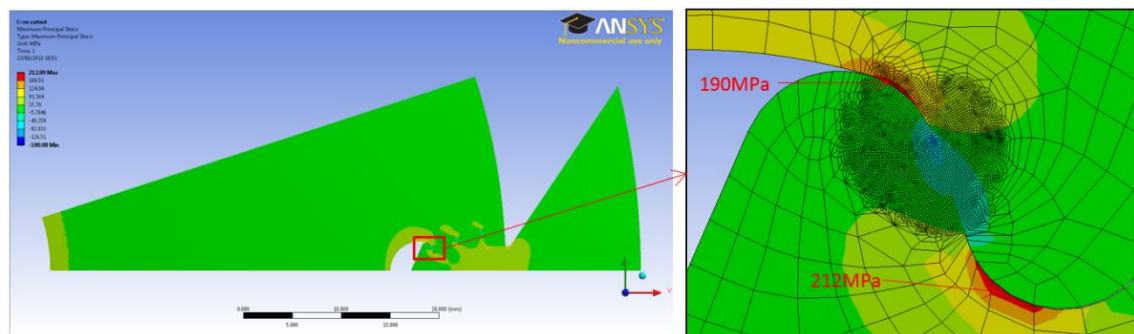


Figure 8-4: Showing maximum principal stress in the Fir Tree root at 12,500rpm.

This work demonstrated that it is possible to achieve a design which would, subject to practical validation, be safe at the required operating speed. A radial displacement of 0.03mm, above the nominal rotor radius of 57.8mm, was observed in the rotor outer diameter at 12,500rpm; this was felt to be acceptable given the 0.3mm airgap.

An attempt was also made to make use of a Design of Experiments based optimiser (this type of optimiser is described in detail in Chapter 2) to support this analysis. However, similar to the case with the electromagnetic optimisation of SRMs, the number of

parameters to be considered and non-linearity of the mechanical behaviour of the fir tree root were found to be too high for this to be a useful tool. This supports the findings in [114].

8.2.3 Impact of Fir Tree Root on Electromagnetics

This final design of fir tree root was analysed in the electromagnetic finite element software, in order to understand whether the mechanical changes would affect electromagnetic performance. Indeed, it was found that the inclusion of the fir tree root had a significant impact on the electromagnetic performance of the motor, with the result of this analysis shown in Figure 8-5 and Figure 8-6.

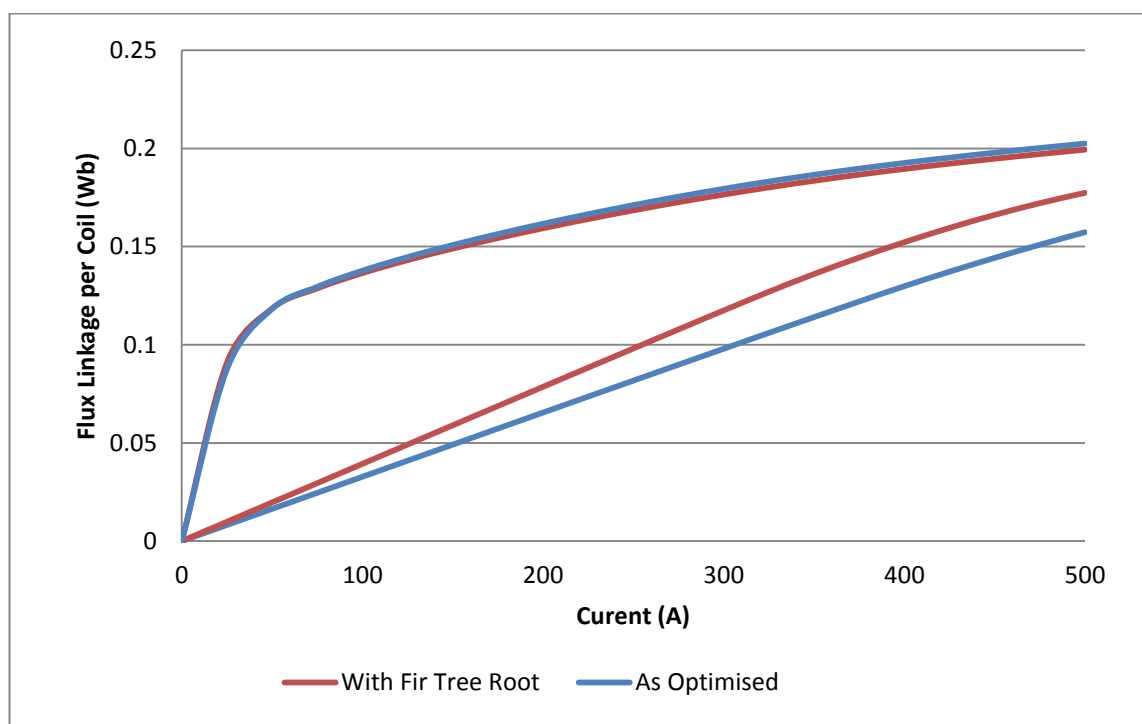


Figure 8-5: Showing the impact of the fir tree root on motor flux linkage - current characteristic.

The inclusion of the fir tree root resulted in a large increase in flux leakage in the rotor unaligned position; some 13%. This in turn reduced the area of the flux linkage - current locus and therefore torque production at 500A peak by 16%. At the target 280Nm, peak winding loss would therefore be in the region of 13.5kW (an increase of 50%) under ideal conditions; this was considered to be too high.

Due to the concern over the unacceptably high level of loss in the SRSRM2 with fir tree root, the decision was taken instead to consider the largest of the optimised motors from the previous chapter; the SRSRM4. This much larger machine was considered as it

would naturally have lower losses than the SRSRM2 machine. As 3D effects (in terms of their impact on losses) had yet to be considered and which would further dilute performance, this was considered to be prudent. These two designs are contrasted with the Nissan Leaf's IPM in Table 8-2. The selected machine's laminated core volume is some 30% larger than the Leaf's IPM, though its mass is very similar.

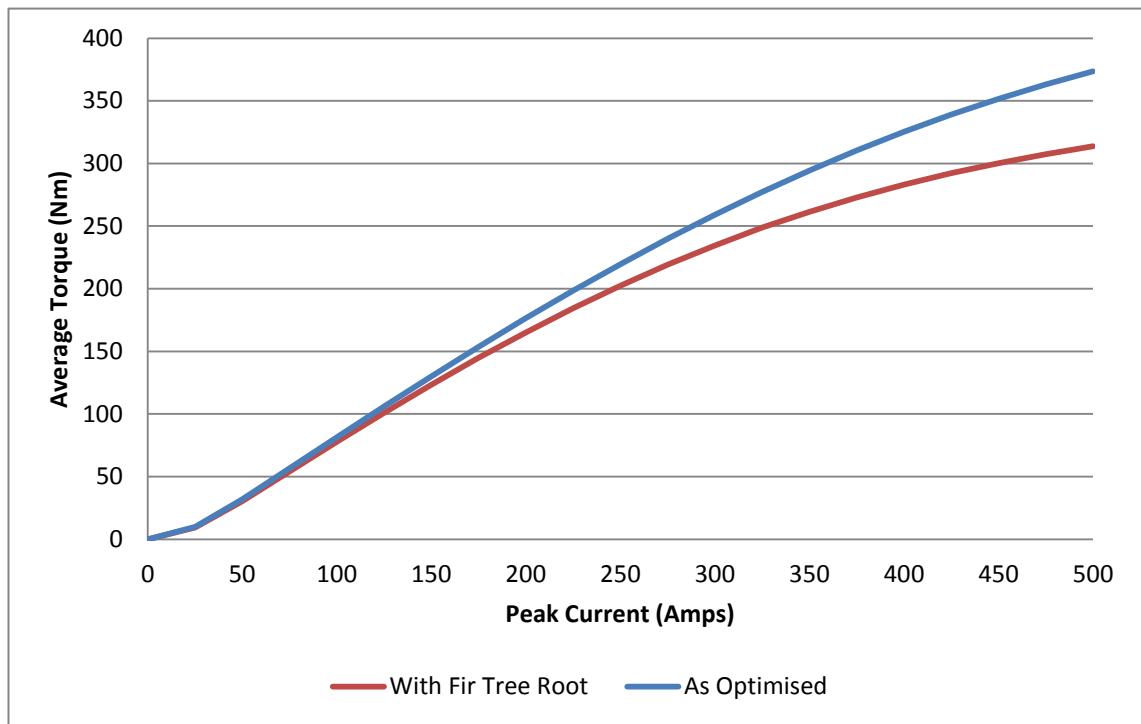


Figure 8-6: Showing the impact of the Fir Tree Root on Motor Torque (calculated from Phi-MMF). Assumes perfect current control.

Table 8-2: Comparing the SRSRM4 design with the optimum SRSRM2 and Nissan Leaf Machines.

	Stator OD (mm)	Stack Length (mm)	Volume (l)	Turns per Phase	Active Mass (kg)	Efficiency (%)	Objective Function
SRSRM4	246.2	159.1	7.6	40	32.8	97.3	94.02
SRSRM2	229.6	136.4	5.6	44	25.2	97.3	94.78
Nissan LEAF IPM	200.4	151.5	5.7	N/A	32.0	Not Known	-

A fir tree root was again manually optimised for use with the SRSRM4 motor as seen in Figure 8-7.

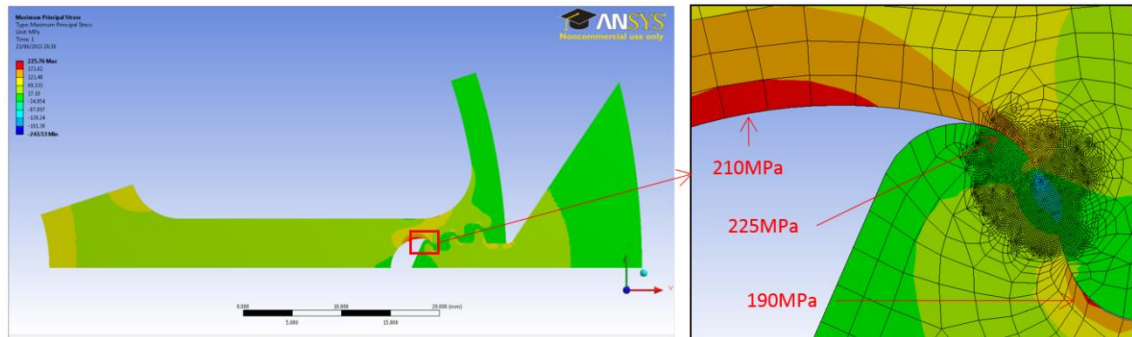


Figure 8-7: SRSRM4 Fir Tree Root design showing Maximum Principal Stress at 12,500 rpm.

A tensile safety factor of 1.37 was achieved in the rotor support with this design; this safety factor was lower than for the SRSRM2 machine due to the larger airgap diameter and therefore increased centripetal forces in the SRSRM4 machine.

This design includes a cut-out in the rotor support. Initial modelling with a coarser mesh (0.05mm in the contact region) had shown that this was likely to equalise pressure between the teeth, reducing overall stresses by the order of 5%. Later modelling with the improved mesh (0.01mm) in fact showed that this trend was reversed, with stresses increased from 190MPa to 225MPa with the inclusion of the cut-out; however the cut-out design remained acceptable and had by this stage already been manufactured and so was retained for the prototype. This demonstrates the importance of selecting the correct mesh size during structural analyses.

Following a number of investigations it was decided to keep the number of turns at 60 per phase (assuming 600V supply), in line with the results of the optimisation in Chapter 7. Motor performance was again modelled in 2D at each of the three key operating points: base speed at peak torque, rated speed at peak power and also at the optimisation condition, 3500rpm 40Nm, results being shown in Table 8-3. Figure 8-8, Figure 8-9 and Figure 8-10 show phase currents and torque profiles for each of the three cases.

Table 8-3: SRSRM4 performance at key operating points with final fir tree root. Copper loss stated at winding temperature of 150°C.

Parameter	Case 1	Case 2	Case 3
Speed	2,750rpm	10,500rpm	3,500rpm
Torque (Modelled)	285.8Nm	71.9Nm	39.3Nm
Torque Ripple	57%	246%	135%
Power	82.3kW	79.0kW	14.4kW
Copper Loss	7,357.5W	3,189.2W	192.0W
Iron Loss	907.6W	1240.4W	535.1W
Total Loss	8,265.1W	4,429.6W	727.1W
Efficiency	90.9%	94.7%	95.2%
Advance Angle	75°	90°	25°
Conduction Angle	180°	200°	170°
Current Limit	333.3A	183.3A	47.7A
RMS Current	178.9A	117.9A	28.9A
Operating Mode	Current Control	Constant Current + Current Control	Current Control

All cases in Table 8-3 have advance angle optimised to the nearest 5 electrical degrees and conduction angles to the nearest 10 electrical degrees. Each point is simulated under current control, utilising a simple bang-bang controller. In addition Case 2 is operated under constant current mode, with the conduction angle being increased beyond a half electrical cycle. This means that the current does not fall to zero; this increases motor torque (allowing constant power to be achieved) but also increases motor winding losses.

If the 3500rpm, 40Nm case (Case 3) is considered, these results showed that losses increased from the 501.8W predicted, in Chapter 7 without fir tree root, to 727.1W when this modification is incorporated, an increase of 45%. Nevertheless, despite this trend, the worst case peak losses from Case 1, at around 8kW, were considered to be manageable for the prototype.

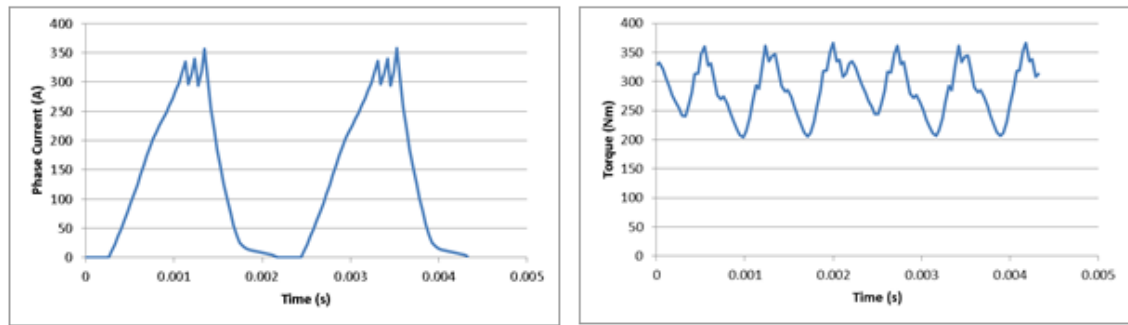


Figure 8-8 'Case 1' operating point (base speed, peak torque) showing (left) phase current and (right) torque.

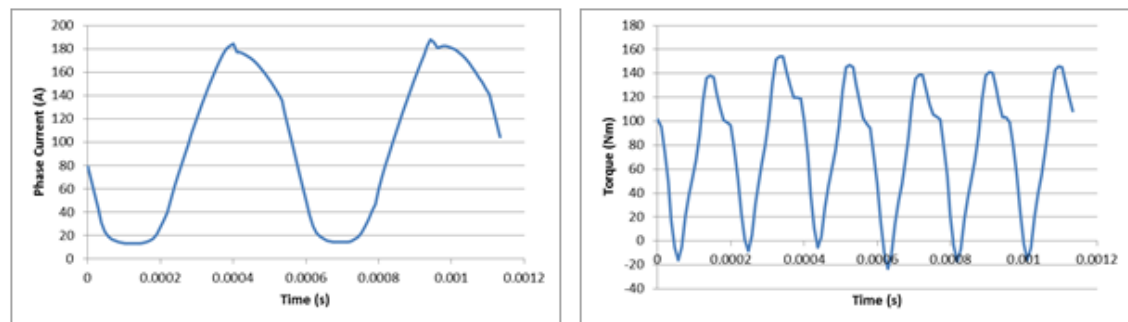


Figure 8-9 'Case 2' operating point (rated speed, peak power) showing (left) phase current and (right) torque.

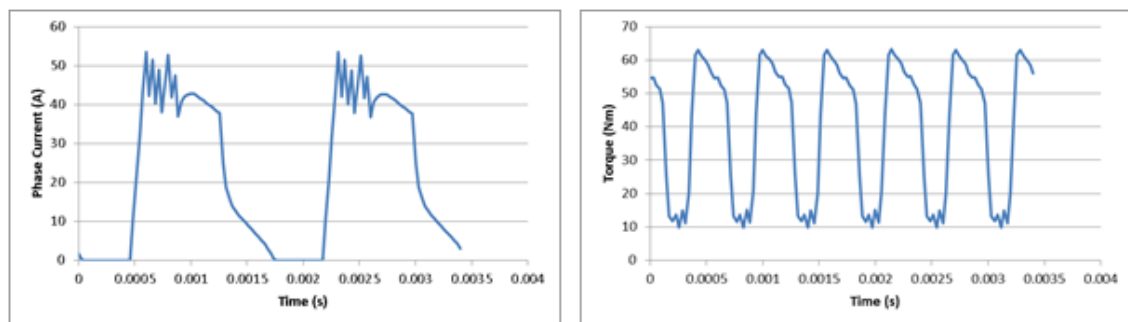


Figure 8-10 'Case 3' operating point (optimisation condition) showing (left) phase current and (right) torque.

8.2.4 Rotor Support Eddy Current Losses

Finite element modelling showed that inclusion of the fir tree roots would cause significant, time varying magnetic fields in the rotor support structure (Figure 8-11). A 3D finite element based analysis was therefore used in order to estimate eddy current losses in the rotor. It was found that the rotor support would be subject to very high eddy current losses, with eddy currents flowing from the web between adjacent sets of rotor segments as is shown in Figure 8-12.

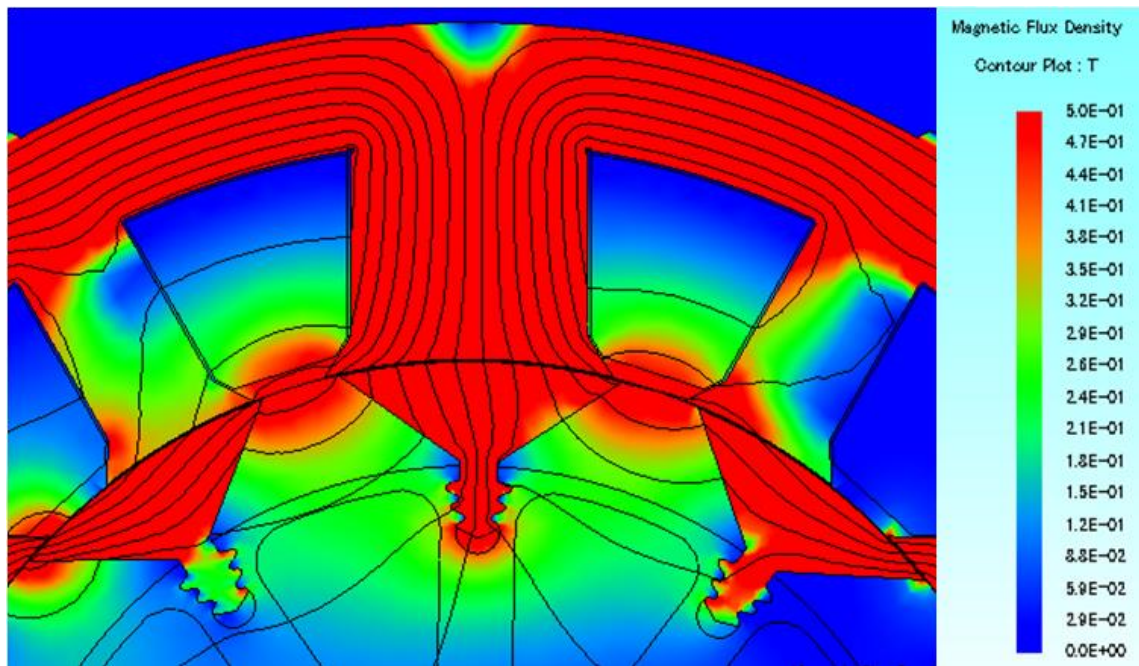


Figure 8-11: Plot of magnetic flux density showing show relatively high flux densities are present in the aluminium rotor support. Motor operating at 10,500rpm, 80kW.

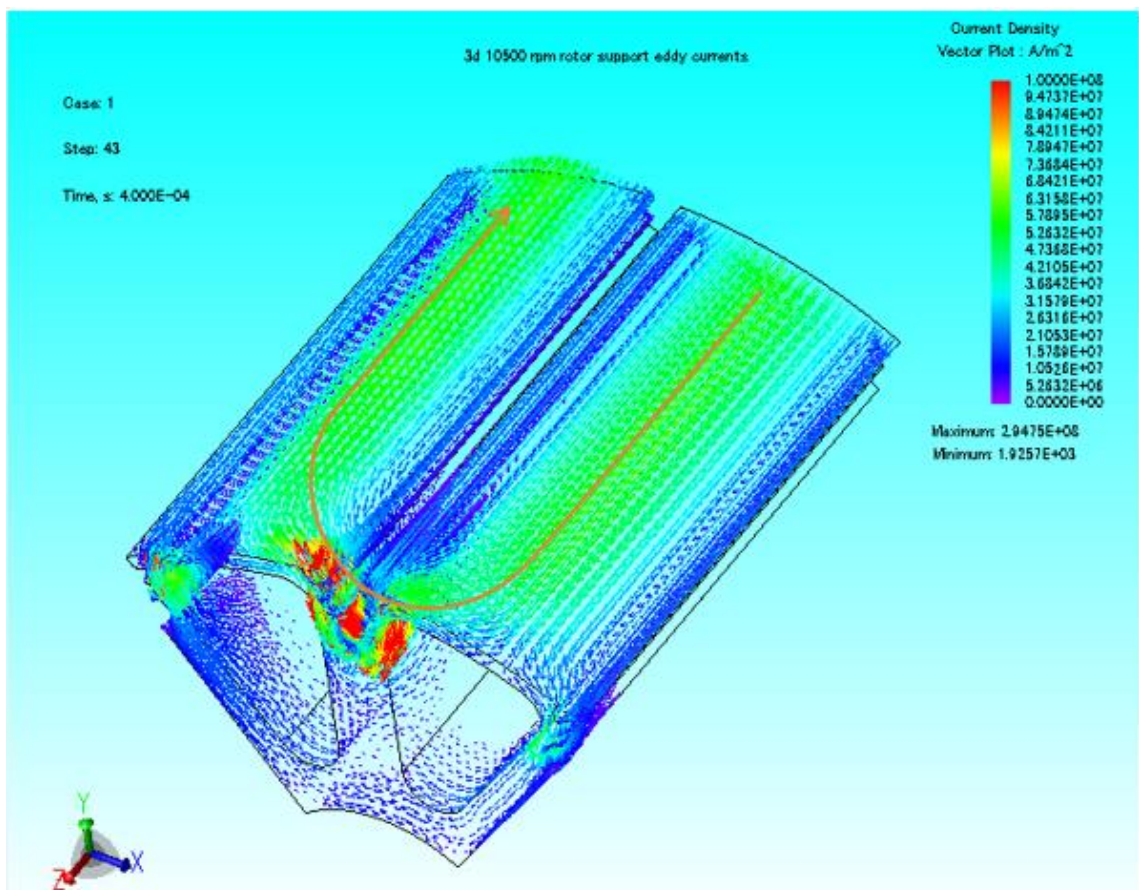


Figure 8-12: 3D Finite Element analysis of eddy current losses in the rotor support structure.

This modelling was undertaken in a simplified manner in order to reduce solution time and as such results are indicative only. One stator coil pitch was considered, with three stator teeth and three rotor segments being modelled. With the rotor held in the unaligned position, a representative current waveform, taken from a 2D transient with motion simulation, undertaken at 80kW/10,500rpm, was applied to the coil. From this modelling losses of 16kW were estimated in the rotor support at 10,500 rpm. These were induced by a time varying magnetic field which varied between 0 and 0.4T.

This level of loss would clearly be unacceptable as it decreases motor efficiency very significantly at higher speeds, whilst also making it necessary to intensively cool the rotor, increasing motor complexity and therefore costs. Therefore, based on the same principal applied in the lamination of electrical steels, the use of insulated aluminium laminations in the rotor support was considered to be a likely solution.

Eddy current losses in laminations steels can be simplified to an expression (based on Steinmetz) where losses are proportional to the square of the magnetic field and also the square of the electrical frequency and proportional to conductivity; assuming that the lamination has a thickness less than 2 skin depths [115]. A rough hand calculation was undertaken that suggested that a 2mm lamination might be acceptable. This was then confirmed by 3D modelling (Figure 8-13) which showed that losses would be reduced to the order of 200W.

8.3 Stator Detailed Design

8.3.1 Stator Coreback Design

In Chapter 6 the design of an outer rotor PM machine, also using compressed aluminium coils, was discussed. This motor used a ‘keyed tooth’ stator design; this design had a single piece stator coreback with each tooth being individually made and held to the coreback through the use of a tapered key (see Figure 8-14). This design had been shown to have a minimal impact on the permeability and loss of the stator core; this was thought to be because the design did not result in compressive stresses in the lamination material.

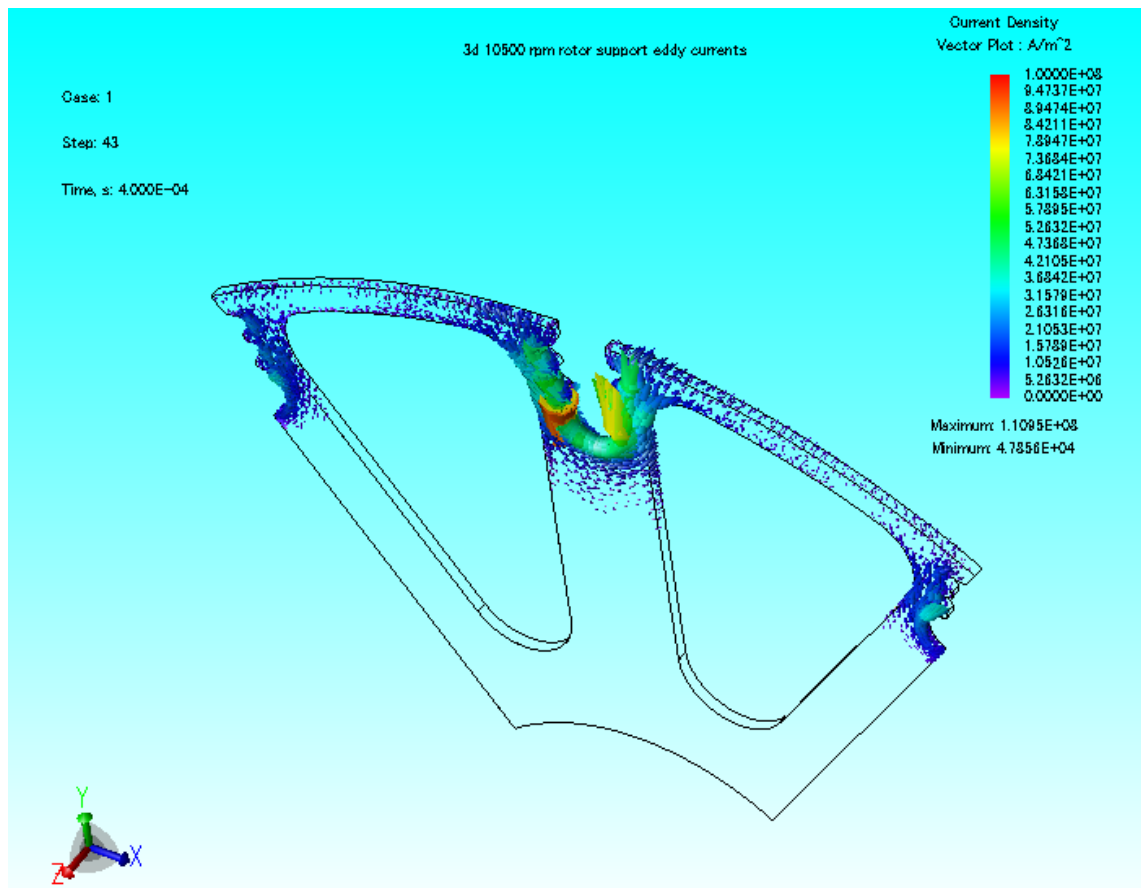


Figure 8-13: Showing reduced eddy currents in a 2mm rotor support lamination.

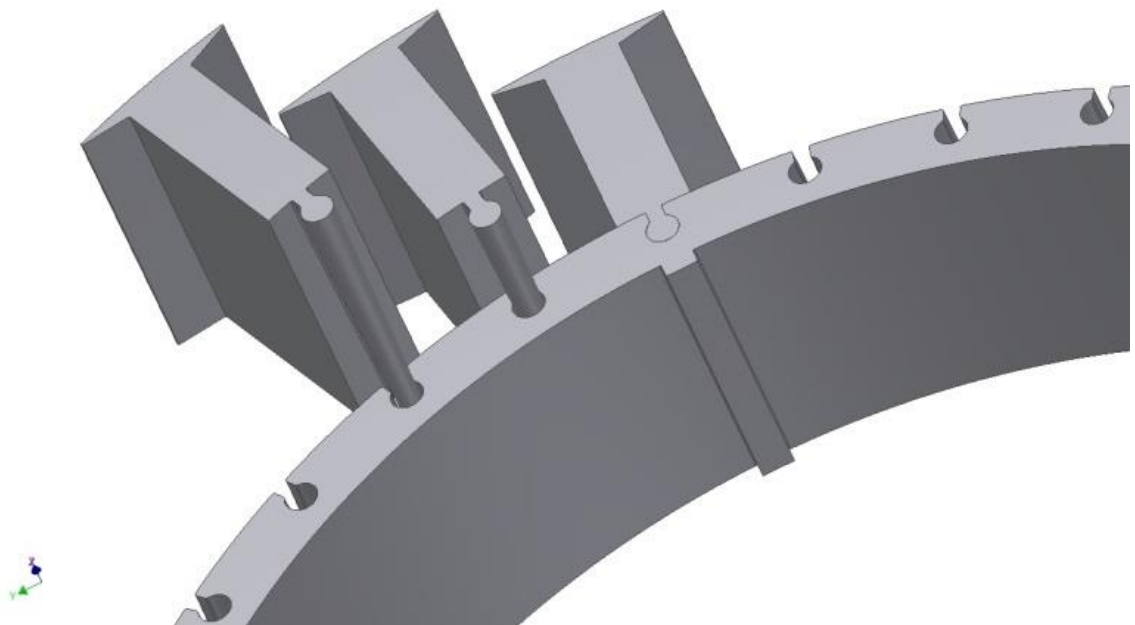


Figure 8-14: From Chapter 6, showing the keyed tooth stator design applied to an outer rotor permanent magnet machine.

However for application in a high volume automotive application this design has weaknesses; it relies on the manufacture of a tapered key which would be difficult assuming the use of stamped laminations, most likely requiring an additional machining operation. Equally, with the coreback being cut as a single ring, this would potentially lead to inefficient use of the raw lamination material, leading to a high percentage of waste during the punching process.

As a result it was decided that a different design should be found. This would need to combine the benefits of the keyed tooth design, whilst eliminating its weaknesses.

In order to achieve these goals it was decided that a segmented stator arrangement would be considered. Such designs are relatively common in automotive traction motors, with Honda and Hyundai using such a design (see Chapter 2 for details). Equally, the university had had recent experience of such segmental machines, for example [92].

However in this case a modified design would be needed for two reasons. Firstly the single tooth wound, segmental rotor SRM has an inter-coil spacer tooth which needs to be considered. Secondly, in the case of the referenced segmented stator designs, it is understood that the windings are bobbin wound onto the fully assembled stator tooth. This is not possible using pre-compressed windings as their method of manufacture means that they must be slid onto the stator tooth following manufacture.

As a result the design shown in Figure 8-15 was proposed⁴. This design features alternating wound and inter-coil teeth, with the wound tooth being designed so that a compressed coil can be assembled to it following winding compression.

The stator segments are designed so that they will self-align once secured in a stator housing. It was intended that compressive stress on the laminations would be minimised, in order to avoid degradation of electrical steel properties. As a result it was decided that there would not be an interference fit between the assembled stator core and the motor housing; as such keys were implemented on the inter-coil segment in order to lock the stator into position.

⁴ The support of Dr Andy Steven, part of the research team in Newcastle University's Design Unit, in the development of this concept is acknowledged and cannot be understated.

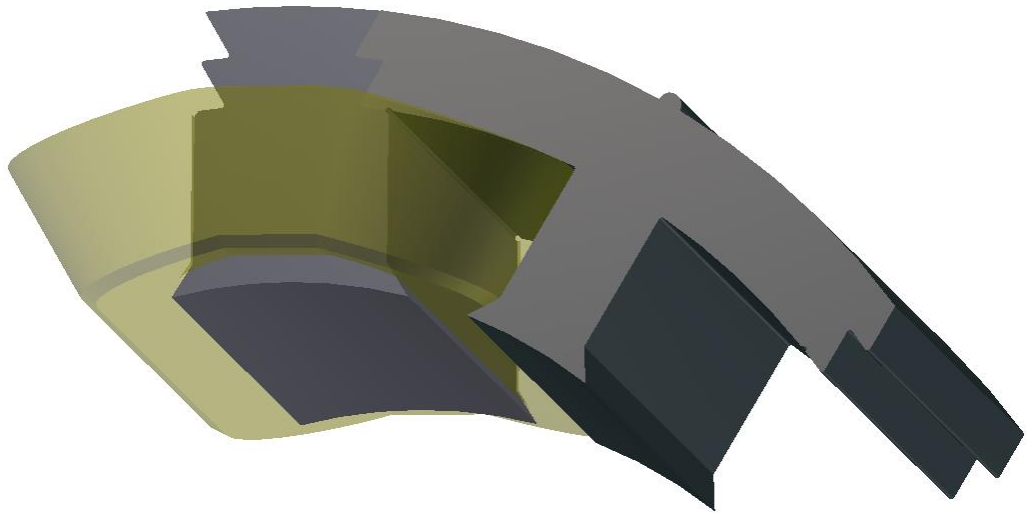


Figure 8-15: New stator core construction concept. Wound tooth is shown left, fitted with transparent coil. Inter-coil segment is shown right.

A risk with this approach was that the lack of a stator shrink fit would be expected to have an effect on the heat transfer between stator coreback and water jacket. However it was predicted that this would not be a significant problem as when the coreback heated up due to stator losses, differential expansion of the stator lamination stack when compared to that of the directly water cooled stator jacket would ensure a good thermal contact between coreback and stator housing; this assumption can be checked by simple calculation.

The stator laminations would be designed to fit the water jacket precisely, with tolerances leaving, worst case, a 0.1mm clearance. Steel has a coefficient of thermal expansion of $13\mu\text{m/m/K}$, therefore a temperature delta of 31.3°C between laminations and jacket would be required to close this gap. The thermal conductivity of air is 0.024W/m/K and the stator core surface area is 0.123m^2 , therefore the thermal resistance of the 0.1mm airgap between laminations and water jacket would be 0.034K/W . It is therefore possible to calculate that total losses of 924W in the stator would be sufficient to create the required 31.3°C temperature drop across the interface, causing its closure. This would mean that at the higher loss conditions, Case 1 and 2 in Table 8-3 (presented earlier), there would be sufficient power flow from the stator to the water jacket to close the gap. However the real situation would be somewhat more

complex, with there being as much as a 115°C temperature gradient between windings and coolant water (see Section 8.4.2 for details). This would mean that there would be a large temperature gradient between inner portions of the stator laminations and the outer surface of the water jacket also encouraging the interface gap to close.

8.3.2 Compressed Coil Detailed Design

The design of the compressed coil consisted of two stages. Firstly analysis was required to confirm the level of AC loss in the coil and therefore whether it would be necessary to use a stranded conductor. Secondly the layup of the coil on the bobbin and design of the compression tooling was considered.

8.3.2.1 AC Losses

AC losses may be induced in electrical conductors which are exposed to the time varying magnetic field in the airgap of an electrical machine. This effect is proportional to the square of the motor's electrical frequency and the square of the time varying flux density. This phenomenon is of particular consequence where there is a large gap between stator teeth tips, as is the case with the proposed design. As this effect is most acute in the conductors nearest the airgap, where flux densities are highest, in this machine it was decided to leave a gap between the coil and airgap of at least 2mm.

In order to quickly, flexibly and accurately estimate these losses, a numerical method was developed which used flux density data from finite element modelling coupled with a spreadsheet to calculate the ac losses in each conductor. This technique was developed as an extension to that proposed by Hall [96].

The procedure was undertaken as follows:

- 1) A 2D transient finite analysis was undertaken at the desired operating condition, in this case 80kW at 10500rpm; 30 time-steps were simulated for a single electrical cycle.
- 2) For each timestep the finite element tool was used to plot a B vs distance (1000 steps) from the part of the coil at the centre of the slot and closest to the airgap radially out to the stator coreback (see Figure 8-16).

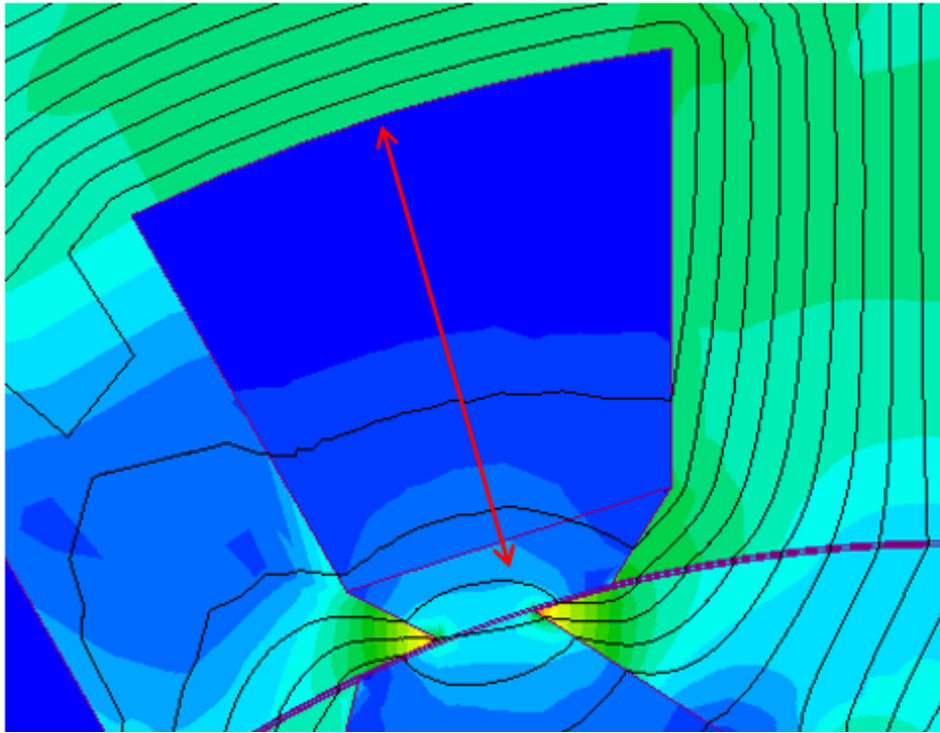


Figure 8-16: Showing line over which B vs distance was plotted for different rotor angles, in order to allow dB/dt to be plotted at different depths in the stator coil.

- 3) The loss per conductor strand was then calculated for each time instance and distance, assuming a certain conductor diameter, according to the following expression [115]:

$$P_{ac} = \frac{\pi}{64} \cdot \sigma \cdot l \cdot d^4 \cdot \frac{dB^2}{dt} \quad (8.1)$$

Where σ is the conductivity of the conducting material, l the length of the conductor in the slot, d the diameter of the conductor and dB/dt the time varying magnetic field at that time and distance. These losses are then averaged over time providing, for a given depth in the slot, an average AC loss value for a conductor of that diameter.

- 4) Loss versus distance is then plotted and approximated by a cubic line of best fit. Based on assumptions about the layout of the conductors in the slot, it is then possible to estimate the average loss in each conductor strand. The sum of these losses then provides the total loss for that winding at that operating point.

This analysis resulted in the conclusion that a 1.4mm aluminium strand would give losses of 1.33kW at 10,500rpm. It was desirable to make use of this diameter of conductor for pragmatic reasons: there was a large stock left following the construction of the motor in Chapter 6, but also because (as will be seen in the following section) this diameter would form a good basis for a sensible winding layup (see following section) and allow the achievement of the desired fill factor.

As DC winding losses at that speed were now, with the inclusion of the fir tree root, predicted to be 3.19kW, this would lead to total winding losses of 4.52kW. This is much lower than 7.36kW of copper loss observed at base speed, peak torque (an estimation of AC losses at base speed suggests that they will be in the order of 100-200W).

Even factoring in iron loss (907.6W at base speed, 1,240.4W at 10,500rpm) total motor losses would remain lower than at base speed. This therefore suggested that, whilst use of 1.4mm stranded conductors could increase overall motor losses substantially at higher speeds, high speed operation would remain a lower loss state than base speed / peak torque.

8.3.2.2 Compressed Coil Manufacturing Design

Full details of the coil manufacturing procedure are provided in Chapter 9, which deals with the manufacturing of the prototype electrical machine. However as part of detailed design a number of factors were considered and trials undertaken.

The coil would, developing on from that described in Chapter 6, be manufactured in stages. Firstly the stranded conductors would be wound onto a bobbin. The wound coil would then be compressed in a bobbin, punch and die assembly (Figure 8-17 shows a representative CAD model). This is physically a much larger set of tooling than that manufactured in Chapter 6.

The bobbin, punch and die assembly was, in this case, designed such that the coil would be over-compressed by circa 2%, allowing the coil to spring back, following compression, by the circa 1%, plus margin, observed in Chapter 6.

Calculations were undertaken in order to decide the layup of the coils on the bobbin. The machine would be wound with 30 turns per coil, with each coil having a cross sectional area of 17.8mm^2 in order to achieve the desired fill factor of 75%. Assuming

use of 1.4mm aluminium conductors, this fell between a conductor with 11 or 12 strands per turn, offering a total cross-sectional area per turn of 16.9mm^2 and 18.5mm^2 respectively; therefore a fill factor of between 71.5% and 77.9%.

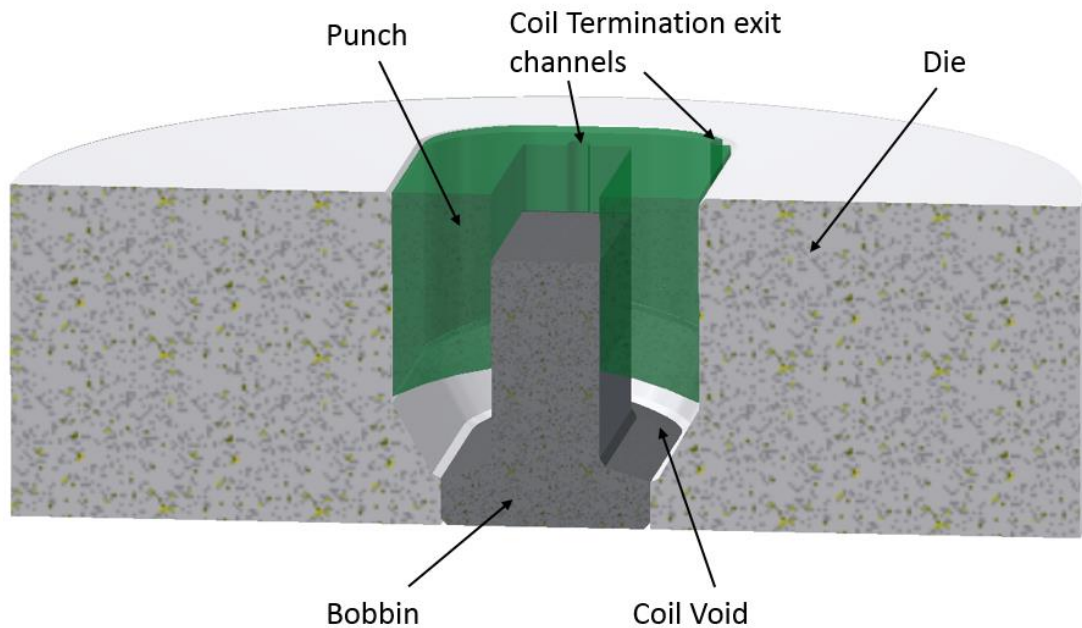


Figure 8-17: Bobbin, die and punch 3D CAD model, shown in section.

It would therefore be necessary to use a 12 strand coil to achieve the required fill factor. From previous work [76] the ultimate limiting influence on compressed coil fill factor was insulation thickness. Whilst the fill factor in the slot would be 77.9%, when slot liners (0.3mm Nomex assumed) and the maintenance of a clearance between coil and airgap are taken into account the fill factor of the coil itself would be 88.4%. This fill would be predicted to provide a single coil resistance of $0.023\ \Omega$ or $0.046\ \Omega$ for a phase.

The IEC60317 standard defines the maximum thickness for the insulation used in different grades and classes of winding wire. For the Grade 2, Class H conductor to be used with this machine, average wire diameter accounting for insulation can be shown to be 1.486mm, an increase of 6% in diameter and therefore 12% in cross sectional area. Taking this into consideration overall coil fill (including insulation) can be shown to be 99.5%, extremely close to the absolute limit. In fact if maximum diameter strands were used, this would result in a factor of 101.7%, meaning that the compressed coil would not fit in the motor slot. However as will be seen later, it was nevertheless possible to compress coils to this extent for the prototype, however a more realistic limit of perhaps

98.5% would be preferable allowing for the use of conductors over the average diameter; this reduces slot fill factor to around the original objective of 75%.

In order to avoid circulating currents between the strands it was decided to transpose the wires. However excessive twist would potentially make it more difficult to achieve the desired high fill factors, therefore it was decided to make the coils with a single transposition per winding turn.

The use of 30 turns lent itself to being wound with six layers of 5 turns, meaning that when both start and finish conductors could be positioned at the top of the coil. This is shown graphically in Figure 8-18.

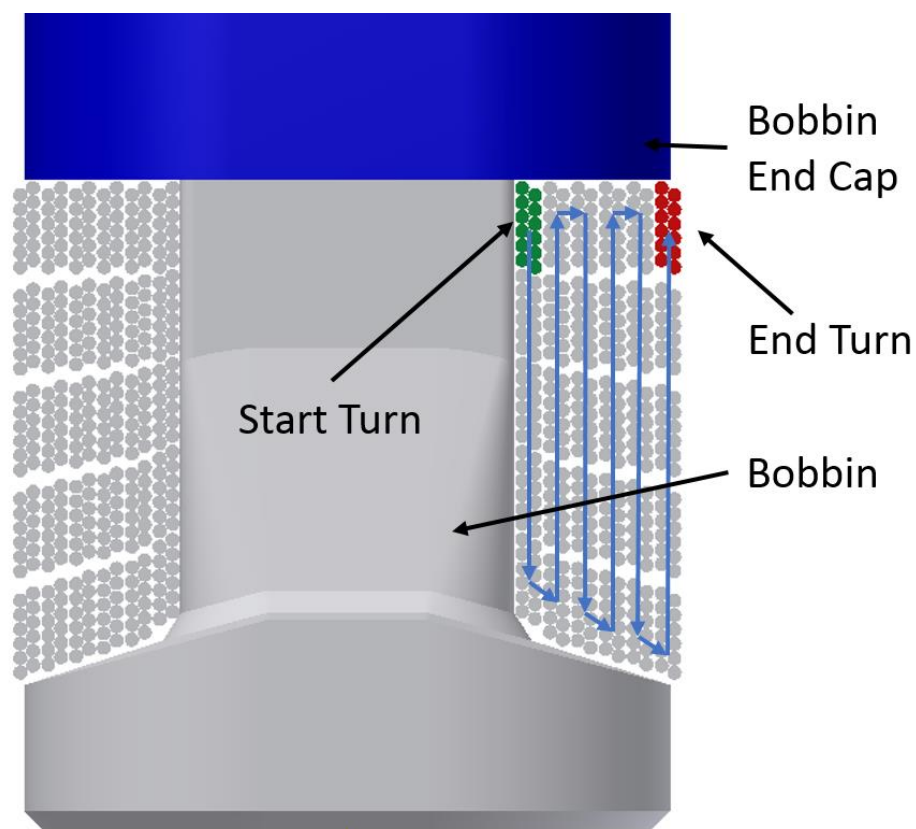


Figure 8-18: Winding layup onto bobbin.

Here the stranded coils are shown flattened; experimentation has showed that bobbin wound stranded wire tends to flatten in this way. The coil compression tooling was designed in order to allow the start and finish conductors to exit the tooling without being compressed: again see Figure 8-17.

When compared to the coils manufactured previously in Chapter 6, calculations showed that with these much larger coils, a larger force would be needed to compress them. For the earlier coils a force of 150kN (15 tonnes, equating to a pressure of 250MPa) was sufficient to compress the coils. For this new coil, with a surface area 26.5 times greater, a force of 4000kN (or 400 tonnes) would be required to achieve the same pressure; it was possible to access a 500 tonne press, allowing the required pressure to be achieved.

Initial prototype coils were manufactured and trial fitted, including slot liners, to a 10mm thick aluminium prototype of the motor coreback (see Figure 8-19). This prototype demonstrated that a slight modification would be required to the motor coreback, with small 1mm cut-outs added (Figure 8-20). These would prevent the nomex slotliner from ‘bunching’ and becoming trapped in the coreback interface between the stator teeth, preventing correct closure of the coreback.

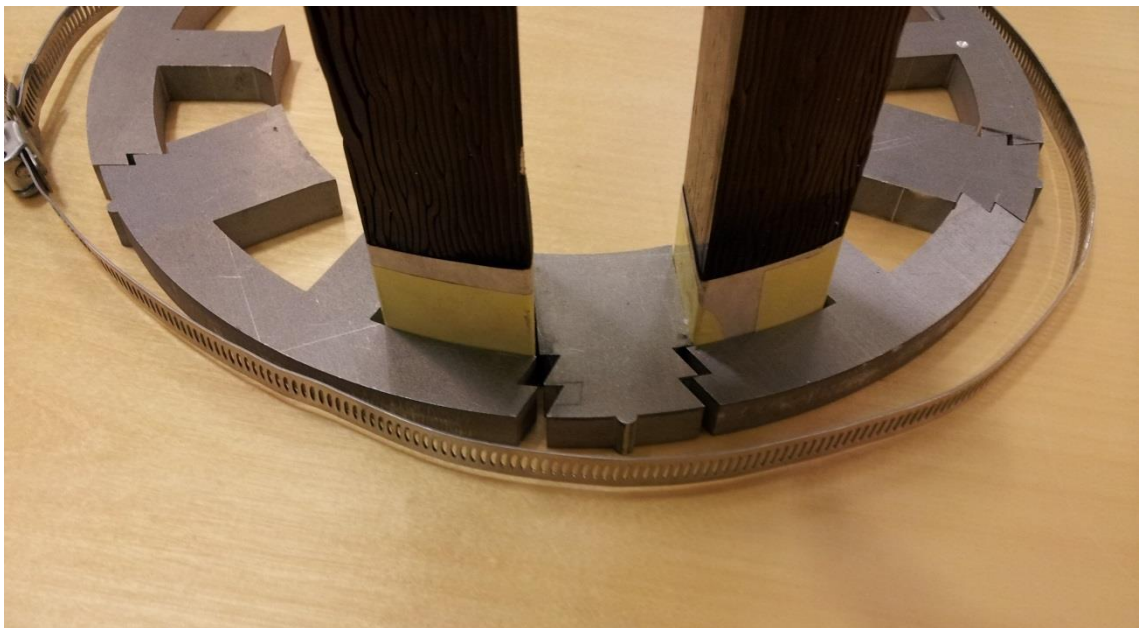


Figure 8-19: Aluminium coreback prototype with compressed coil.

8.3.3 Water Jacket Design

For this prototype the water jacket would, to reduce one-off manufacturing costs, need to be machined from solid, unlike in the case of the Nissan Leafs’ IPM machine where a cast jacket is used [9]. As is shown in Figure 8-21, the prototype water jacket is designed with four circumferential channels; this is based on a design common to a number of other machines known to the university. Keyways are included to locate the stator and prevent any rotation.

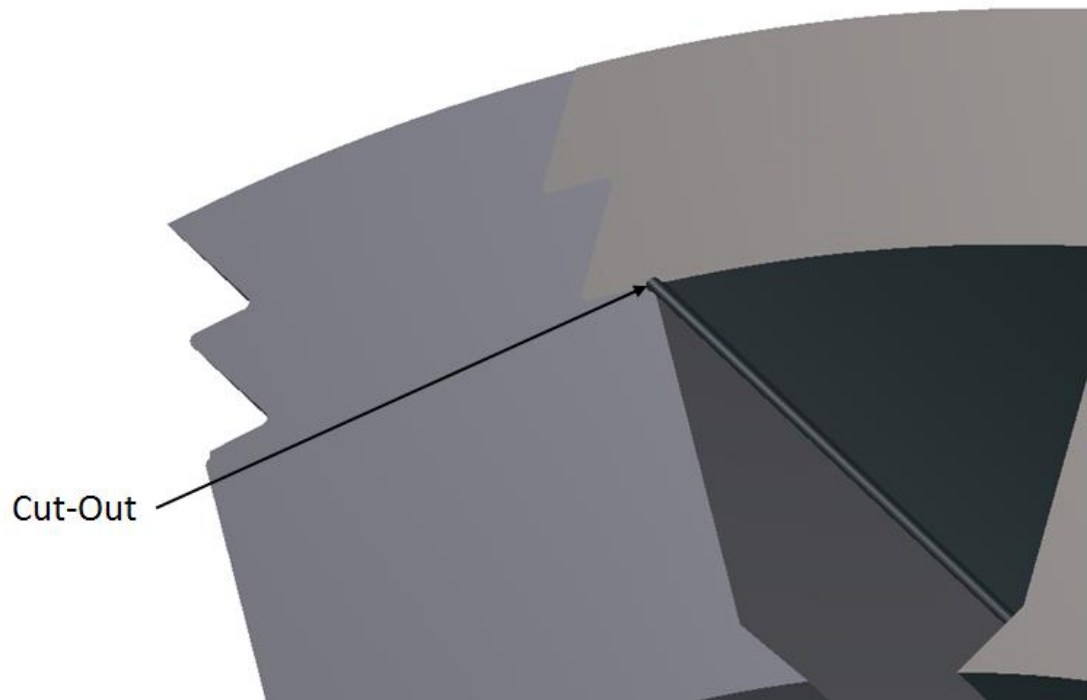


Figure 8-20: Cut-outs implemented in coreback to prevent slot liner bunching.

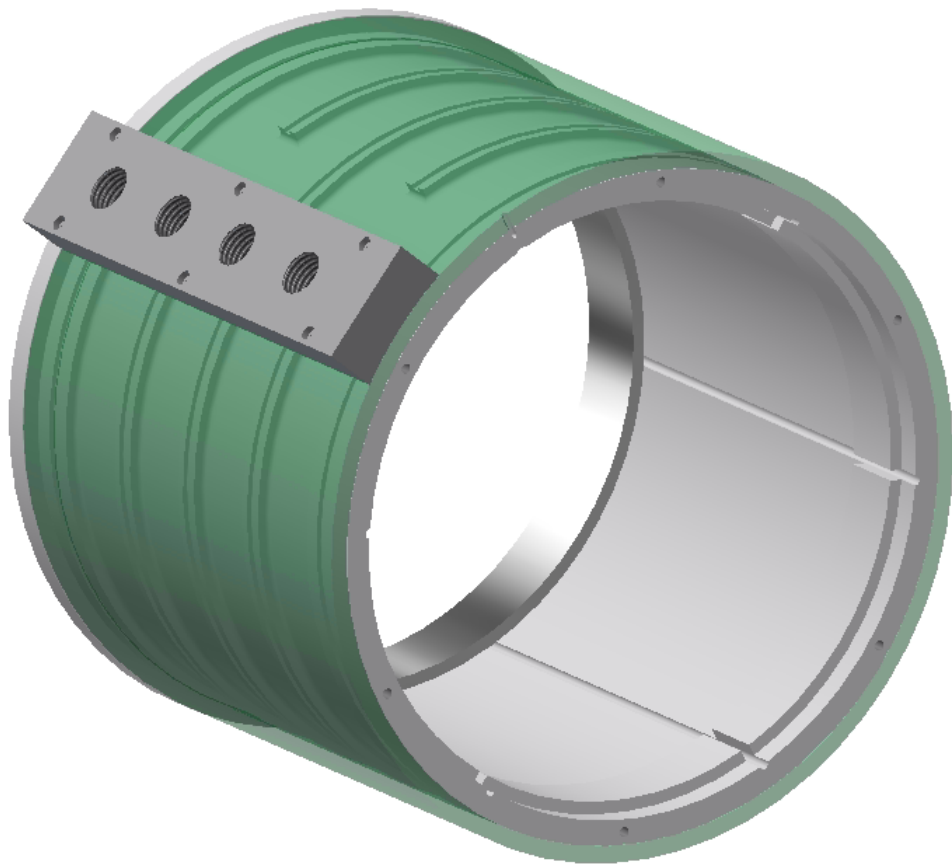


Figure 8-21: Water jacket, with the outer jacket shown as transparent (green).

The channels were in turn split into pairs, with each pair connected to a cold water source, either in series or parallel. Half inch BSP connectors were assumed which have a cross sectional (flow) area of circa 200mm². The channel was therefore designed to have a similar cross sectional area of 171.5mm², with a width of 34.3mm and a height of 5mm. The inner water jacket is sealed by use of an outer water jacket and nitrile rubber o-ring seals.

For the purposes of this design, it was assumed that the outer water jacket, which is held off the motor inner water jacket by the o-rings, is perfectly insulated from the active elements of the motor. This means that a total heat transfer surface between the water jacket and contained water is considered to be 0.138m².

8.4 Predicted Motor Performance Envelope

8.4.1 Predicted Motor Efficiency

Based on the analysis presented in this chapter, projections can be made about the overall electromagnetic efficiency of the motor. These will form the basis of the validation of the motor design in Chapter 10.

Table 8-4 extends Table 8-3, presented earlier, to include both the electromagnetically modelled winding and iron losses as well as including the other losses discussed, for example AC winding losses and eddy current losses in the rotor support.

For these categories of loss, modelling has been, as has been discussed, undertaken only at 10,500rpm; to scale these losses (which are the result of eddy currents) to the other operating points the following simple proportionality is assumed:

$$P \propto \hat{B}^2 \cdot \omega^2 \quad (8-2)$$

Where P is the loss value to be considered, $\hat{B}$ the maximum flux density (taken from FE) in the part component being considered and ω the rotational velocity.

Friction and windage losses are not considered at this stage; complex to predict due to the segmental rotor design, they can be easily calculated from testing (see Chapter 10).

Table 8-4: SRSRM4 performance at key operating points with final fir tree root. Copper loss stated at winding temperature of 150°C.

Parameter	Case 1	Case 2	Case 3
Speed	2,750rpm	10,500rpm	3,500rpm
Torque (Modelled)	285.8Nm	71.9Nm	39.3Nm
Torque Ripple	57%	246%	135%
Power	82.3kW	79.0kW	14.4kW
Copper Loss (DC)	7357.5W	3189.2W	192.0W
Copper Loss (AC)	364W	1328W	27W
Iron Loss	907.6W	1240.4W	535.1W
Eddy Current Loss (Rotor Support)	35W	219W	2W
Total Loss	8664.1W	5976.6W	756.1W
Efficiency	90.5%	93.0%	95%
Advance Angle	75°	90°	25°
Conduction Angle	180°	200°	170°
Current Limit	333.3A	183.3A	47.7A
RMS Phase Current	178.9A	117.9A	28.9A
Operating Mode	Current Control	Constant Current + Current Control	Current Control

8.4.2 Thermal Modelling

Thermal modelling of the motor was undertaken for two reasons. Firstly in order to confirm that the motor was likely to be able to meet its requirements thermally. Whilst little is known of the duty cycle assumptions which underpin the design of the Nissan Leaf, it was felt that it was essential that it should be possible to operate at peak power for at least 30 seconds. Due to the materials selected in the design of the motor, particularly the conductor material, a maximum operating temperature of 200°C was considered acceptable. If an maximum inlet coolant temperature of 85°C is considered (typical for automotive applications) then this equates to a temperature rise of no more than 115°C. Secondly it was desirable to make some thermal predictions so that these could be validated by prototype test.

Based on the design and losses discussed in this chapter, a thermal model of the motor was constructed. This thermal model made use of both a 3D finite element model of the active elements of the motor and a lumped parameter model in order to represent the interfaces between the active elements of the motor and the external environment.

The finite element model (Figure 8-22) included the active elements of the motor design alongside the rotor support. One quarter of the motor was modelled, with 180° rotational symmetry and axial symmetry assumed. Table 8-5 defines the material properties set for each element of the finite element model; these were generally taken from [116] with the properties of Nomex slot liner found at [117]. The lumped parameter model (Figure 8-23) provided the detail of the boundary conditions for the finite element model, including interconnections between components as well as the external water jacket.

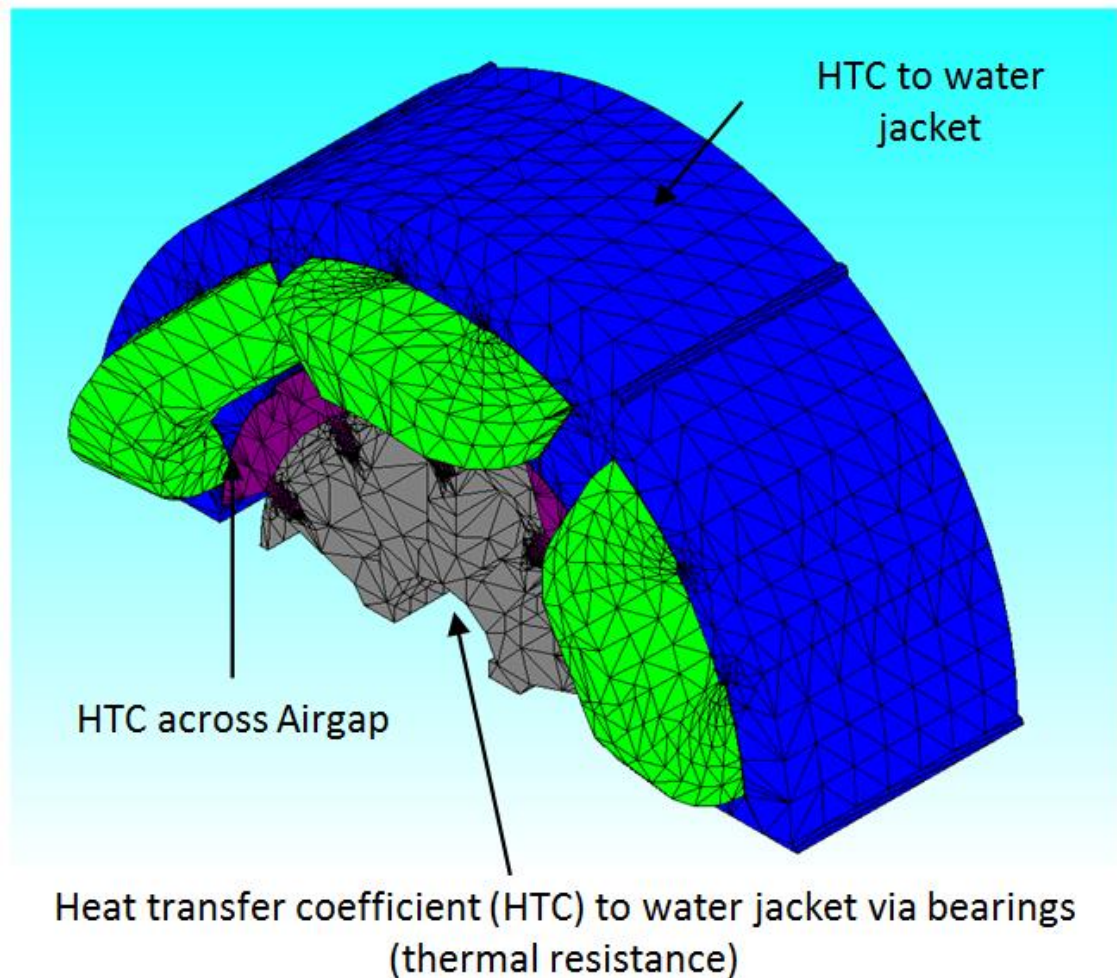


Figure 8-22: Finite element model used for thermal analysis.

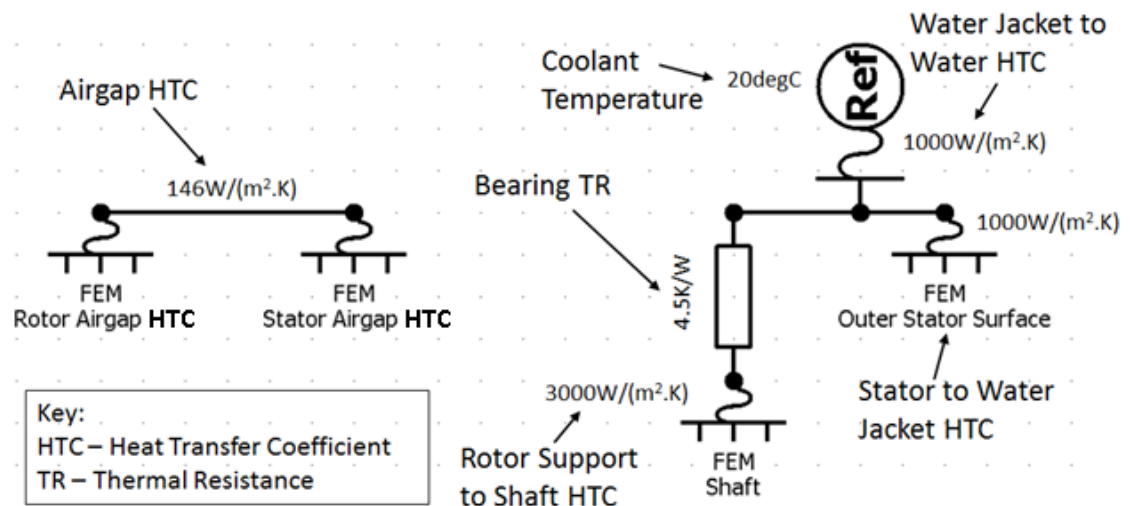


Figure 8-23: Lumped parameter model used for thermal analysis.

Table 8-5: Material properties assumed in thermal analysis

Property	Laminations	Coils	Slot Liner	Rotor Support	Unit
Material	M270-35	Aluminium	Nomex	Aluminium	-
Density	7650	2699	1000	2699	kg/m ³
Specific Heat Capacity	460	900	260	900	J/(kg.K)
Thermal Conductivity	23 ⁽¹⁾	230	0.13	230 ⁽¹⁾	W/(m.K)

Notes: 1) The laminations, coils and rotor support modelled as having isotropic conductivity (see text for details).

A number of simplifying assumptions were made. It was decided to model the coils as solid aluminium, whilst this does not represent the compressed coils accurately, it was felt that insufficient data existed at this stage in order to better define their performance. Equally it was decided that the electrical steel and the aluminium laminations in the rotor support could be considered to have isotropic conductivity; this assumption was made as these parts would be only able to lose heat radially; through the water jacket, across the airgap or into the rotor shaft.

Finally, the model assumes perfect contact between all touching parts, specifically the coil to slot liner and slot liner to stator lamination interfaces and the interface between rotor segment and rotor support.

No attempt was made to model the water jacket using Computational Fluid Dynamics (CFD); instead it was assumed that a heat transfer coefficient of $1000\text{W}/(\text{m}^2\cdot\text{K})$ would be achievable. Based on the author's experience with other, recent projects, this was felt to be a reasonable prediction. For this initial model it was assumed that no heat would be lost through the end windings by convection or conduction with the air. Finally the model assumes an ambient temperature of 20°C with coolant temperature also 20°C ; this could then be scaled later as desired to represent higher ambient temperatures.

Losses were injected into each component of the model, appropriate to the loss case being considered. The thermal model was run in each of the conditions detailed in Table 8-4 and the results are summarised in Table 8-6.

Table 8-6: Thermal performance of the SRSRM4 Segmental Rotor SRM. Maximum temperatures are recorded.

Parameter	Case 1	Case 2	Case 3
Speed	2,750rpm	10,500rpm	3,500rpm
Torque (Modelled)	285.8Nm	71.9Nm	39.3Nm
deltaT (60secs)	85°C	71°C	3°C
Time for deltaT of 115°C	90s	205s	N/A

Figure 8-24 shows the thermal model injected with losses for Case 1 (2750rpm) and after a time period of 60 seconds. As would be anticipated, this case was thermally the most demanding and the end windings are shown to have reached a temperature of 105.4°C after this time, a rise of 85.4°C , well within the 115°C limit. Figure 8.25 plots the increase in temperature of the end winding, slot winding, stator and rotor laminations against time.

The portion of the coil in the slot was found to be consistently 15% cooler than that in the end winding; it was felt that this differential could be reduced by potting of the end windings, with a thermally conductive potting compound. However this was not felt to be a desirable manufacturing method, either for the prototype or indeed for mass

production and so was rejected. This decision was later reviewed as will be seen in Chapter 10.

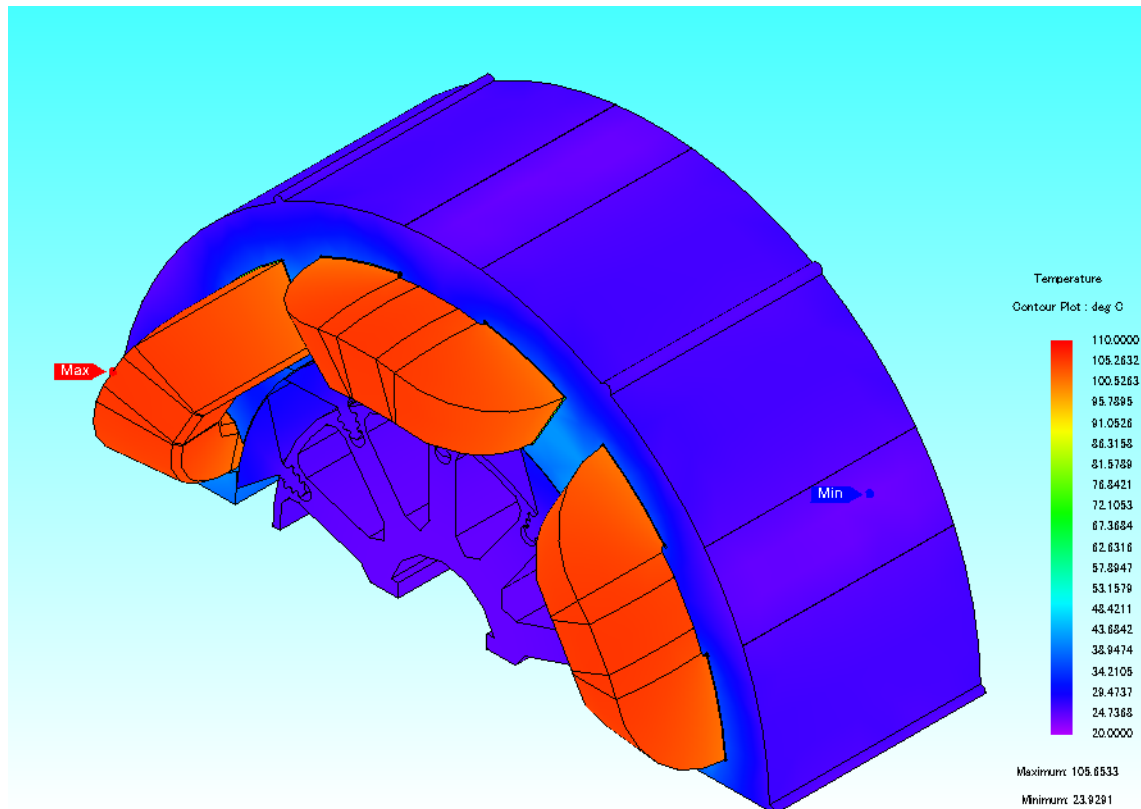


Figure 8-24: Predicted thermal distribution after 60s, Case 1 (2750rpm, 280Nm)

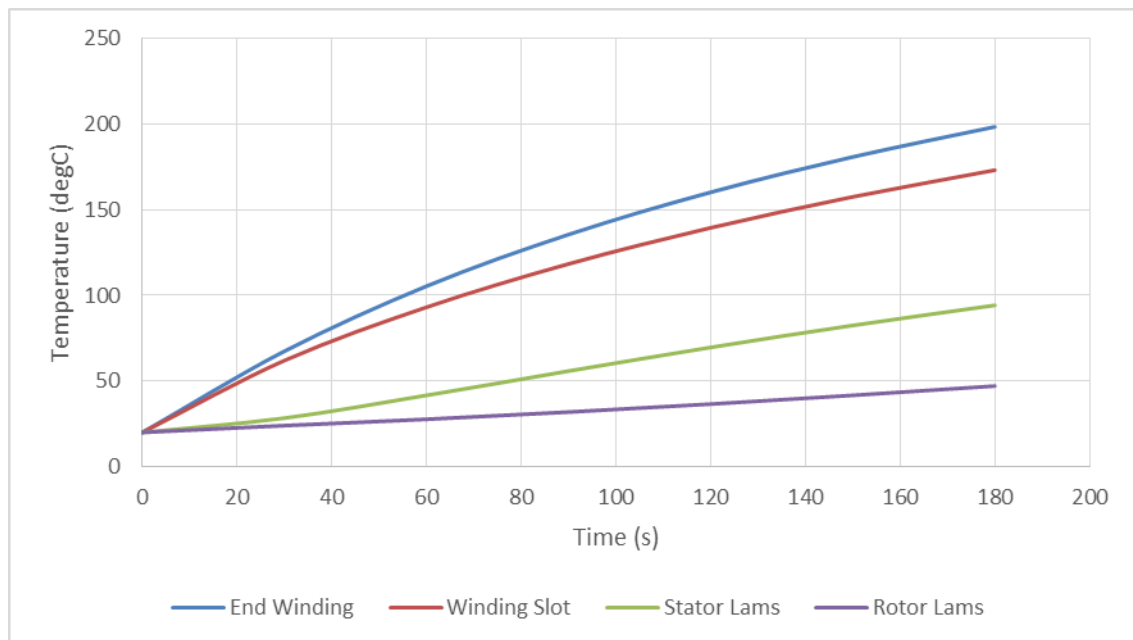


Figure 8-25: Temperature at various location of the motor for Case 1 (2750rpm, 280Nm)

For Case 2, it was observed that at steady state the temperature of the rotor exceeded that of the stator by 84°C. Whilst it was unlikely that the motor would be operated continuously in this way, it raised concern that the motor's airgap could close under similar operating conditions as the aluminium rotor support has a much higher coefficient of thermal expansion when compared to the steel stator core.

As a result of this final observation from the thermal modelling, it was decided that a more detailed assessment of the risk of airgap closure during motor operation was required. The perceived risk was that, should the airgap suddenly close at high motor operating speeds, significant damage would result to the motor with potential safety implications both for a prototype but also more acutely were a production version used in a real vehicle.

8.5 Prototype Safety: Airgap Closure Modelling

The thermal modelling data for both Case 1 (2,750rpm) and Case 2 (10,500rpm) was used as input to a linked mechanical finite element model. The steady state temperature profiles taken from these cases (see Figure 8-26 for the 10,500rpm case) were applied to the appropriate motor components in a structural finite element model. The model was then solved in order to observe displacement due to thermal expansion. The rotational velocity of the rotor was also considered as this could also result in radial expansion of the rotor.

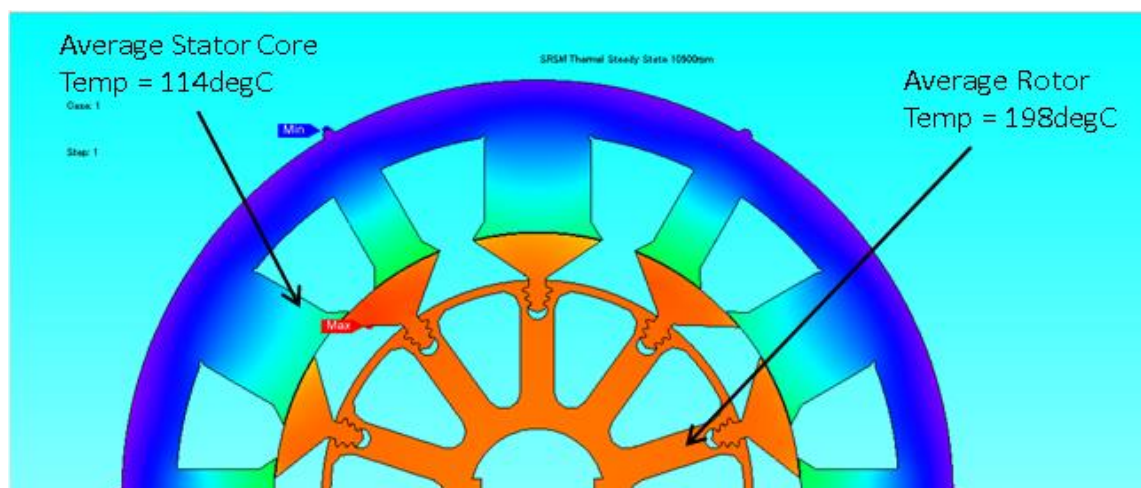


Figure 8-26: Steady state temperatures in the stator core and rotor at at 10,500rpm, 80kW.

At 2,750rpm the airgap closure was found to be relatively small, with the gap reduced from 0.30mm to 0.25mm. However at 10,500rpm a more significant effect was noted, with the airgap closing from 0.30mm to 0.09mm (see Figure 8-27).

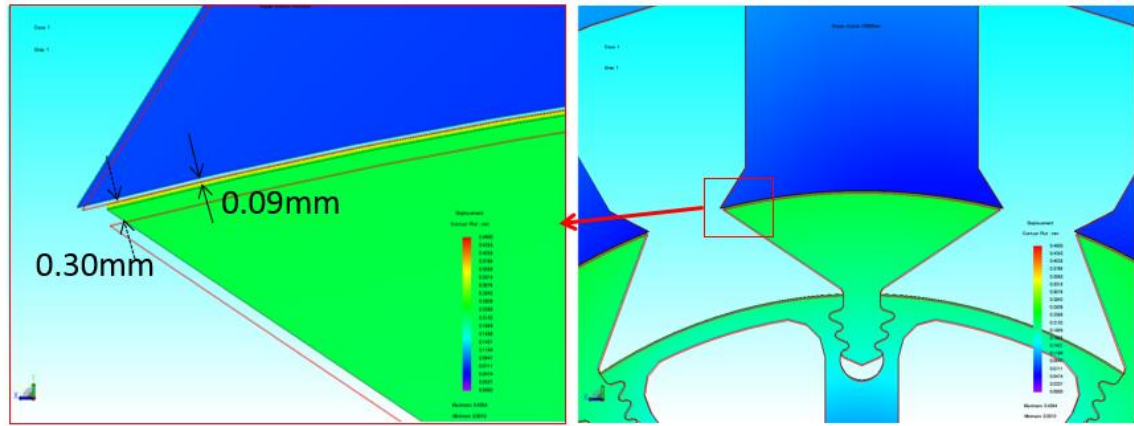


Figure 8-27: Differential thermal expansion of the rotor vs stator at 10,500rpm, 80kW showing resulting closure of the airgap.

As maximum airgap tolerances (mass production) were expected, from discussions with industry partners, to be in the region of $\pm 0.1\text{mm}$ (taking into account the combined effects of different build tolerances), this level of airgap closure was of concern. The decrease in airgap was dominated by the thermal expansion of the aluminium core; centripetal forces contributing only 0.01mm. As a result the decision was taken to increase the motor's airgap to 0.35mm (at 20°C). With tolerances taken into account this would ensure that the minimum airgap at 20°C would be no less than 0.25mm and that even in the case shown in Figure 8-27, the airgap would remain greater than 0.05mm. Whilst this would reduce motor performance at lower temperatures, when warmed to operating temperature it would be expected that the airgap would again close and therefore regain the nominal 0.3mm; this appears to be confirmed by modelling which shows that even in Case 3 (3,500rpm / 40Nm), the airgap could be expected to close by more than 0.03mm. As a result it was not felt necessary to remodel the motor performance with this larger airgap.

8.6 Final Prototype SRSRM4 Motor Design

Table 8-7 summarises the final design of the electrical machine and it is shown in Figure 8-28, without the water jacket, and in Figure 8-29, with the water jacket. The second figure also shows details of the winding terminal boxes, resolver mounting and

water jacket inlets. Fixings are not shown. Selected drawings of motor components can be found in Appendix 6.

8.7 Conclusions

This chapter has discussed the detailed design of the prototype Segmental Rotor SRM. The most striking design change has been the inclusion of a fir tree root to secure rotor segments to rotor support. This has been necessary in order to ensure that the root has sufficient strength to resist the centripetal forces present during an overspeed condition. This mechanical change has had a significant impact on the electromagnetic performance of the motor, increasing winding losses by a sufficient degree to prevent the use of the best performing motor from the optimisation in Chapter 7. Instead a larger motor, also selected as part of the optimisation process, has been used as the basis of the detailed design process.

This chapter has also assessed the effects of eddy current losses in the rotor support structure, finding these to be potentially very high. The use of laminated, aluminium rotor core sections has been shown to reduce these losses down to acceptably low levels.

The design of the stator coreback and compressed winding has been finalised. The stator coreback has been separated into self-locating, modular components allowing manufacture of the coils prior to integration into the stator. The coils have been designed using aluminium conductors and tooling has been designed which is intended to achieve a 77% fill factor. The windings have been designed to take into account induced AC losses due to the high frequency magnetic fields in the motor, these have been limited by the use of stranded and transposed conductors.

An assessment has been made of the motor's performance at three operating points, base speed / peak torque, maximum speed / peak power and the optimisation point. This has taken into account all of the electromagnetic losses predicted, including the previously mentioned rotor support eddy current losses as well as AC losses in the windings. These losses have formed the basis of a thermal analysis of the performance of the motor which has predicted that it will be possible to achieve the peak operating points for significantly more than 30 seconds without motor overheating, even with an 85°C inlet temperature.

Finally the effect of the motor's thermal response on the length of its airgap has been investigated, with the use of a large diameter aluminium rotor core leading to a predicted partial airgap closure. This has led to the decision to make a small increase in the airgap length for the prototype, in order to accommodate any possible risk. However it is assumed that this will not affect motor performance as the analysis has also shown that once the motor is at operating temperature it is likely that the airgap will return to near its baseline 0.3mm dimension.

Table 8-7: Final 80kW Segmental Rotor SRM Design

Parameter	Value
Machine Type	Segmental Rotor Switched Reluctance Motor (Radial Flux, Inner Rotor)
Rated Power	80kW
Rated Torque	280Nm
Base Speed	2750rpm
Maximum Speed	10,390rpm
Efficiency (40Nm, 3500rpm)	95.0%
Stator Slots	12
Rotor Segments	10
Lamination Material	M270-35
Stator Outer Diameter	246.1mm
Rotor Outer Diameter	155.6mm
Stack Length	159.1mm
Length with End Windings	224.2mm
Active Mass	32.7kg
Winding Configuration	3 Phase, single layer (with intercoil teeth), 2 coils per phase.
Winding Material	1.4mm Aluminium, Class H, Grade 2 enamelled wire
Winding turns per phase	60 (12 strands per turn)
Winding resistance (20°C)	0.046 Ω

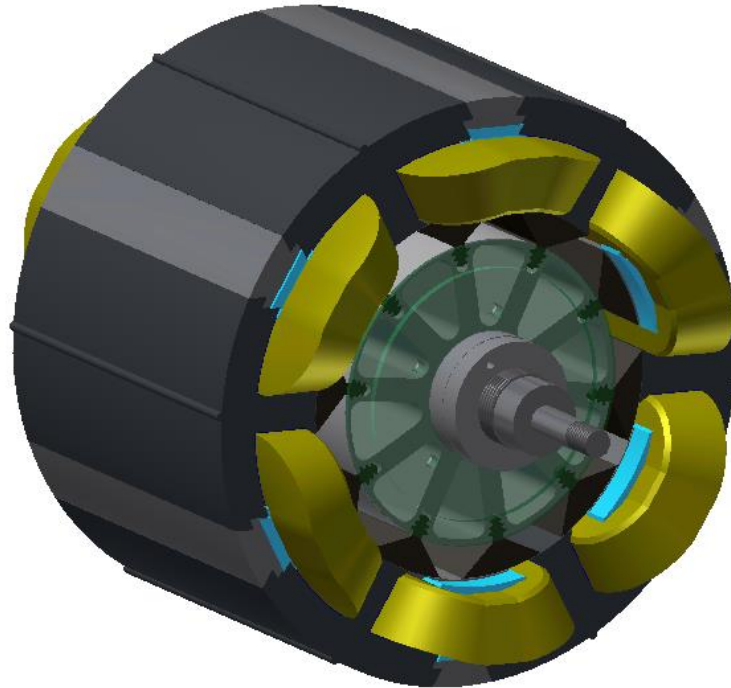


Figure 8-28: SRSRM4 final design without water jacket

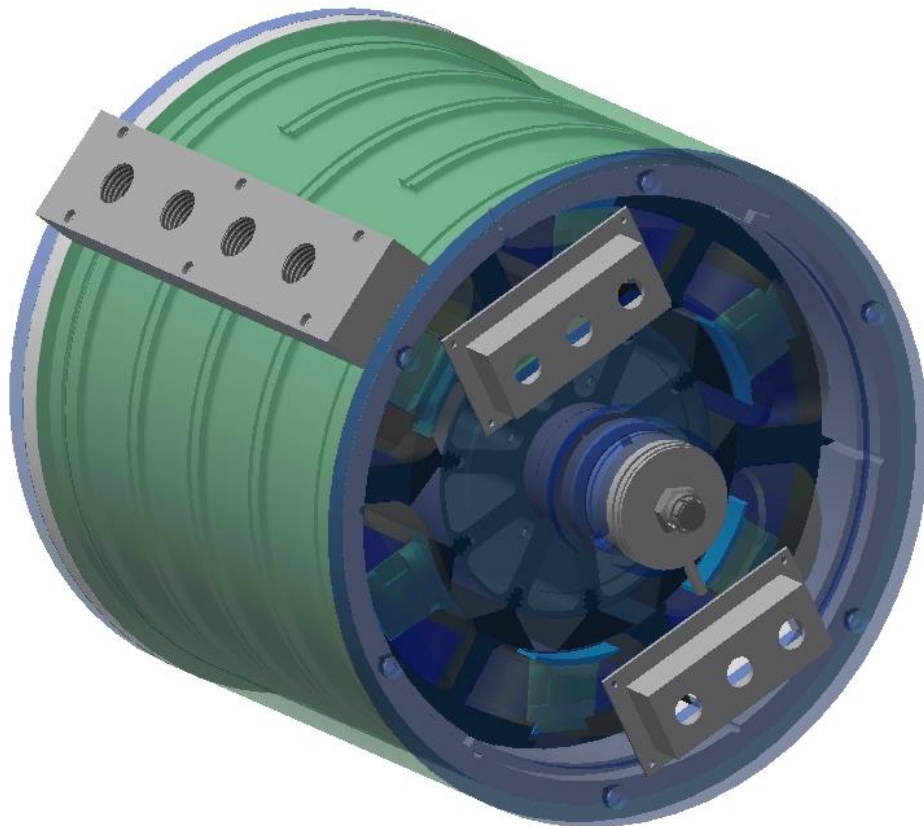


Figure 8-29: SRSRM4 final design with water jacket.

Chapter 9. Construction of an Automotive Segmental Rotor SRM

This chapter describes the construction of the prototype 80kW Segmental Rotor SRM. This motor, whose optimisation was discussed in Chapter 7 and detailed design in Chapter 8, has been developed to closely match the performance of the Interior Permanent Magnet Motor developed by Nissan for the Leaf Electric Vehicle.

This chapter first discusses the construction of the stator. The manufacture of the segmented, modular stator core is described as are the manufacturing techniques applied to produce the large, compressed aluminium coils used by this motor. Their assembly into the stator core and then into the motor's water cooling jacket is reviewed. Whilst the manufacture of the coils is found to produce a reliable and repeatable component, the process of their assembly into the stator is found to require further refinement.

The chapter then discusses the construction of the rotor, with particular reference to the manufacture and assembly of the electrical steel rotor segments to the aluminium rotor support structure. The process of rotor construction is found to be successful with, in particular, very good tolerances achieved in terms of rotor segment concentricity.

Finally, overall assembly of the motor is discussed.

9.1 Stator Construction

9.1.1 Stator Laminations

The stator lamination stack is formed of two key components; the wound tooth element, onto which each of the six stator coils is assembled, and the inter-winding tooth element which completes the stator coreback (see Figure 9-1). Six of each component are required to construct the full stator.

A stack of M270-35A laminations was bonded, as for previous prototypes, using an Araldite two part epoxy resin, consisting of Araldite LY5052 epoxy and Araldur 5052CH hardener. Each laminated steel square sheet had sides of length 300mm and the stack was made up of 445 laminations, giving a stacking factor of 98%. This was lower than achieved in previous prototypes as it had been found that a slightly thicker glue layer provides a more reliable bond during the cutting process. This stack was large enough to allow the cutting of all motor parts from the single block, see Figure 9-2.

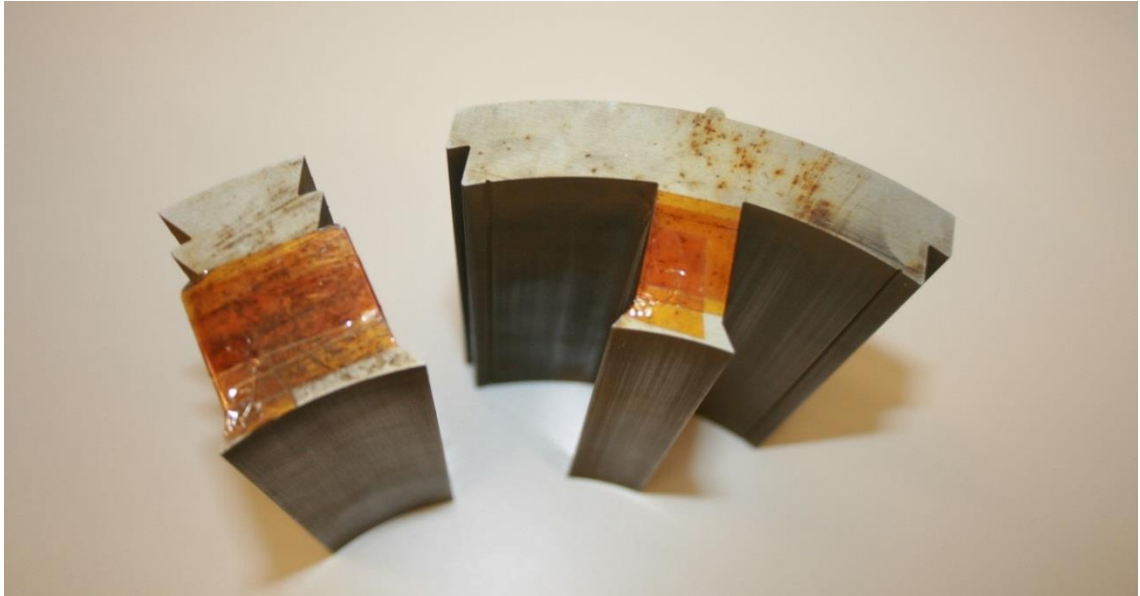


Figure 9-1: Showing stator laminated stator parts. (Left) is the wound tooth and (right) the spacer tooth part.



Figure 9-2: M270-35A bonded lamination stack showing how all motor lamination steel could be cut from a single 300mm by 300mm block.

For prototype construction, lamination parts were cut using an Electrical Discharge Machining (EDM) wire erosion machine. Shown in Figure 9-1, the resulting stator parts show some surface corrosion after cutting; this is due to the EDM process, which requires the parts to be held underwater. Once removed from the lamination stack, the parts were cleaned of corrosion and wrapped with a thin layer of Kapton tape in order to

reduce the risk of delamination during handling; however despite this precaution a certain level of delamination did occur, generally between two sheets in the middle of the stack, however this was not found to impact construction.

Looking forward to the design goal of this project, to develop a motor which could be used in a production electric vehicle, it is recognised that the EDM process is not scalable for mass production; it is slow and expensive. For volume production, it is instead proposed that laminated parts would be stamped and then interlocked, rather than bonded and then wire cut.

9.2 Coil Manufacture

The manufacture of the motor's compressed aluminium coils proved to be a multistage process, more complex than that developed in Chapter 6, involving the manufacture of several pieces of tooling.

9.2.1 Tooling

As with the compressed coils in Chapter 6, the required tooling consisted of punch, die and bobbin. This tooling was manufactured from a class D9 tool-steel with the use of a computer controlled milling machine. The final tools are shown in Figure 9-3.



Figure 9-3: Showing final punch (left), die (bottom) and bobbin (right) set.

9.2.2 Stranded Wire Manufacture

The design required the use of 12 twisted strands of Class H aluminium wire, with each individual strand having a diameter of 1.4mm. This conductor was manufactured at the university from a single stranded coil.

Twelve 15.65m lengths of wire were wound onto individual bobbins. Each strand would allow for the required 30 turns per coil, multiplied by the average length of turn plus lengths at each end of the coil to allow for termination (equivalent to an additional two turns). These 12 wires were then linked at one end and slowly wound off the bobbins until they reached their full extents; this avoided any tangling. The wires were then cut from the bobbins and held together in 12 parallel strands. From each end of the now parallel stranded wire, 16 twists were now manually added (32 in total); this would allow for a single transposition of the stranded wire per coil turn with the two additional twists to accommodate the coil's terminating leads. The now twisted, stranded wire was then secured at each end and wound onto another bobbin

9.2.3 Bobbin Winding

The coils were then bobbin wound on the bobbin tool. This was undertaken on a workshop lathe as shown in Figure 9-4.

A plastic cap was added to the open end of the bobbin (shown in Figure 9-4), in order to hold the coils in place during bobbin winding. This cap was slotted in order to secure the start winding termination in the correct position.

As was discussed in Chapter 8, for this machine design it was critical that both winding terminations exited at the top of the coil; this was to ensure that coil interconnection would be possible within the motor housing. In order to achieve this six layers, each consisting of five winding turns, would be required (see Chapter 8 for details). After each layer had been wound, a soft, wooden drift was used to flatten the strands in place; this reduced any 'bulging' in the unpressed coil, which would make it difficult to later slot into the die assembly to allow compression.

Finally the coil was wound with Kapton tape. This held the individual turns in place whilst protecting the coil from abrasion during the pressing process.

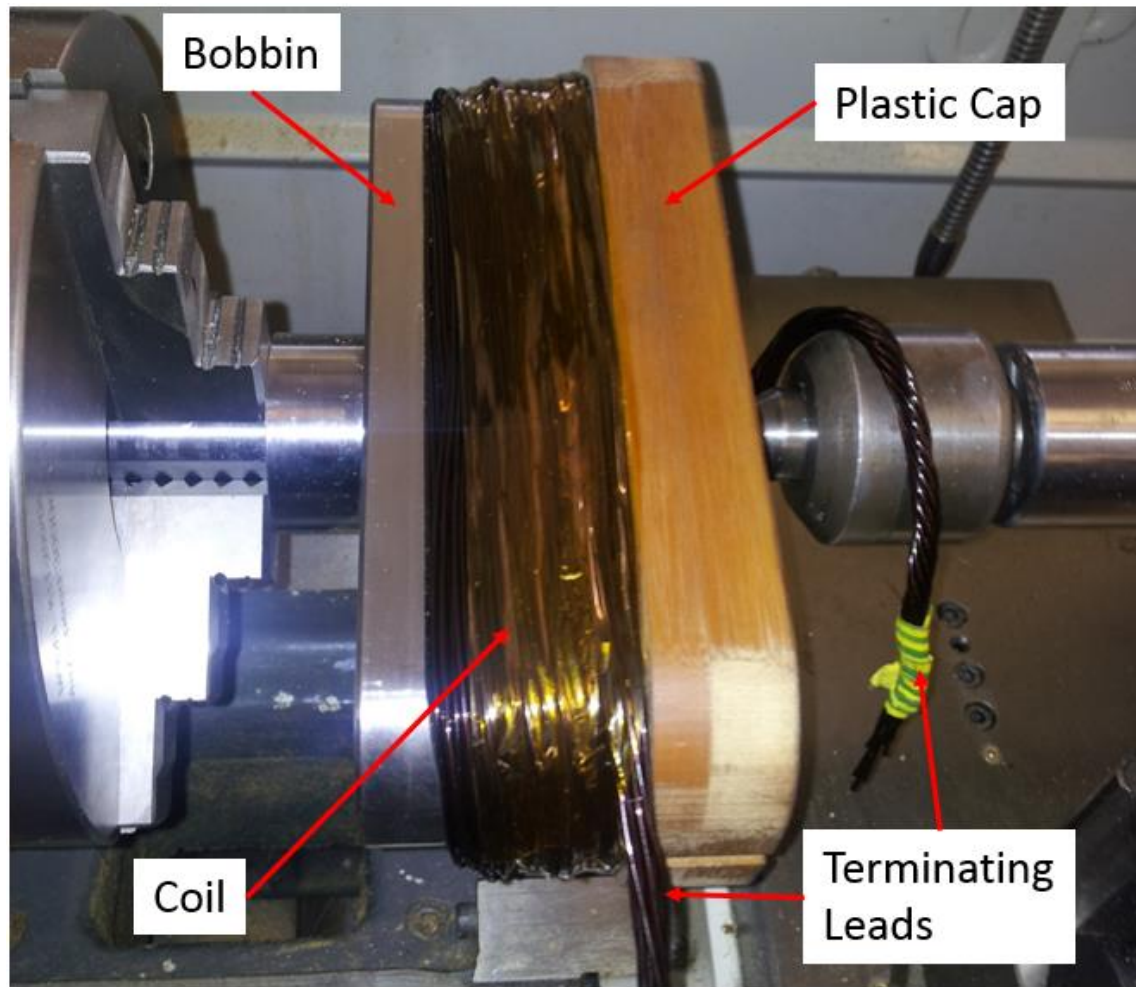


Figure 9-4: Showing a bobbin wound coil, prior to compression.

9.2.4 Coil Pressing

Based on the work in Chapters 7 and 8, a fill factor of a 77.9% was targeted for these coils (fill factor stated in terms of the machine slot).

For two reasons, a two stage pressing process, in place of the single stage process developed in Chapter 6, was developed; firstly this was to allow protective inserts (to be described in the following paragraphs) to be included prior to the final press and secondly to allow 'blank' coils to be manufactured at lower pressure which could then be taken as a set to the 500 tonne press, located in a separate building, for final compression. Figure 9-5 shows the progression from uncompressed coil through blank to final, completed coil.

The first stage of the process involved fitting the bobbin into the die and then covering the coil with the punch. Where necessary, it was possible to ease the coil into the die with the use of a leather hammer, without damage to tool or coil.

Coil terminations were laid in specially prepared slots in the punch and die in order to prevent them being sheared during pressing (shown in Figure 9-9, for the final stage of compression).



Figure 9-5: Coils at three stages of construction (left to right); following bobbin winding, the 'blank' following first stage compression and completed coil following final compression.

The punch, die and bobbin assembly was then compressed to approximately 30 tonnes and the 'blank' coil then extracted.

The bobbin was then again assembled with the die, however this time two inserts were added, one to the base of the coil and one at the top. These inserts were found to be required, as under full compressive pressure some of the conductor aluminium was extruding between the different parts of the tooling, as shown in Figure 9-6. This was found to be caused by the distortion of the tooling when fully compressed; this would have been avoided if the tooling could have been hardened prior to use (as would be the case for mass production), however this was not possible with the university's facilities.

Instead it was decided to use rapid prototyped, sacrificial plastic inserts to mitigate this effect. These were designed in CAD and then 3D printed. The lower insert is shown fitted in the die in Figure 9-7, where it occludes the gap between die and bobbin. The top insert took the form of a 2mm thick conformal sheet, which sat over the top of the coil, as shown in Figure 9-8. These inserts proved successful and were found to prevent

the extrusion of the aluminium during prototyping, with the plastic instead being sacrificially extruded. However, as previously stated, it is anticipated that hardening of the tool would also have prevented this extrusion without the need for additional components.



Figure 9-6: Showing how aluminium wire extruded between die tooling under compression.



Figure 9-7: The rapid prototyped insert to prevented extrusion of the aluminium wire between bobbin and die.



Figure 9-8: Showing the top insert, used to protect the coil from extrusion between the punch and the bobbin / die.



Figure 9-9: Die tooling positioned in 500 tonne press ready for compression. Wire terminations are shown laid flat in specially prepared channels.

In addition acrylic, heat resistant braid was slid onto each of the winding terminations, such that they were covered during their transition from inside to outside of the volume to be compressed. This was to provide a level of abrasion protection to these vulnerable parts, preventing damage during coil compression.

With both inserts fitted the coil is then fully compressed (250MPa, equating to 400 tonnes), Figure 9-9 shows the coil in position on the press, ready for final compression. Force is steadily increased until the required pressure is applied and then held for 1 minute; Figure 9-10 shows the tool fully compressed by the press. The pressure is then released and reapplied and again held for one minute; this was recommended by colleagues in the School of Mechanical Engineering as a method of work hardening the coil and therefore decreasing spring-back after pressing, however this process was not found to have a quantifiable effect. Spring-back was measured to be 1.2mm, equating to 4.5%; this is much higher than seen in Chapter 6, however this is thought to be due to the elastic behaviour of the plastic inserts and is within the allowable tolerance.

Finally the bobbin and punch were pressed out from the die (Figure 9-11). The coil was then manually removed from the bobbin and the protective tape, inserts and braided sleeves removed. Close up detail of a finalised coil is shown in Figure 9-12.



Figure 9-10: Punch pressed flat into die under 400 tonnes force. Termination wires remain undamaged.



Figure 9-11: Bobbin and Punch removed from die, clearly showing compressed coil and both top and bottom inserts.

This process took a significant amount of effort to refine. Two sets of punch, die and bobbin tooling were made and up to twenty coils pressed before the process was finalised. Of particular note was the need to compensate for deformation of the tooling, through the use of the previously described inserts. However the development of a method of protecting the coil terminations, exiting from the die and punch, was also time intensive.

Finished coils were visually inspected for damage and either repairs made to correct minor flaws (slight abrasions) or the coils rejected if more significant problems were identified. Undamaged coils were finally tested to 1kV using a Baker Instruments surge tester [118], which is designed to detect turn to turn faults. All coils were found to successfully pass these tests.



Figure 9-12: Showing final compressed coil details.

Figure 9-13 shows a cut through of one of the compressed coils. The deformation of the conductors to form hexagonal cross sections indicates that a very high fill factor has been achieved.

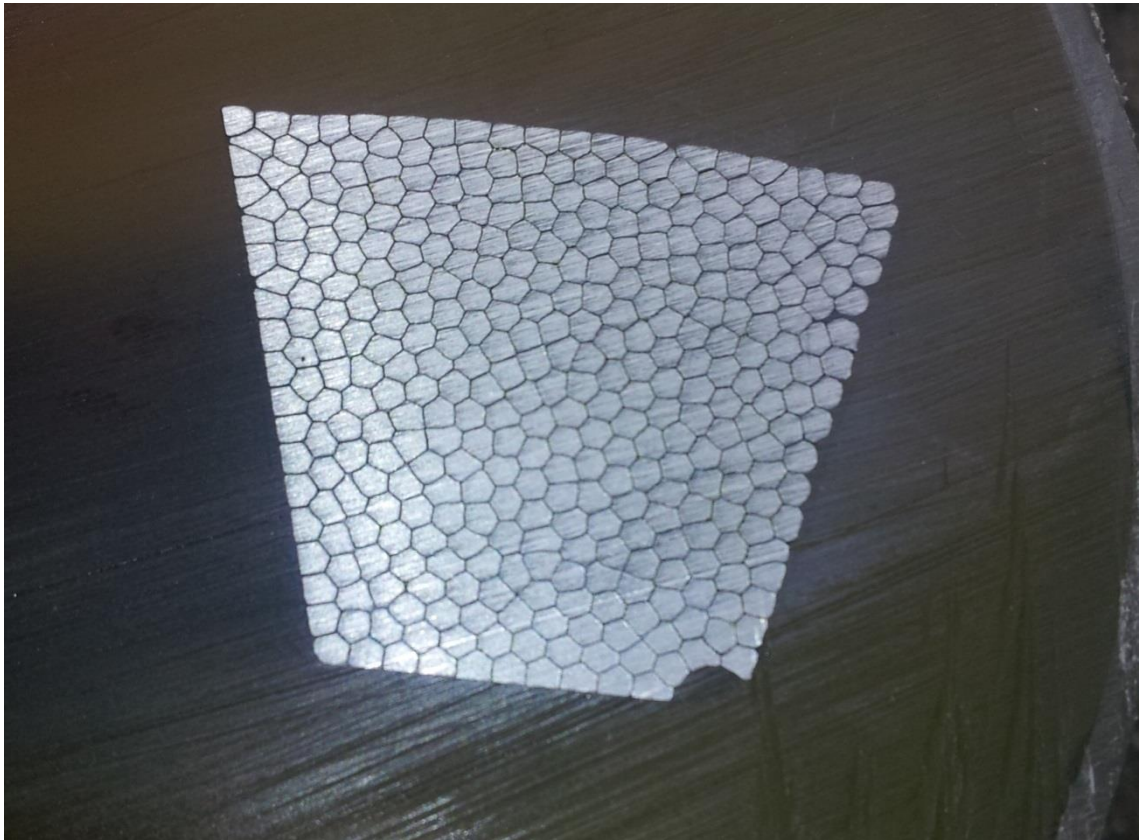


Figure 9-13: Showing the cross section of a coil, with the deformed, hexagonal conductors indicating that a very high fill factor has been achieved.

9.2.5 Coil Assembly with Stator Components

It is essential that coils are protected from shorting with the laminated stator components. In order to achieve this it was decided to use a combination of 0.3mm Nomex slot liner and high temperature plastic inserts.

A cutting template was designed and printed onto 0.3mm Nomex sheets for the slot liner. For each half coil, a piece was cut such that it would fully wrap the coil, protecting the coil from fouling the stator laminations (see Figure 9-14). This slot liner piece was designed so that it would overhang the stator laminations by 0.8mm at each end.

Plastic end cap inserts were also designed and machined from high temperature thermoset plastic, using a CNC milling machine (see Figure 9-15). These inserts were designed so that they would clip to each end of the wound stator tooth, and then be held in place using Kapton tape.



Figure 9-14: Slot liner cutting template.



Figure 9-15: Wound tooth end-cap insert.

The wound tooth, once fitted with these inserts, and coil, protected with Nomex slot liner, could then be assembled. Each of the assembled, wound teeth was then placed into a fixture, interspersed with the inter-winding tooth sections (Figure 9-16). These were temporarily clamped in place with jubilee clips in order to allow phase winding interconnections to be made.

Each of the 12 winding strands was individually stripped of 20mm of its enamel protection and windings were interconnected using 25mm², compressed butt crimps. These crimps were then protected with high temperature cable sleeving. External connections were made using 25mm² copper stranded wire, again crimped and protected with sleeving.



Figure 9-16: (Left) wound tooth fitted with slot liner, end cap and compressed coil. (Right) wound tooth assembled with inter-winding teeth in fitment.

9.2.6 Stator Assembly into Water Jacket

The motor water jacket is formed of inner jacket, outer jacket and an inlet terminal plate (see Figure 9-17). All parts were manufactured from solid 6082-T6 aluminium.

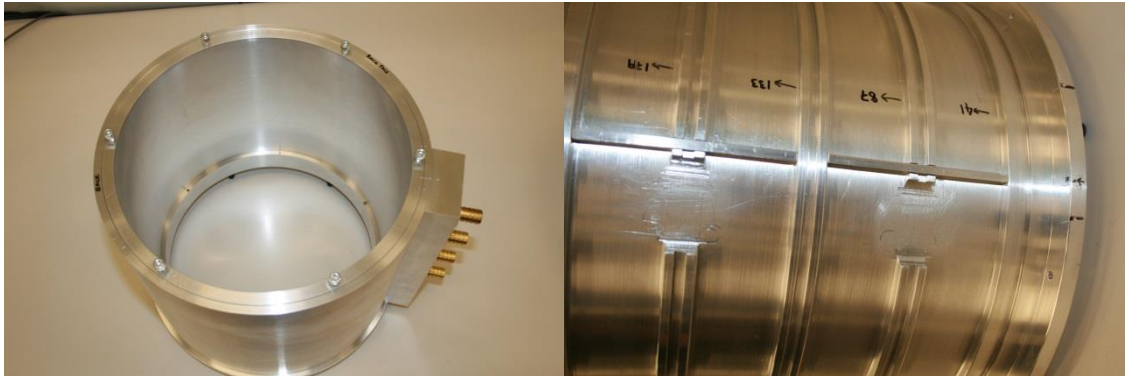


Figure 9-17: Stator water jacket components: (left) assembled and (right) the inner jacket showing water channels.

Once the winding interconnections were completed, the stator laminations were inserted into the inner motor water jacket (see Figure 9-19). The laminations were designed to have a ‘transition’ (nominally perfect with no clearance or interference) fit to the water jacket. However, even when compressed together using jubilee clips, the outer diameter of the segmented laminated core structure was found to be both ovalised and oversize; whilst in one radial axis the dimensions were oversized by 0.3mm of the required diameter of 246.2mm, in the other axis the stack was found to be more than 0.9mm oversize. It was clear that the larger than expected dimensions were due to some of the stator teeth not having closed as intended with the neighbouring teeth. This was felt to be due to a number of factors, this included potentially the coils, when fitted with Nomex slot liner, being oversize. It was also felt that perhaps the Nomex slot liner, despite the modification discussed in Chapter 8, was still bunching up at the interface between the different stator teeth. This was not an ideal situation as the intention had been for there to be no interference fit between stator core and water jacket, in order to avoid any increase in iron losses or decrease in permeability, due to stresses in the laminated core. However it was felt that the gaps between the coreback sections would

close when fitted into the water jacket, meaning that there would in fact be no hard interference fit.

In order to reduce the stator core's dimensions, the securing jubilee clips were replaced with heavy duty ratchet straps. These improved this situation, reducing the oversize to 0.1mm in one axis and 0.3mm in the second. This was felt to be acceptable if the stator inner water jacket were fitted once heated to 200°C. This would give a 0.2mm clearance (due to thermal expansion) each side as the stator housing were slid into place.

An attempt was made to fit the water jacket in this way; it was possible to slide approximately 75% of the length of the jacket in place before the inner water jacket cooled and locked with a section of the stator core still protruding. The assembly was allowed to cool overnight and then, using a combination of gas torch to heat and expand the water jacket and workshop press, the jacket was fully slid into position.

Unfortunately this process caused the development of a 0.25mm axial 'step' in one of the laminated teeth. In addition the stator bore was not in general found to be within the required tolerances for circularity, with it being ovalised by 0.2mm. These issues were corrected by the machining of the stator bore (Figure 9-18), resulting in a minimum dimension of 156.2mm and maximum of 156.3mm versus a nominal of 156.25mm. This would result in a larger than intended airgap in one axis of 0.4mm, whilst being smaller in the other axis at 0.3mm.

The stator was then once more electrically tested using a winding test system supplied by Baker Instruments. This tested both potential earth shorts to the case at up to 1.5kV (both 'Mega' and 'HiPot' tests were undertaken) as well as checking for turn to turn shorts at up to 1kV (Surge test). All tests were passed.

The stator was then finally assembled with the outer water jacket. This was held in place using the radial pressure due to the o-rings and also axially clamped by the motor end caps. Winding interconnections were exited from the machine through a terminal box and terminated with crimped rings (25mm², M10 ring). Finally the water jacket was successfully pressure tested to 3 bar for 2 hours.

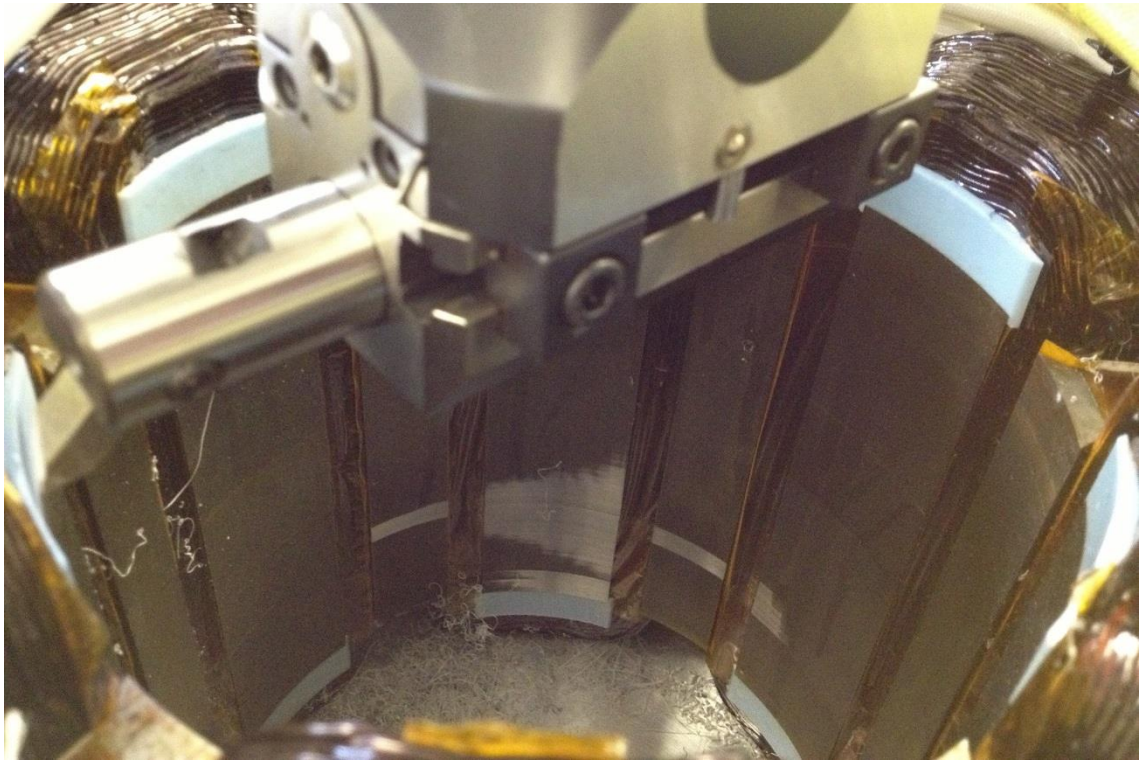


Figure 9-18: Stator bore was machined to final dimensions using a milling machine. Picture shows how a 0.25mm step in the lamination stack was reprofiled in this way.



Figure 9-19: Stator laminations fitted into inner-water jacket and under test with Baker Instruments motor winding test system.

9.3 Rotor Construction

The rotor was constructed from shaft, rotor support, rotor segment laminations and supporting parts.

The rotor segments were cut from the same block of M270-35A steel as was used for the stator laminated components (see Figure 9-2). The cut rotor segment is shown with the stator laminated parts in Figure 9-20.

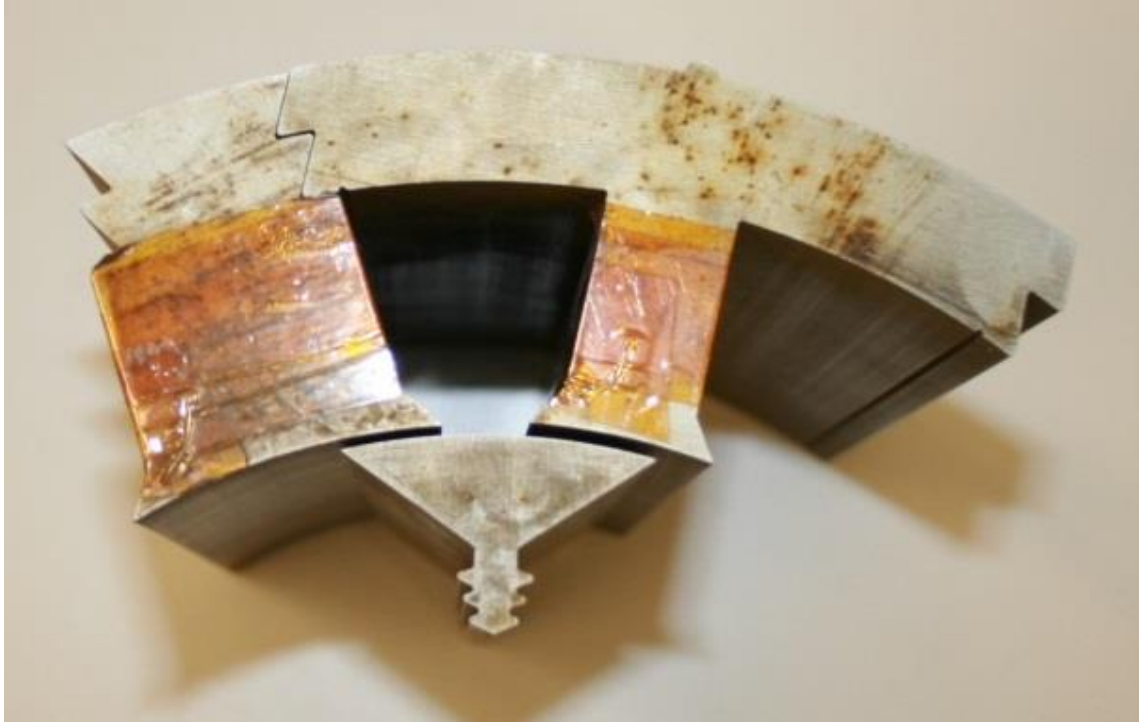


Figure 9-20: Rotor segment shown with stator lamination parts.

The rotor support structure was similarly made from laminated, EDM cut parts; however in this case it was made from 2mm thick aluminium pieces.

As with electrical steel laminations, in order to prevent the propagation of eddy currents along the axial length of the machine it was necessary to insulate each lamination. It was initially hoped that a combination of a glue layer and the aluminium's own oxide layer would provide sufficient insulation, however when continuity between glued layers of these 2mm aluminium sheets was checked, it was found that resistance was very low and was thought to be insufficient to prevent eddy current propagation.

As a result it was decided, and confirmed by experimentation, that spraying each layer with a clear, electrically insulating acrylic lacquer would insulate the laminations. 79,

2mm aluminium sheets were cut and then prepared in this way (see Figure 9-21). The rotor support was assembled to the shaft, with a rotor end cap fitted at one end and keyways in the rotor shaft used to locate each support lamination.

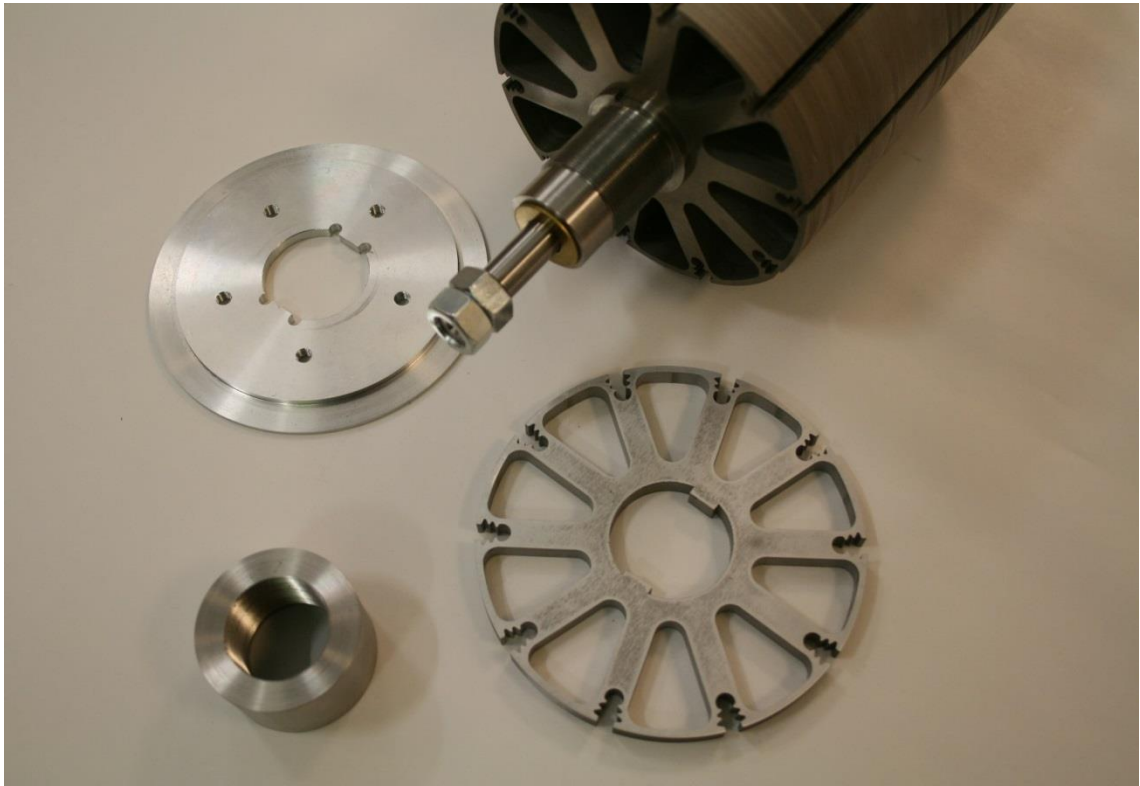


Figure 9-21: Showing (top right) rotor shaft fitted with aluminium rotor support laminations. (Bottom right) is shown a rotor support lamination, (bottom left) the nut used to clamp the assembly axially and top left the rotor end cap.

Cut into each sheet was the supporting fir tree root design, developed in Chapter 8. The rotor support to rotor segment interface was manufactured with a transition (nominally perfect) fit. Therefore in order to fit each rotor segment a shop press was used to drive the segment into the rotor support; this was a successful process, resulting in very tightly seated rotor segments (see Figure 9-22). Finally the rotor was fitted with its end plates, securing nuts and bearings.

The eccentricity of the rotor was measured and found to be no more than 0.03mm, well within design tolerances. This in turn demonstrated that this process could be used to construct a rotor which could achieve a 0.3mm airgap length, without the need for a final rotor machining process.

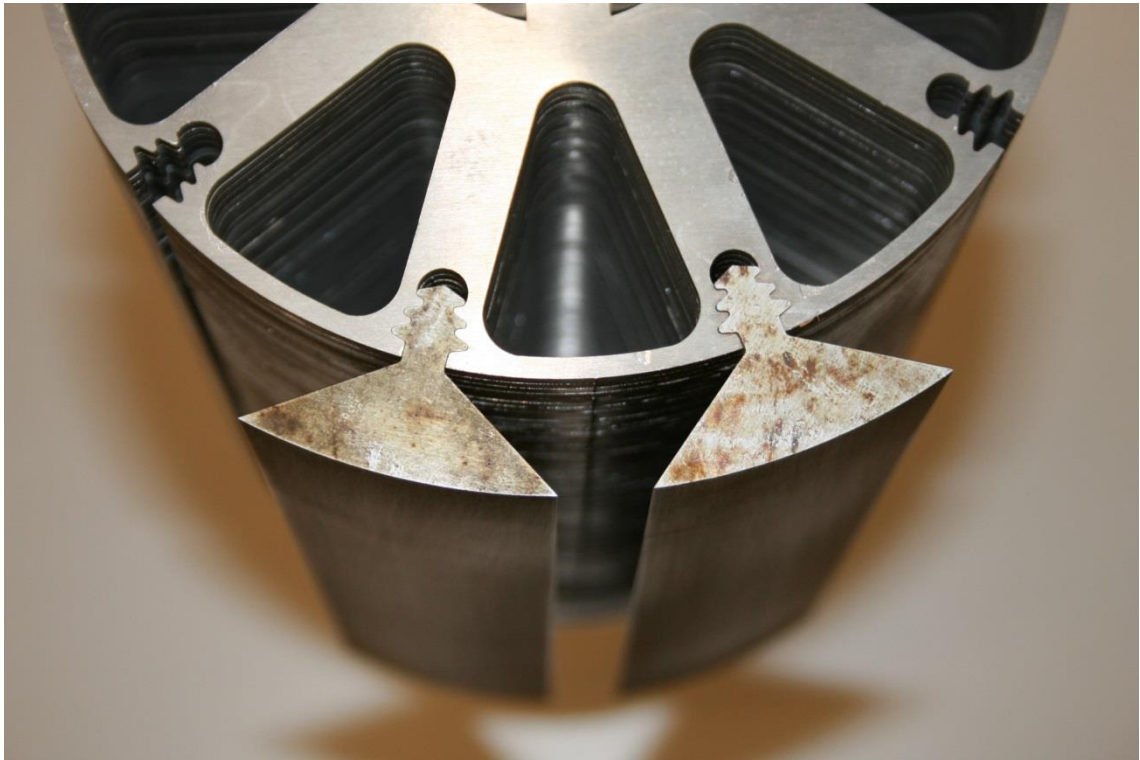


Figure 9-22: Rotor support fitted with two rotor segments.

The axial tolerances of the stack were also measured and found to be $\pm 0.5\text{mm}$. This was larger than intended and was due to inconsistencies in the pressing of each rotor segment lamination stack into the rotor support. This, however, would have little impact on overall motor performance. Equally it is suggested that it could be corrected in future builds through use of an improved process, which would make use of a fixture to ensure that each stack was consistently pressed into the support.

The rotor was then balanced to G2.5 at 10,500rpm using a Schenk rotor balancer. As had been trialled in Chapter 4, a system of bolts and washers was used to add mass in order to achieve the required balance.

9.4 Final Motor Assembly

The rotor was finally fitted into the stator housing (Figure 9-23) and both motor end caps fitted. The rotor was found to turn freely. It was not possible to directly measure rotor eccentricity, however testing discussed in Chapter 9 suggested that the consistency of flux linkage with phase current in the aligned rotor position between phases was good, suggesting a good level of concentricity and therefore balance between the phases. Figure 9-24 shows the completed motor fitted to the test rig, awaiting testing.

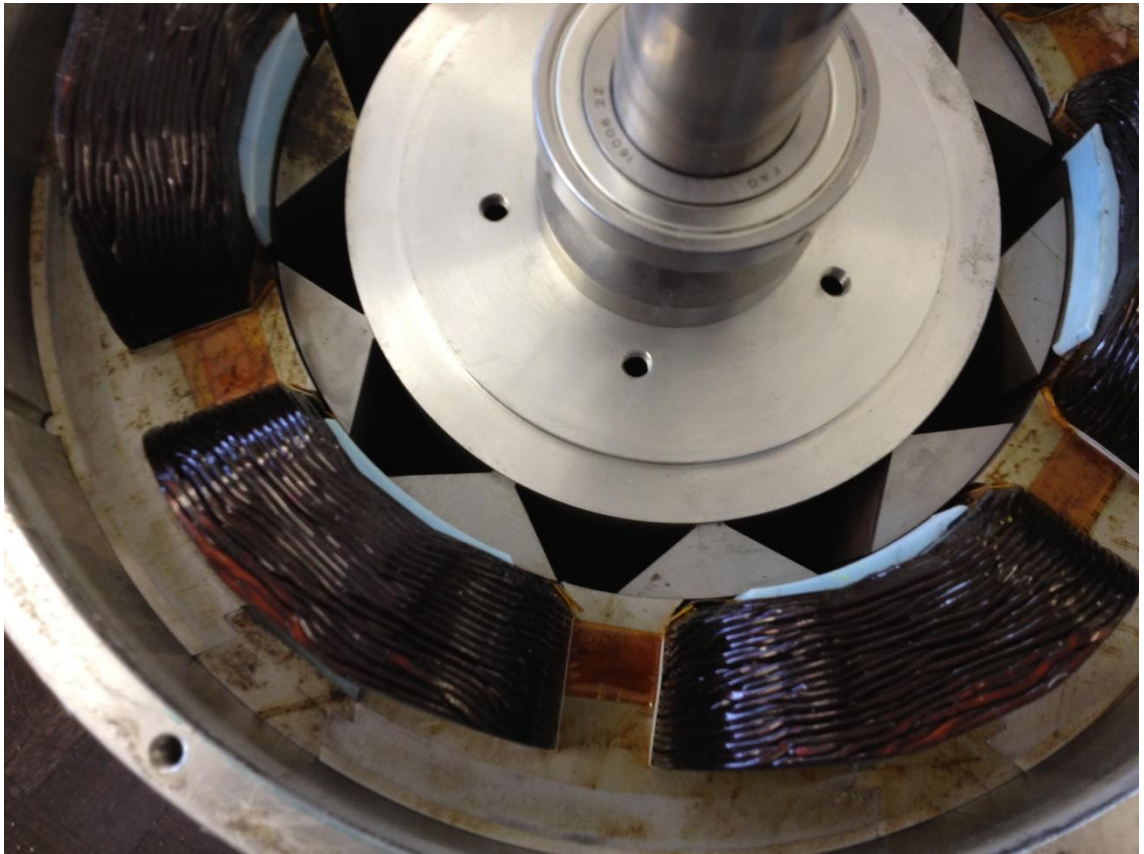


Figure 9-23: Showing the segmental rotor fitted to the stator.

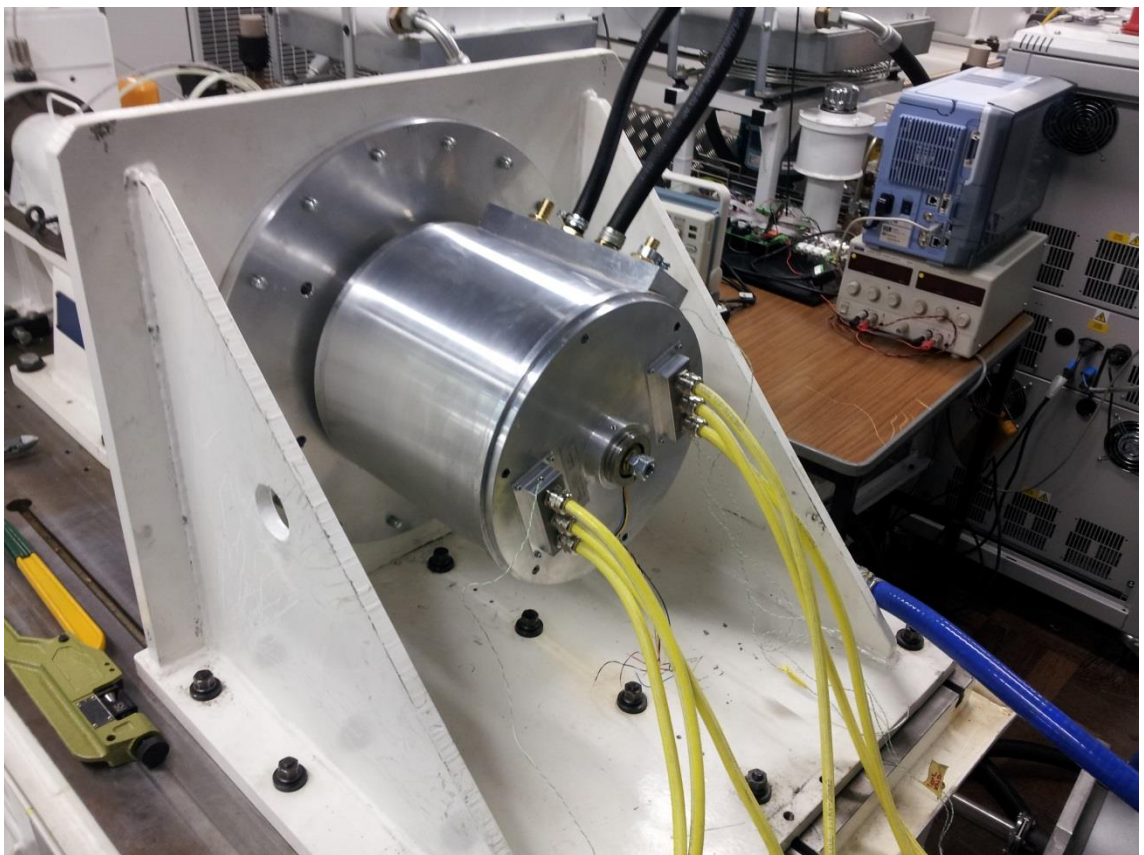


Figure 9-24: Showing completed 80kW Segmental Rotor SRM mounted on the test rig.

9.5 Conclusions

Varying levels of success were achieved in the manufacture of the different components of this electrical machine.

The manufacturing process for the segmental rotor was found to be successful. A simple process, which could be readily scaled up to mass production, was used to manufacture the rotor support and segments. The M270-35 lamination parts could be stamped and interlocked; the aluminium rotor support laminations could equally be stamped. The concentricity tolerances which were achieved ($\pm 0.03\text{mm}$) were found to be suitable for mass production.

The manufacture of the compressed aluminium coils of this size was also successful, though became relatively complex. The need to use stranded wire complicated the manufacturing process. As a result sacrificial plastic inserts and protective braid coverings were needed to prevent damage to the coils during compression. However it is felt that further development along with the use of more accurate and hardened tooling could resolve these issues to the process more suitable to volume production; however the process is without doubt more complex than the use of simple bobbin wound coils. A fill factor of 77.9% (aluminium area to slot area) was achieved, whereas in comparison uncompressed, stranded, bobbin wound coils prior to compression having been estimated to achieve only an approximate 40% fill. As a result the motor losses and winding thermal conductivities are both significantly improved compared to the use of an equivalent bobbin wound coil.

Stator manufacture, using the system of interlocking wound and unwound teeth, also showed promise but was less successful and would require further development. The intention of this process was to allow construction of the stator from modular parts without the need for any post machining of the stator bore. However in this case machining was required in order to achieve acceptable bore tolerances. The major limitation was ovalisation of the stator and the reasons for this are not at this stage fully understood. Further work will be undertaken as part of the future projects discussed in Chapter 12.

Overall this chapter has shown that an 80kW Segmental Rotor SRM can be manufactured using what are likely to be mass production scalable techniques.

Chapter 10. Validation of 80kW Segmental Rotor SRM Design

This chapter covers the validation of the 80kW Segmental Rotor SRM prototype developed in Chapters 7- 9. It describes the testing undertaken to validate the motor design. This includes static testing to generate flux linkage / current characteristics for the motor; from these results static torque is derived. Static thermal testing is undertaken in order to validate the thermal modelling in Chapter 8.

As will be seen, during thermal testing the interconnections between the compressed windings failed and the motor was damaged. An investigation into the causes of this failure is undertaken and its results presented.

The motor was rebuilt (with some limitations) and a set of running tests undertaken. The full range of testing was limited by the availability of a suitable DC power supply to 60kVA and by torque limits on the dynamometer. However a bespoke 250kVA asymmetric half bridge converter was used to support partial dynamic testing of the motor.

Dynamic testing was undertaken to characterise friction and windage losses as well as to confirm the efficiency of the motor under the optimisation operating condition (3500rpm / 40Nm), as defined in Chapter 7. During this testing higher than expected losses were identified in the aluminium rotor support which led to complete closure and therefore seizure of the motor airgap. Possible solutions are provided to this problem.

Finally, a number of observations are made about the general performance of the prototype electrical machine, including its control and acoustic noise.

10.1 Winding Resistance

Phase winding resistance was measured at 20°C. Table 10-1 contrasts the measured winding resistance for each phase, compared with that predicted in Chapter 8.

The measured resistance is on average 11.6% higher than predicted, which in turn will lead to increased copper losses by the same proportion.

Whilst this is large difference in percentage terms, in terms of phase resistance it equates to a maximum of just 7mΩ. This is therefore expected to be attributable to the use of crimped interconnections and to the copper leads used to terminate each motor

phase. Indeed this conclusion is supported by findings following a rebuild of the motor, discussed later in this chapter.

Table 10-1: Measured Phase Resistance vs Prediction (20°C).

	Predicted	Phase A Measured	Phase B Measured	Phase C Measured
Resistance	0.046 Ω	0.053 Ω	0.050 Ω	0.051 Ω

10.2 Static Flux Linkage / Current Tests

Following the procedure outlined in Chapter 4, a static flux linkage / current characteristic for the motor was developed. Each phase was tested individually, with flux linkage being recorded at 1° (mechanical) increments, which equates to 10° (electrical) in this 12 stator slot / 10 rotor segment machine.

Figure 10-1 compares the characteristics for each motor phase in the aligned and unaligned position. There is minimal variation between the unaligned curves, however the aligned curves do show some differences. This is thought to be due to the variation in airgap length between phases due to the stator ovalisation, as discussed in Chapter 9.

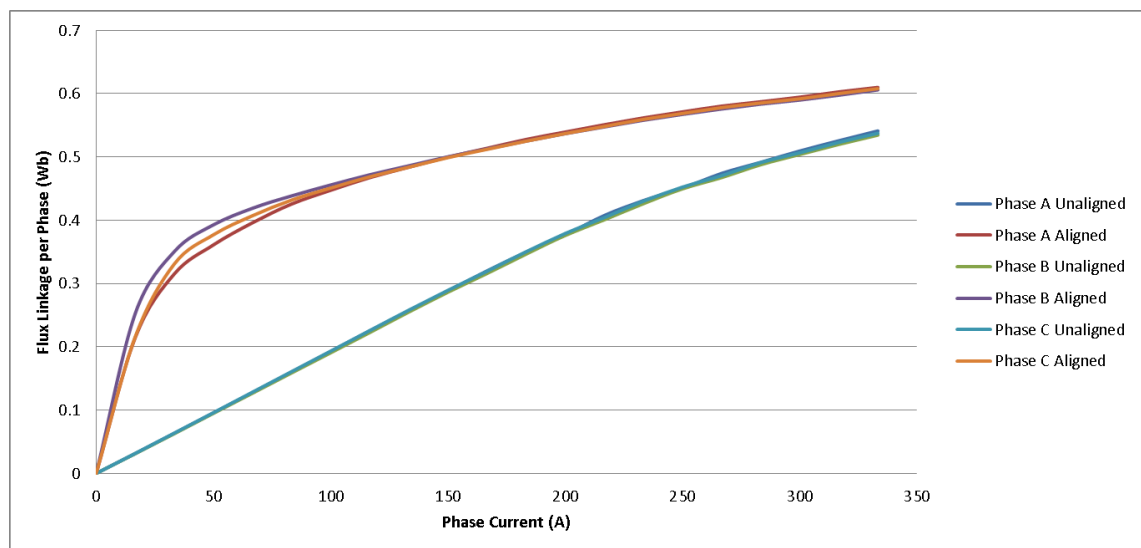


Figure 10-1: Showing Experimentally Measured Aligned and Unaligned FLux Linkages for each Phase of Prototype Segmental Rotor SRM.

In order to compensate for the variation between phases, Figure 10-2 presents an average characteristic, taking the mean of the three phases.

Figure 10-3 then compares the average characteristic, in the aligned and unaligned position, with the predictions from 3D finite element modelling.

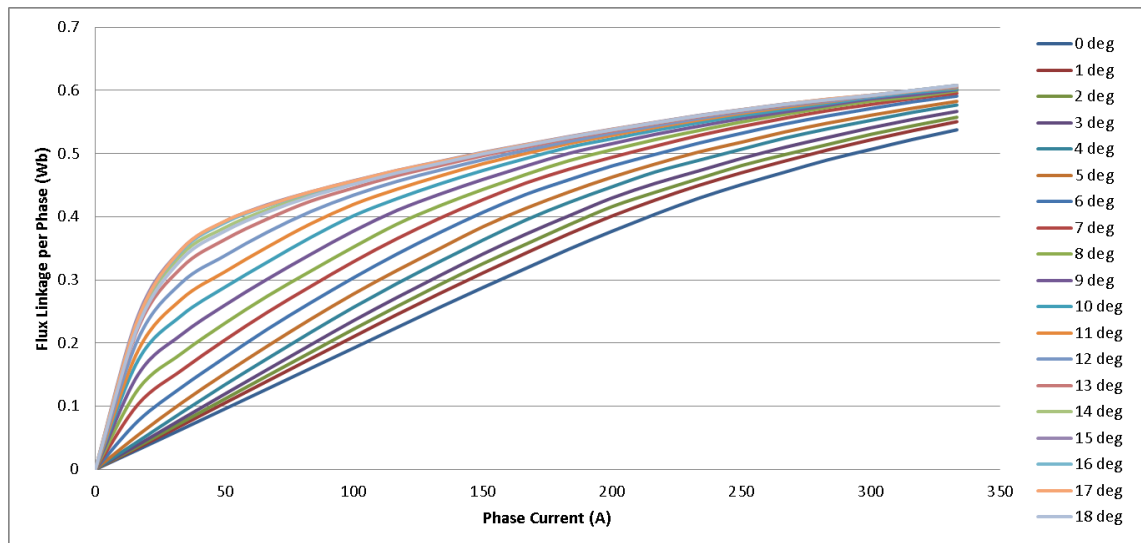


Figure 10-2: Showing Flux Linkage vs Phase Current and Rotor Angle (mechanical degrees). This characteristic is the average of the three phase characteristics recorded.

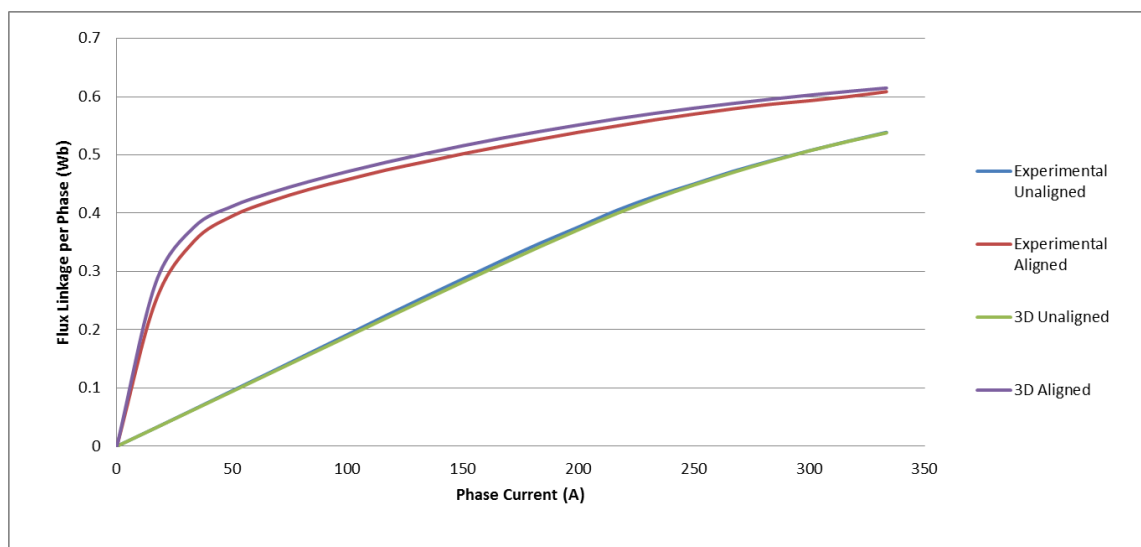


Figure 10-3: Comparison of Flux Linkage vs Current plots from Experimental measurements and from 3D Finite Element Analysis

In Figure 10-3 there is again little variation in the unaligned position; this demonstrates that the 3D modelling is able to accurately predict end winding leakage flux. There is however a difference between the aligned characteristics; in Chapter 8 the airgap length was increased to 0.35mm at room temperature in order to mitigate potential airgap

closure during motor operation. However this was not reflected in the 3D modelling as it was shown that, as the motor warms to its normal operating temperature, the differential thermal expansion between the directly cooled stator laminations and less well cooled rotor would see this gap narrow and therefore the aligned inductance increase. However there is no easy method to demonstrate this effect statically, with it needing to be confirmed during dynamic testing as will be seen later in this chapter.

In order to confirm that the difference in the aligned characteristics is due to the increased airgap length, a number of static 3D models were run. The conclusion of this work was that the experimental results most closely matched an airgap of 0.36mm. However it was also noted that the electrical steel appeared to be saturating earlier than had been predicted, at approximately 98% of the modelled values; this is unexplained and cannot be accounted for in the lamination stacking factor which was also approximately 98% and had already taken into account during finite element modelling. Figure 10-4 compares the aligned and unaligned curves from test with those from this revised modelling.

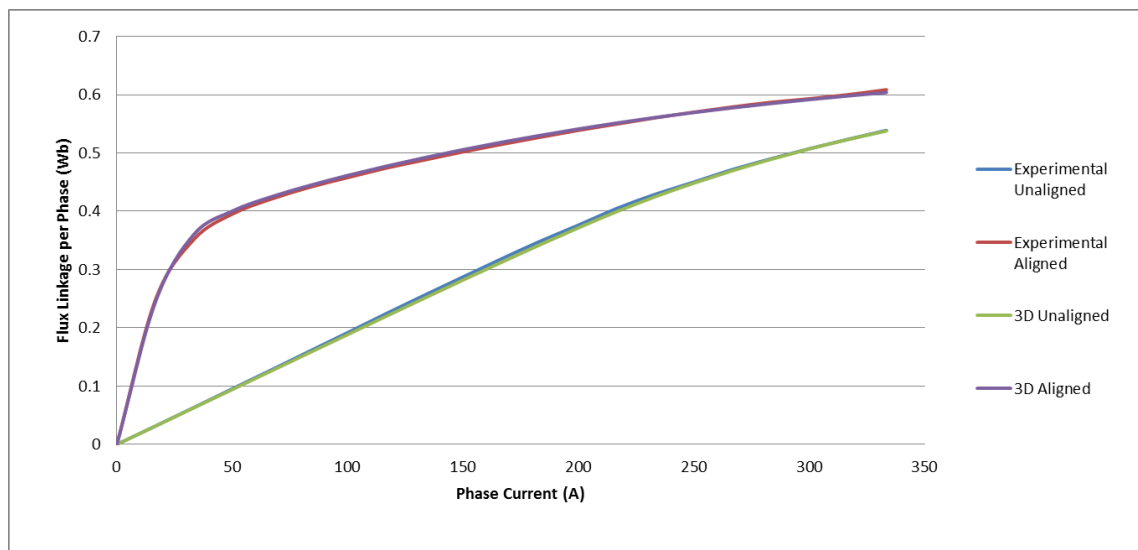


Figure 10-4: Comparison of Flux Linkage vs Current plots from Experimental measurements and from revised 3D Finite Element Analysis which assumed 0.36mm airgap, 98% lamination stacking factor and reduced material saturation to 98% of previously modelled values.

From these flux linkage characteristics average torque can be calculated, Figure 10-5 provides a comparison between the 3D finite element modelling (both baseline and revised) and experimental results for the prototype motor. A significant difference is observed between the baseline 3D model and experimental results (Figure 10-3).

Experimentally estimated average torque, with a peak current of 335A, is shown to be lower than predicted by the modelling, falling from 318Nm to 293Nm, or 9%. The difference is smaller when compared with the revised model, assuming 0.36mm airgap length and 98% electrical steel saturation (Figure 10-4), producing 300Nm for a peak current of 335A, this is just 2.4% higher than the experimentally calculated torque.

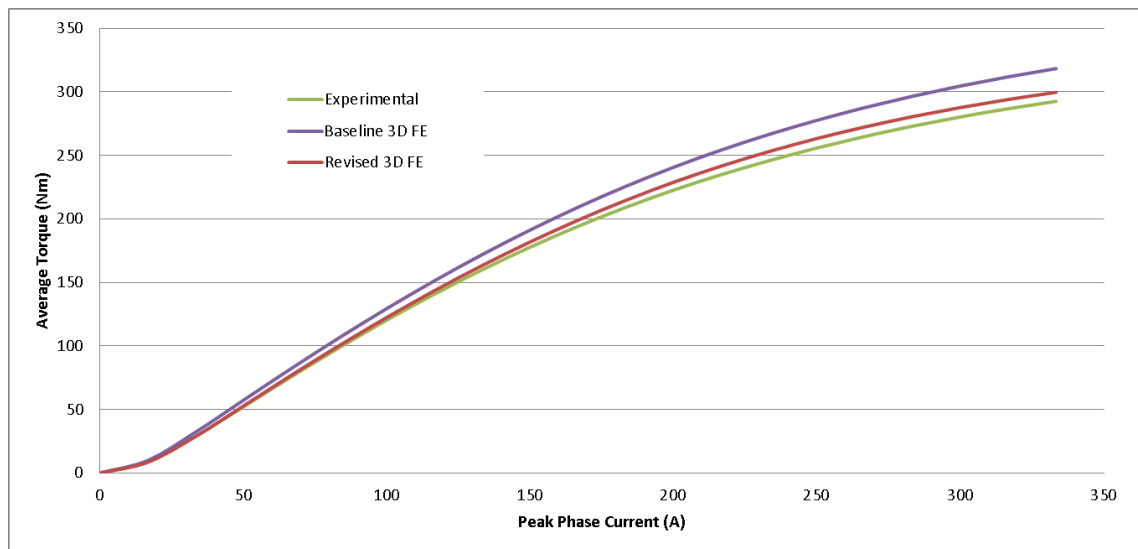


Figure 10-5: Average Torque vs Peak Phase Current calculated from Flux Linkage for both Prototype Motor and from both baseline and revised 3D Finite Element Analysis.

However, as discussed in Chapter 8, it is assumed that the airgap length will close to nominal (0.3mm) during steady state operation due to differential expansion of the aluminium rotor hub. If this assertion is correct then, assuming the 98% saturation factor, it is predicted that experimental motor torque for 335A would increase from 293Nm to 305Nm, within 4% of the baseline 3D FE prediction of 318Nm.

Table 10-2 summarises this data, comparing winding losses for peak torque at low speed based on these findings. This shows that the prototype motor, operating steady state, with the airgap therefore reduced to 0.3mm, would be predicted to produce 1.09kW more loss (22%) than modelled in Chapter 8. Of this 11% is due to the increase in winding resistance and 11% to the early saturation of the lamination steel.

Table 10-2: Summary of baseline, measured and predicted copper losses for 280Nm at low speed. Assumes perfect current control with a 180degree conduction angle.

	Baseline 3D FE	Experimental	Revised 3D FE ($l_g = .36\text{mm}$)	Revised 3D FE ($l_g = .3\text{mm}$)
Torque	280Nm	280Nm	280Nm	280Nm
RMS Phase Current	191 A	212 A	206 A	200 A
Phase Resistance	0.046 Ω	0.051 Ω	0.051 Ω	0.051 Ω
Winding Loss	5,030 W	6,876 W	6,492 W	6,127 W

10.3 Static Torque Estimation

As no suitable equipment was available to directly undertake a static torque test for this motor, instead the flux linkage characteristic was used to estimate static torque versus rotor angle. Figure 10-6 shows the resulting calculated static torque compared to 3D finite element results.

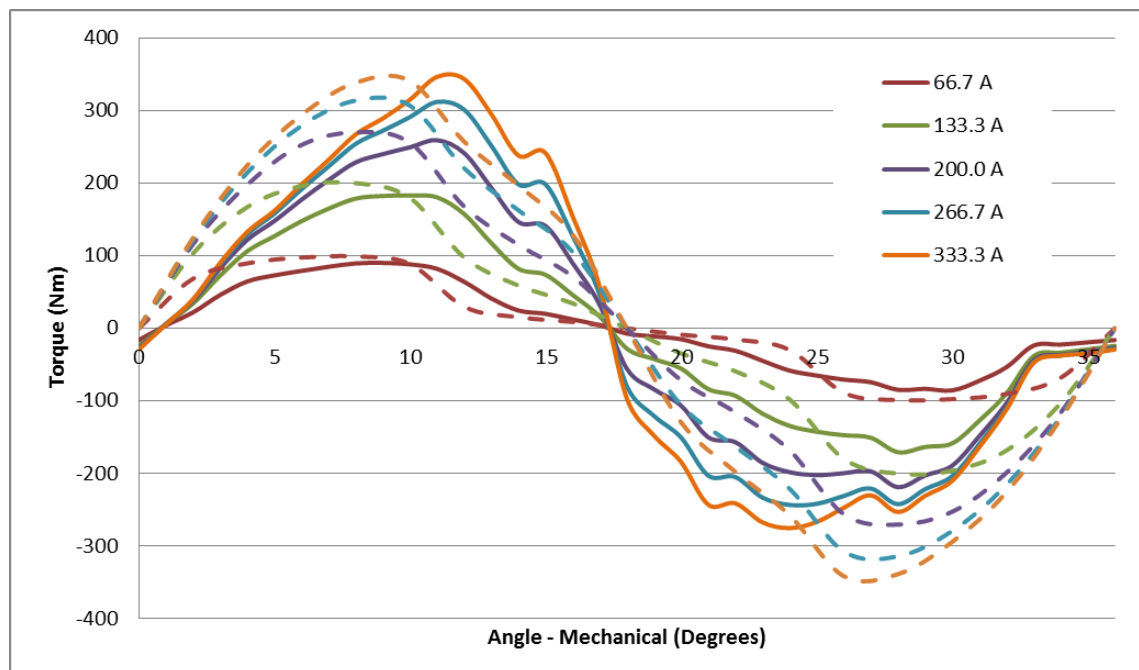


Figure 10-6: Static Torque for different levels of DC phase current. (Solid Lines) are taken from test, (dotted lines) from 3D finite element modelling.

Whilst it is possible to see some common features between the experimental and modelled characteristics, they are far from consistent. This is primarily as the

experimental data contains considerable levels of noise. This noise is related to the accuracy of the angular measurement achieved during static testing where position tolerance was $\pm 0.1^\circ$ (mechanical). This effect is likely to be magnified by a small degree of flexure of the aluminium rotor support and segment root structure, leading the rotor segments to move position slightly when torque is applied. The data was collected at 1° (mechanical) intervals, therefore even a small positioning error (0.1° or 0.2°) could result in a large error in the coenergy calculated and therefore large perturbations in the calculated static torque profile.

Whilst efforts were made to reduce this, both by averaging the results across the three motor phases and also through the use of a three point running average to smooth the results at each rotor angle, significant difficulties remain with the data. However, as a minimum, the data does demonstrate that the motor is likely to achieve levels of torque comparable to those predicted.

10.4 Static Thermal Testing

A number of tests were undertaken in order to validate the thermal model developed in Chapter 9. Thermocouples were fitted to the end windings, in the slot adjacent to the coil, to the stator lamination tooth and to the inner water jacket. Thermocouple locations are shown on Figure 10-7.

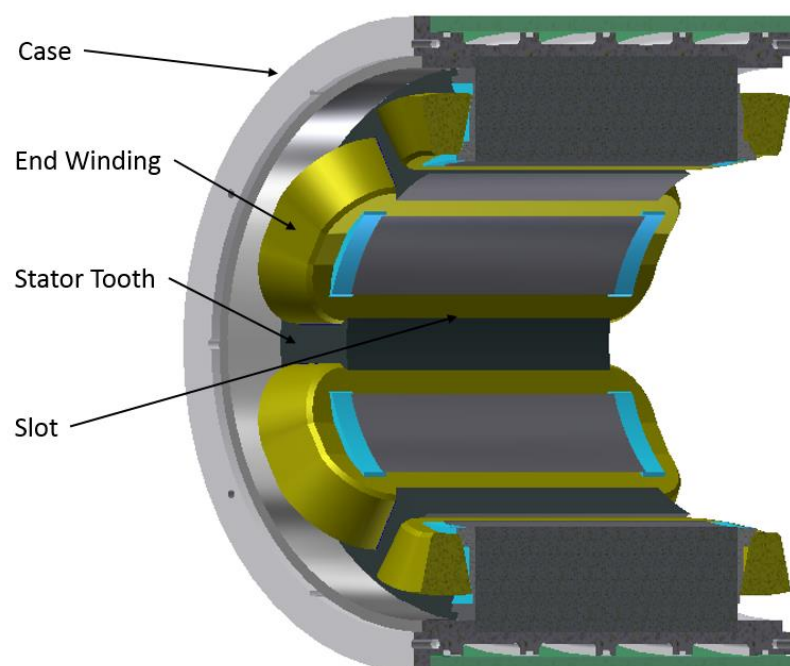


Figure 10-7: Thermocouple locations on prototype motor.

Thermal tests were undertaken with a static rotor and with all three motor phases connected in series. A power supply, which was able to provide a constant power, simulating a constant loss, was connected to the motor coils. The water jacket was attached to a thermostatically controlled chiller, with the temperature set in a hysteresis range of 18-22°C.

It was intended that tests be undertaken from 1kW to 9kW in 1kW intervals and that these results then be compared with the thermal model, however thermal failure of the motor winding interconnections at 5kW prevented this. At 5kW smoking was observed and the thermocouples attached to the winding failed. This fault was later traced to the crimped interconnections between the windings; this will be discussed in detail in Section 10.5.

Tests were successfully undertaken at 1kW, 2kW, 3kW and 4kW (partial) and these will be addressed first.

10.4.1 Thermal Testing 1kW-4kW

Figure 10-8, Figure 10-9, Figure 10-10 and Figure 10-11 show the results of the thermal testing for 1kW, 2kW, 3kW and 4kW of copper loss respectively.

When the results from these tests are assessed, two conclusions may be drawn. Firstly that there are differences between test results and the modelling and secondly that, for 3kW and 4kW tests, the results show significant ‘glitches’ in the winding temperatures recorded. These two issues will be dealt with separately.

10.4.2 Thermal Model Validation

One area where the thermal model correlated closely to the test results was in the stator laminations. In contrast the predicted motor casing temperature was higher than predicted by modelling. This is due to the way in which the thermal model was constructed, with this temperature being measured in the model on the outside surface of the stator lamination stack (see Chapter 8) whereas in the test measurement it is measured on the inner water jacket ‘lip’, as shown in Figure 10-7. Therefore the difference in temperature between model and experimental results is attributable to the measurement location. It should also be noted that, perhaps most clearly from Figure 10-9, it can be seen that the water jacket temperature tracks the input water temperature, with the chiller’s hysteresis being readily observed.

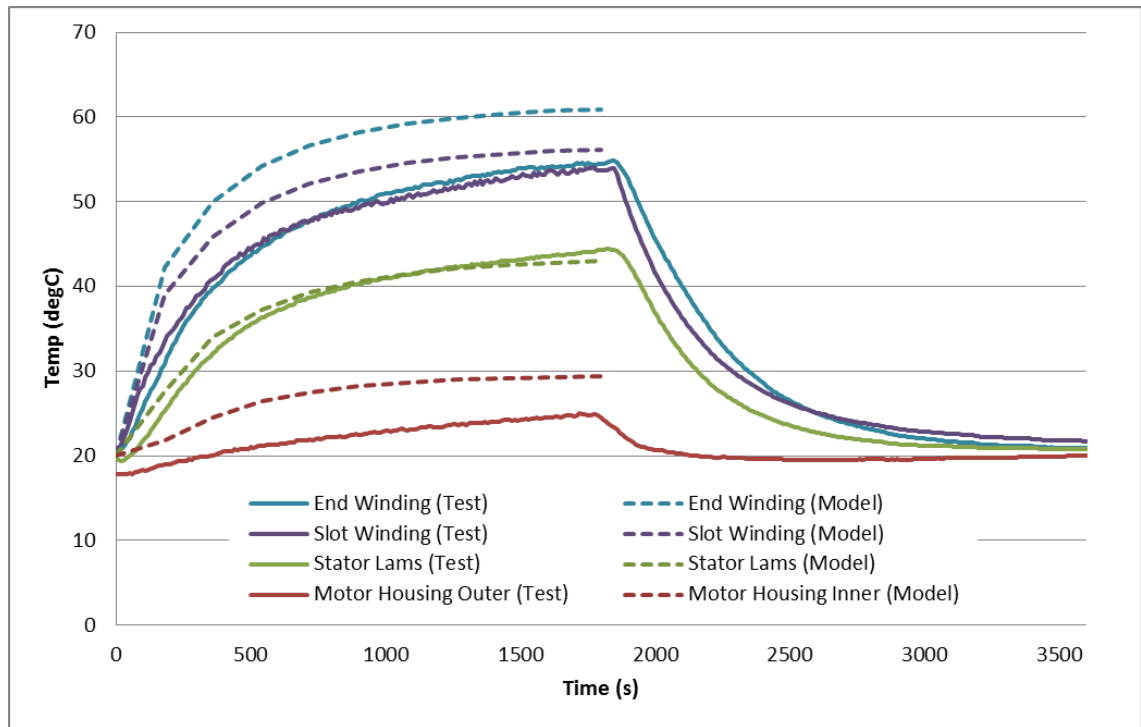


Figure 10-8: Thermal Test Results compared to Thermal Modelling - 1kW of Copper Loss

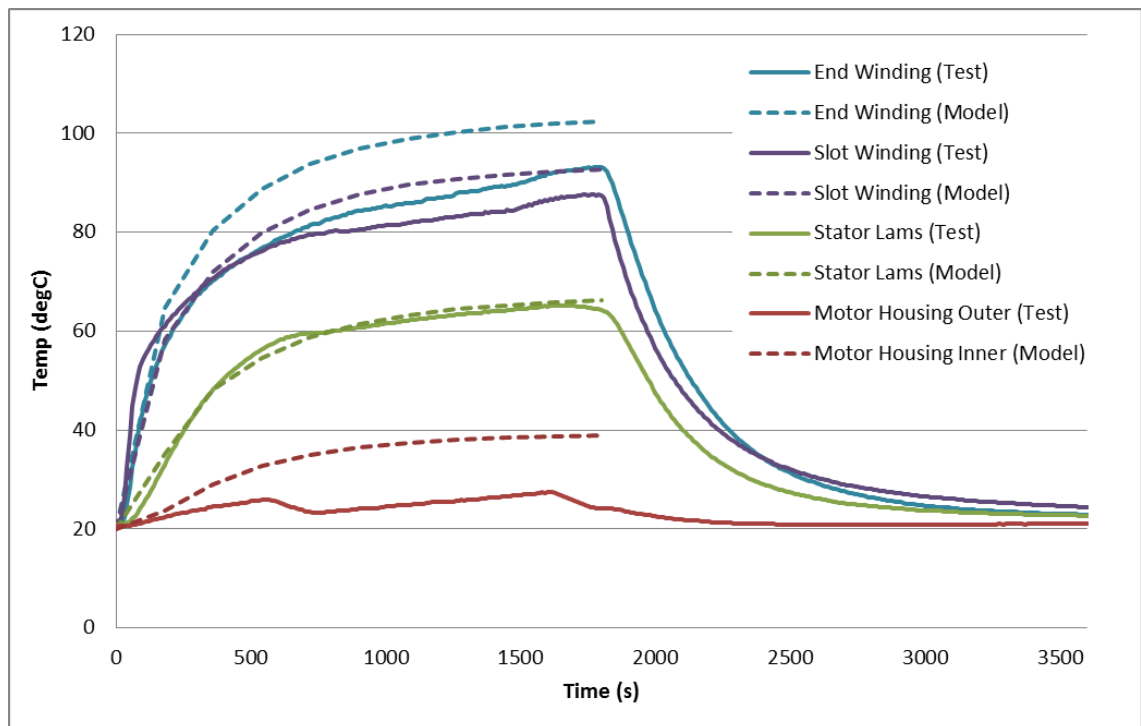


Figure 10-9: Thermal Test Results compared to Thermal Modelling - 2kW of Copper Loss

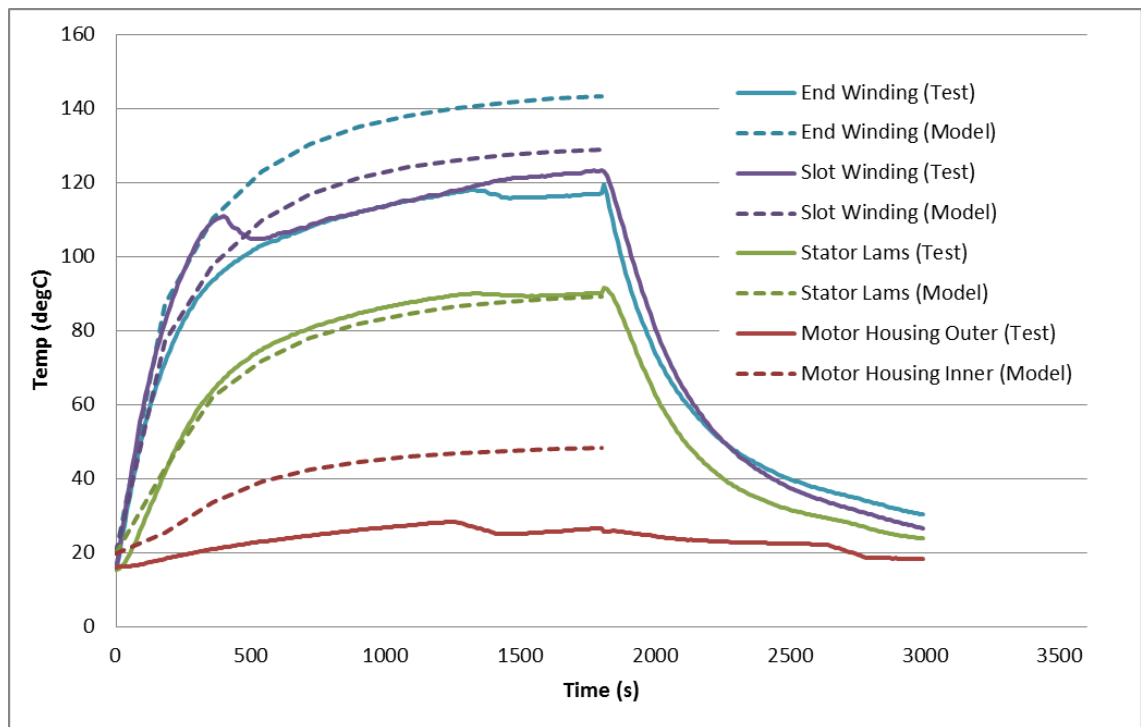


Figure 10-10: Thermal Test Results compared to Thermal Modelling - 3kW of Copper Loss

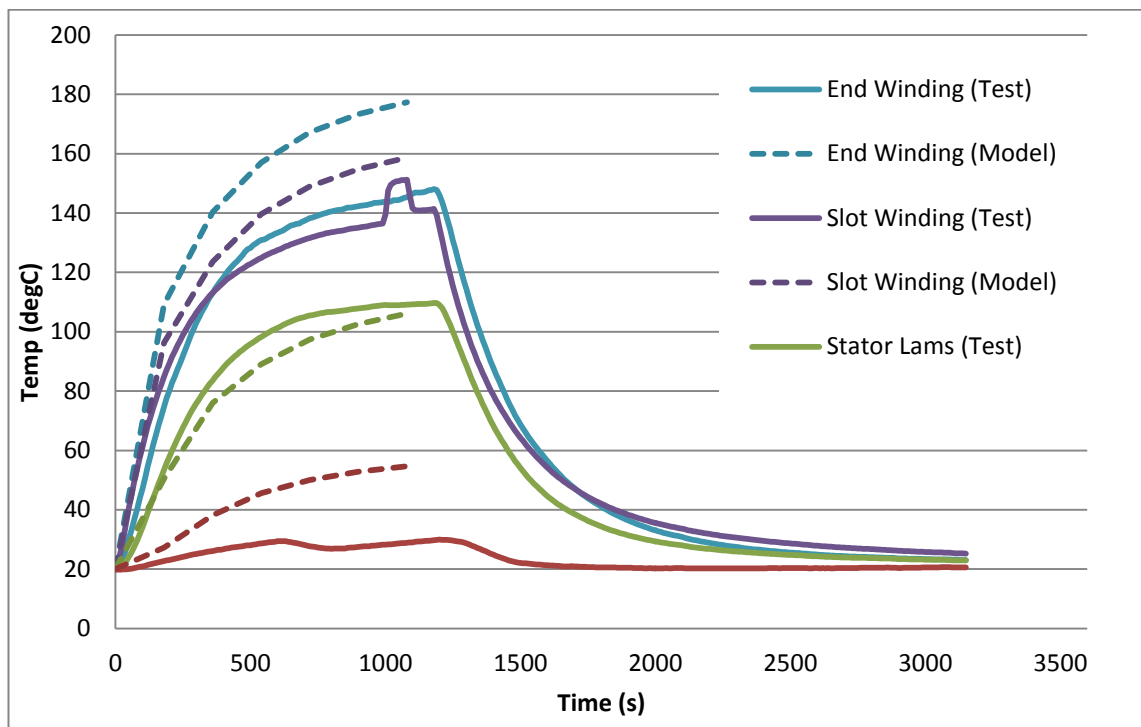


Figure 10-11: Thermal Test Results compared to Thermal Modelling - 4kW of Copper Loss

As will be recalled, in Chapter 9 the decision was made not to implement an interference fit between stator laminations and water jacket; this was based on advice

that the resulting locked in stresses in the stator core would increase iron losses whilst reducing permeability. It is therefore noted that the tests above 2kW all show a difference of more than 31.3°C between the stator laminations and water jacket. This was the temperature difference which, in Chapter 8, was shown to be needed in order to ensure that, by differential expansion, good thermal contact between the stator laminations and inner water jacket.

The motor winding temperature, both slot and end winding, were predicted to be significantly higher than observed in the test. As was discussed in Chapter 8, the thermal model conservatively assumed that there would be no heat loss from the motor's end windings, other than through the slot. It is this assumption, along with a perhaps conservative assessment of heat transfer through the Nomex slot liner, which is expected to explain this discrepancy. In order to address this, the thermal conductivity of the slot liner in the thermal model was increased to 0.2W/(m.K), from 0.13W/(m.K), which was found to significantly decrease this variance; Figure 10-12 shows a representative example for 2kW, showing improved correlation of the results. A similar improvement was also seen at 1kW, 3kW and 4kW.

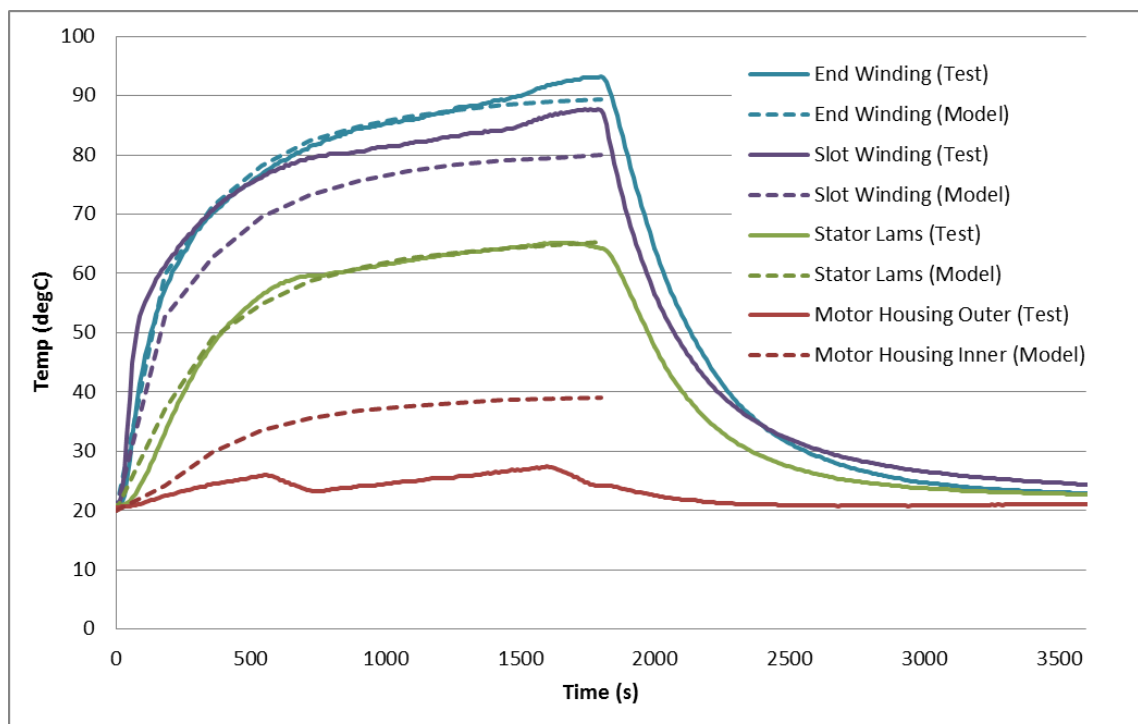


Figure 10-12: Thermal Test Results compared to improved Thermal Modelling - 2kW of Copper Loss

A second observation was that the end winding and slot winding temperatures, predicted to be somewhat different in the modelling, were in fact measured to be closer during test. This is thought to be again due to the location of the thermocouple in the motor slot. Generally thermocouples may be ‘buried’ in the motor winding, however in this case this was not possible due to fear of the compression process damaging the winding insulation. The thermocouple was therefore placed on the coil face which is open to the stator slot, an area (perhaps similar to the case with the end winding) with no direct thermal path to the stator. This would perhaps explain this discrepancy.

10.4.3 3kW and 4kW Winding Loss Test Results

Figure 10-10 shows a ‘glitch’ in the slot winding temperatures measured, whilst Figure 10-11 shows a similar glitch in the slot winding temperatures. As will be seen in the following section, at 5kW the motor suffered a thermal failure where the thermocouple leads were damaged. It is therefore thought that the glitches observed in the earlier tests are probably early signs of the impending failure of the motor winding interconnections.

10.5 Winding Interconnection Thermal Failure

10.5.1 5kW Winding Loss Test

During the 5kW motor test, the thermocouple in the end winding was observed to fail and the test therefore halted. The motor was disassembled in order to identify the cause of this failure. This was traced to the interconnections between windings and the damage is shown in Figure 10-13.

This failure was a source of concern as it was intended that the motor would be able to operate at loss levels much higher than this, with up to 7.4kW of copper loss and with total motor losses exceeding 8.5kW.

The motor was stripped down and the coils electrically checked using the Baker Instruments tester, repeating testing undertaken in Chapter 9, and found to have no shorts to the casing or turn to turn faults, with all tests passing. This meant that the motor coils had, at least at 5kW of loss, operated acceptably and that the failure was limited to the winding interconnections.



Figure 10-13: Showing damage to the winding interconnections following 5kW winding loss test.

From observations of the damaged motor, it was estimated that the interconnections would have reached temperatures in the order of 400°C or more; for example both PTFE (resistant to 350°C) and silicon saturated glass sleeving (resistant to over 400°C for short periods) had broken down.

10.5.2 Failure Investigation and Mitigation

Two theories were developed in order to explain the failure of the motor interconnections. Firstly that the failures were a result of the type of crimp used and secondly that they were inherent to the use of aluminium conductors in the winding interconnections. A series of experiments were designed, both to understand the failure mode and also investigate a solution to the overheating problem.

Three test pieces were constructed (see Figure 10-14). The first used the standard copper butt crimps used during motor construction. The second used a composite crimp, specially designed for use in copper to aluminium connections. The third also used the

composite crimp, however this time potted with a thermally conductive potting compound.

The composite crimp [119] (see Figure 10-15) was recommended by a specialist crimp supplier and had three features designed to improve its performance. Firstly, it featured both a copper and an aluminium end, friction welded together and with the former intended to crimp to the copper cable and the latter to the aluminium cable. This matching of materials is intended to reduce any effects due to differential expansion between the cable and crimp. Secondly the aluminium part of the crimp was filled with an anti-oxidising compound, designed to prevent oxidation (and therefore an increase in resistance of the aluminium) over long periods of time. Thirdly a specific crimping tool was recommended, featuring a hexagonal crimping die, in order to ensure a tight and even crimp (again see [119]).

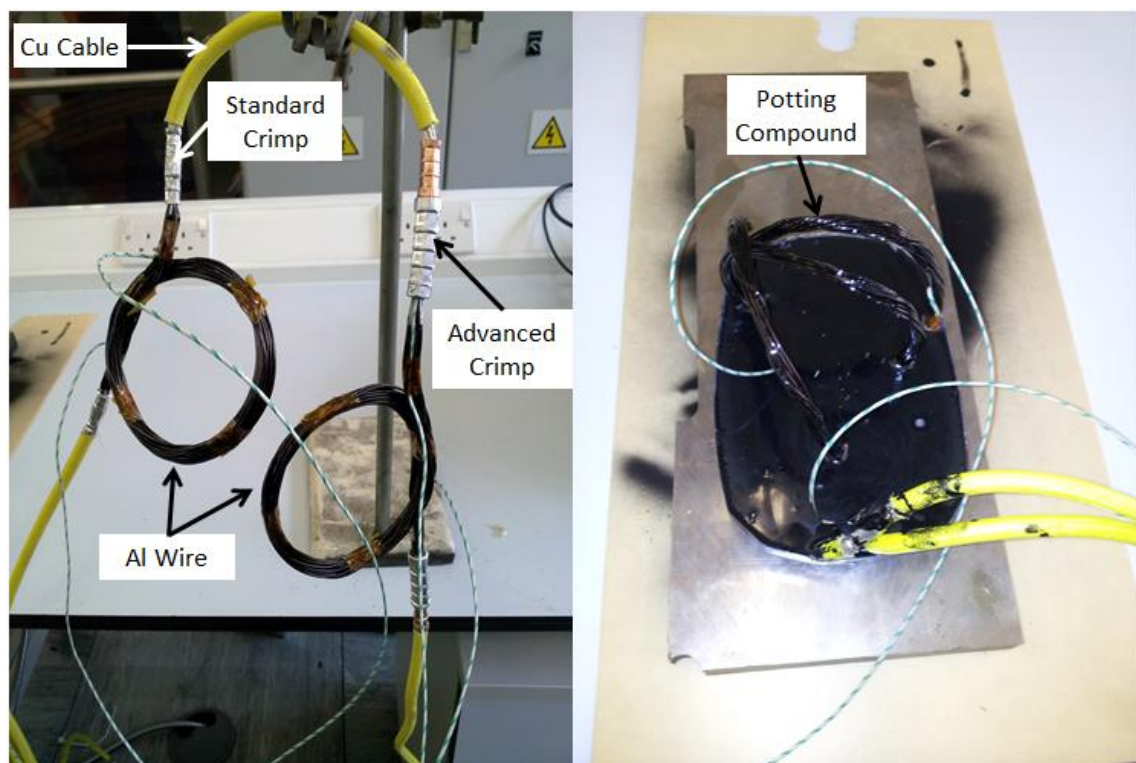


Figure 10-14: Wire and Crimp Thermal Test Pieces. (Left) comparing the performance of standard copper, on the left, and composite Al/ Cu crimps. (Right) test piece potted in a high thermal conductivity polyurethane potting compound.

The potting compound (IRS 3071 [120]), which was also recommended by a specialist supplier, is a high thermal conductivity, 0.75W/(m.K), polyurethane based compound. This material was rated for continuous temperature operation of 125°C, however it was reported to be able to deal with peak temperatures of 200°C. Whilst silicon based potting compounds would have offered higher maximum temperature ratings (275°C), their thermal conductivity was lower at 0.37W/(m.K), meaning higher winding temperatures. It was recognised that the potted test piece was, for reasons of assembly, not completely representative; a much higher ratio of potting compound to conductor was used than would be the case in the electrical machine, meaning that the thermal results would be likely to be somewhat optimistic.

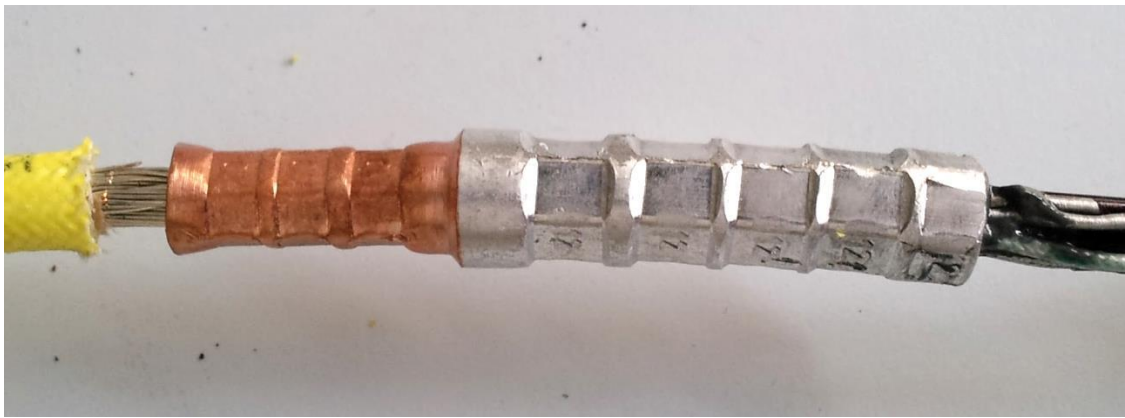


Figure 10-15: Advanced Al to Cu crimp.

A number of tests were undertaken at different current densities, as listed in Table 10-3, with the objective of providing a representative set of test points.

Table 10-3: Crimp test conditions.

Current	Current Density	Comment
100 A _{rms}	5.4 A/mm ²	Equivalent to 150Nm in Prototype SRM
150 A _{rms}	8.1 A/mm ²	
180 A _{rms}	9.7 A/mm ²	Equivalent to 5kW copper loss test point (Section 10.5.1)
200 A _{rms}	10.8 A/mm ²	
250 A _{rms}	13.5 A/mm ²	Equivalent to peak torque (280Nm)

These test conditions were applied cyclically, in order to provide some indication of the impact of thermal cycling on the interconnections; following the tests at higher current

densities, the tests at lower current densities were once more repeated. From these tests a number of findings were made and are discussed in the following sections.

10.5.3 Thermal Ageing of Standard Crimp to Aluminium Wire

It was found that the standard crimped connections to aluminium wire ‘aged’ after only a single thermal cycle, with this effect worsening after two thermal cycles (see Figure 10-16). The figure shows that during the first test, at 100A, after 10 minutes the crimp’s temperature rose to a steady state of 56.7°C (ambient 21°C). After the crimp had been exposed to high temperatures (>200°C) as part of a 200A cycle, the 100A test was repeated and on this occasion the crimp’s temperature rose to 86.4°C after 10 minutes. After a third cycle, the temperature was found to rise to 97.8°C after 10 minutes; this represented an increase in the temperature rise of 215% (temperature rise over ambient) compared to the initial test.

This effect is understood to be due to the rapid oxidation of the aluminium conductor at high temperatures. The raising of the crimp temperature to 200°C or more, during the 200A test, accelerated oxidation so that the crimped connection’s electrical resistance rose very significantly increasing losses and therefore the temperature.

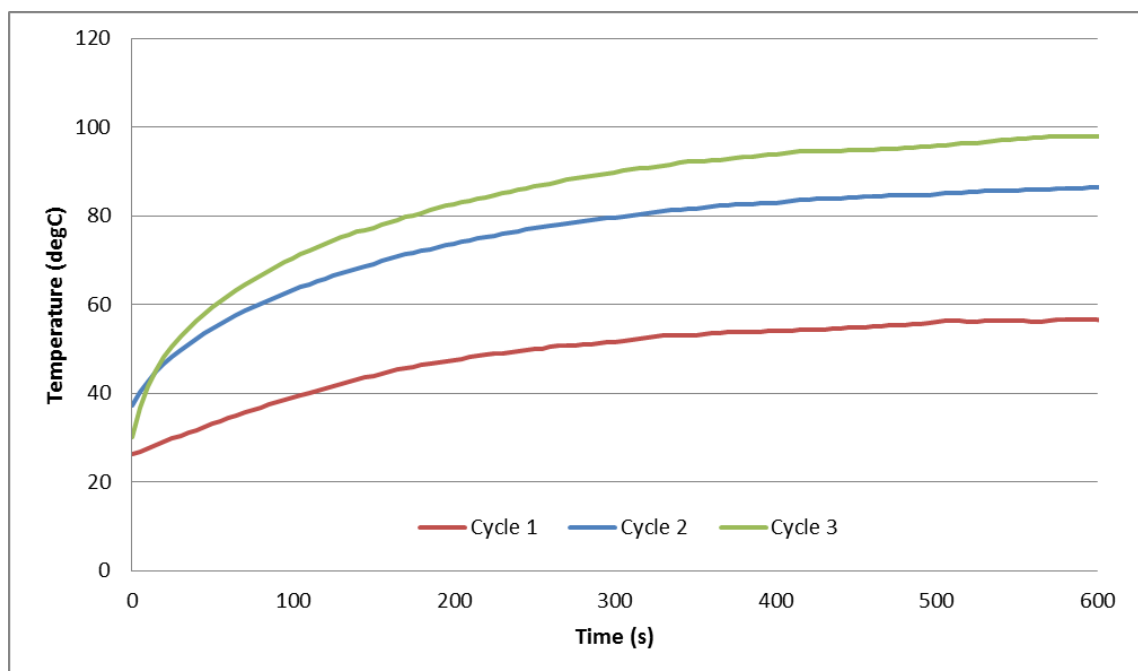


Figure 10-16: Three thermal tests of the same, standard, copper butt-crimp in each case carrying 100A. (Cycle 1) temperature of new butt crimp, (Cycle 2) butt crimp temperature following one cycle of 200A test, (Cycle 3) butt crimp temperature following two cycles of 200A test.

10.5.4 Temperature Gradient between Crimp and Al Wire

The connections were sprayed with a matt black paint, in order to standardise emissivity between the wire, cable and crimp. A thermal imaging camera was then used to compare the temperature in the crimp, aluminium wire and copper cable. It was found that whilst the copper cable was always cooler, there was little difference in temperature between the aluminium wire and the composite crimp. However between the standard crimp and the aluminium wire a significant temperature gradient was observed, particularly in later temperature cycles.

10.5.5 Composite Crimp and Potted Crimp Performance with 100A.

Figure 10-17 shows temperature rise versus time for the standard crimp, composite crimp and potted crimp with an input current of 100A; the third temperature cycle is shown, as described in the previous section.

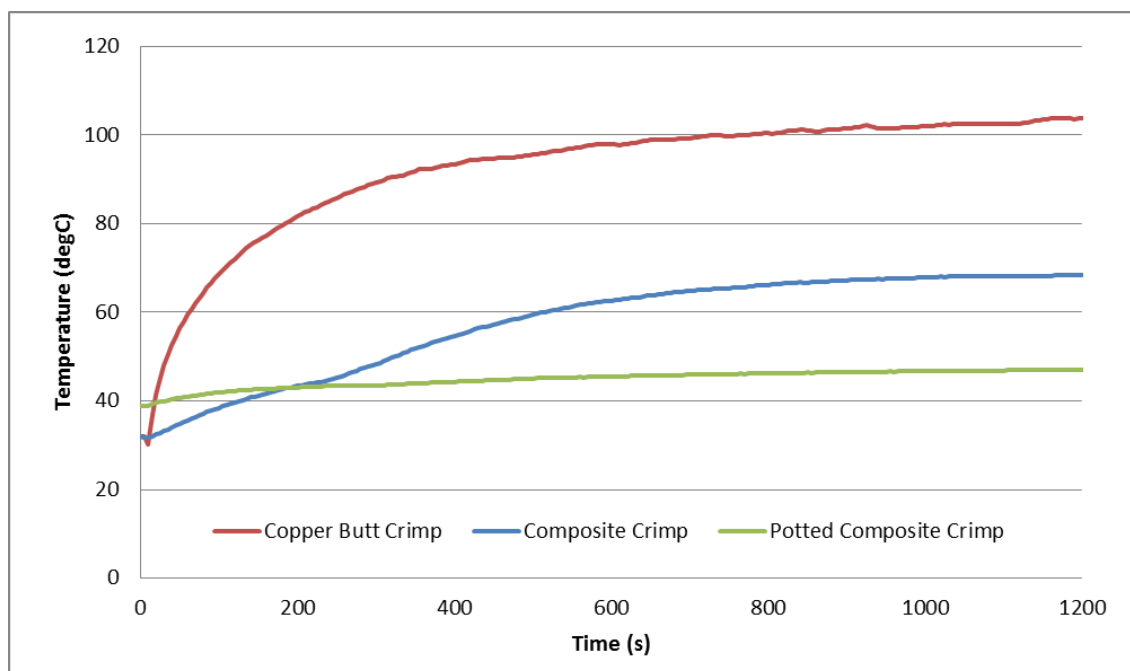


Figure 10-17: Comparison of copper crimp, composite crimp and potted composite performance with 100A input current (3rd test cycle).

The composite crimp was found to perform far better than the standard crimp, after 20 minutes reaching a steady state temperature of 68.4°C compared to 103.8°C for the standard crimp (57% of the temperature rise over ambient of the standard conductor).

The potted crimp achieved even better performance; it reached a temperature of only 47.1°C after 20 minutes, only 32% of the rise observed in the standard crimp.

10.5.6 Composite Crimp and Potted Crimp Performance with 250A.

The performance of the three crimps was also compared at 250A, equivalent to the current required to achieve the MMF to deliver peak motor torque. In line with the approach taken when thermally modelling the motor in Chapter 8, the time was measured for the crimps to achieve a temperature rise of 115°C. This is equivalent to the windings reaching a temperature of 200°C given an 85°C coolant inlet temperature, consistent with automotive requirements.

The results of this test are shown in Figure 10-18. The figure shows that the copper crimp reached 115°C rise in 35 seconds whilst the composite crimp took 150 seconds and the potted crimp 795 seconds. As the motor is designed to be able to achieve peak torque for at least one minute, both the composite and potted crimps would appear to be able to comfortably meet this requirement, even taking into account idealised test conditions.

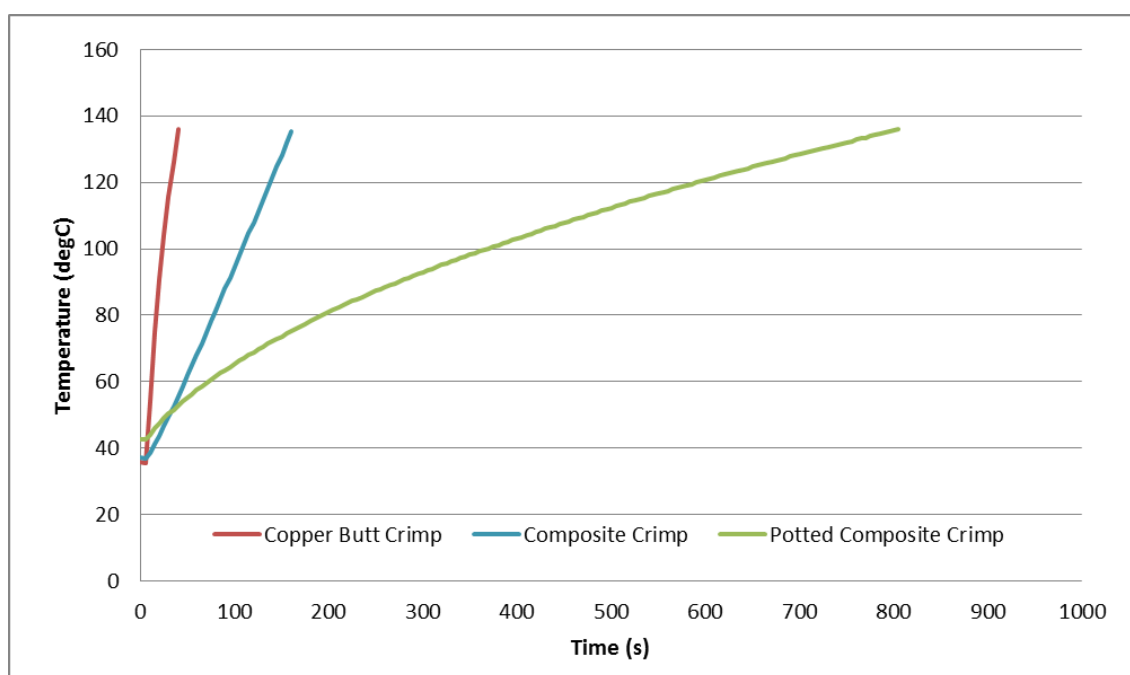


Figure 10-18: Comparison of time for copper crimp, composite crimp and potted composite performance to reach 115°C above ambient with 250A input current.

10.5.7 Duplication of 5kW Thermal Test Conditions.

Finally a current of 180A, equivalent to that used during the failed 5kW test, was passed through the test pieces in order to give an indication of the temperatures reached during the failed motor thermal test. During this test, after 20 minutes, the copper crimp

reached a temperature of 331°C compared to 155°C for the composite crimp and just 65°C for the potted crimp.

10.5.8 Thermal Test Failure Conclusions

As a result of the above testing, it is therefore concluded that the failure of the thermal test at just 5kW of copper loss, compared to the 8.5kW peak loss predicted, was due solely to the use of standard copper crimps to make aluminium interconnections. These crimped aluminium connections suffered from rapid oxidation as the motor temperature rose and this led to thermal runaway, finally leading to motor failure.

However it was found that the fundamental design of the motor, including the use of aluminium conductors, remained sound. The use of either composite crimps or, for an even greater level of design safety, a thermal potting compound, would avoid a repeat of this failure.

10.6 Motor Rebuild

As once stripped down the motor appeared to be largely undamaged, it was rebuilt. However, during the stripping of the coil strands to allow their recrimping a number of strands of two coils broke; it is believed this failure happened due to individual strands having been weakened by the high motor temperatures. This increased the winding resistance of one motor phase, with others unaffected, as shown in Table 10-4.

Table 10-4: Motor phase resistances for repaired motor (20°C).

	Predicted	Phase A Measured	Phase B Measured	Phase C Measured
Resistance	0.046 Ω	0.046Ω	0.065Ω	0.046Ω

Phases A and C were now found to have a lower phase resistance than prior to the rebuild, with resistance in fact being in line with the predictions made in Chapter 8; this is thought to be attributable purely to the use of the composite crimps as the winding interconnections were of similar length to those used in the original build. Phase B has a much higher phase resistance, this is attributable to the damage previously described to two of the coil terminations.

In order to reduce the temperature rise in the interconnections, it was decided to pot the motor end windings using the polyurethane compound tested in Section 10.5. The composite crimps were used to make the motor terminations. Given the fragility of the repaired motor, the terminal design was modified so that each winding termination was individually and rigidly supported (see Figure 10-19), preventing any flex and therefore further damage.

It was also found that the plastic end-cap inserts, used to protect the coils from the end of the lamination stack, had in some cases been deformed due to the high motor temperatures. These had led to the rotor jamming in the stator. Once the rotor had been removed, the plastic inserts were machined in order to ensure they would not foul the airgap during further testing (Figure 10-20). In order to avoid this problem in future, a design change would be required to these parts; this would see their material changed to higher temperature PTFE and the design changed in order to allow a 1mm clearance from the inner face of the end-cap insert to the airgap.

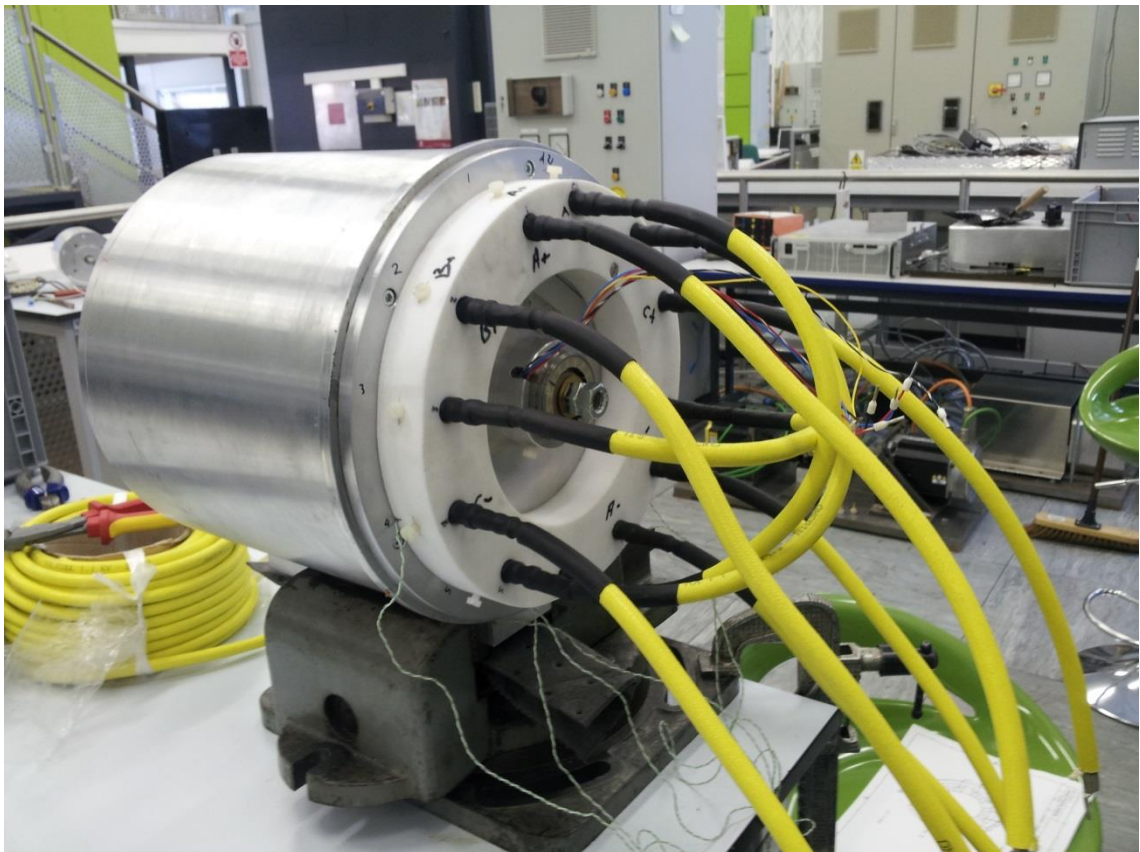


Figure 10-19: Repaired Motor Stator showing new winding termination scheme.



Figure 10-20: (Left) deformed blue-coloured stator end-cap insert and (right) end-cap inserts being machined away as part of motor repair.

10.7 Motor Test: Optimised Operating Point

A university developed, 250kVA asymmetric half bridge converter⁵ was connected to the repaired motor (Figure 10-21). The 80kW Segmental Rotor SRM was used as a test bed for this converter, allowing the hardware and software to be improved as well as allowing the generation of test data to support motor validation.



Figure 10-21: Repaired motor on test rig with University developed asymmetric half bridge converter shown in the background.

⁵ My thanks to Dr Chris Morton, Dr John Bennett, Dr Mingyao Ma and David Winterbourne for their support in the development and construction of this drive.

For various reasons, explained in the following section, the performance testing possible on this test rig was limited, however it was possible to collect data relating to friction and windage as well as at the optimisation operating point, previously discussed in Chapters 7 and 8: namely 3500rpm 40Nm.

10.7.1 Dynamic Test Limitations

For a number of reasons the scope of dynamic testing was limited:

- Testing was limited to less than 90Nm (by the dynamometer) and less than 60kVA (by the DC power supply). The supply could provide a maximum current of $100A_{\text{rms}}$ at 600V;
- For safety reasons it was decided to limit the peak operating speed of the motor to 50% design speed. This was due to there being no opportunity to undertake a controlled, high speed spin-test on the rotor to ensure its mechanical integrity prior to being used on the dynamometer, where any failure would raise safety concerns;
- The damaged motor winding (Phase B) would limit the level of current that could be carried through that winding to about 2/3 of its rated $250A_{\text{rms}}$. However, as maximum winding current would in any case be limited by the supply to $\sim 33A_{\text{rms}}$ per phase, this would not limit motor performance unduly;
- Finally the asymmetric half bridge drive was a newly designed unit and as such suffered from a number of power device failures during testing⁶. Whilst, during the drive development activity, a number of tests of the Segmental Rotor SRM were undertaken near the extremes of the rig's capabilities, these were not instrumented in order to provide detailed motor performance data. Unfortunately, due to diode failures in a number of converter half bridge modules, the instrumented motor testing was limited to operation with only two phases active.

⁶ The design of the asymmetric half bridge converter is beyond the scope of this thesis, however a number of failures of half bridge conduction diodes were experienced during motor testing at 600V. Further analysis has shown that these failures were due to limitations with the hardware protection of the drive coupled to developmental software. The drive software was designed to firstly set an encoder offset, such that zero electrical degrees aligned with the unaligned position of Phase A; it appears likely that this process was not always successful. The drive was then operated with the dynamometer already spinning and due to the alignment error the current advance was applied at the wrong angle, causing the motor to regenerate and produce an over current in the half bridge diode, before the overcurrent protection was able to limit the fault. Unfortunately eliminating this failure mode would require complete redesign of the control board which would not be possible until after the completion of this project.

10.7.2 Friction and Windage Tests

Friction and windage had not been included in the performance predictions modelled in Chapters 7 and 8; it was considered to be somewhat difficult to predict, given the unusual design of the segmental rotor assembly. As a result it was important to measure friction and windage to allow it to be corrected for in the dynamic test results.

The motor was spun, using the dynamometer, in 600rpm steps to 5400rpm. The torque at each operating point was then recorded and the power calculated.

Losses due to friction and windage can be expressed as:

$$P_{fw} = k_f \cdot \omega + k_w \cdot \omega^2 \quad (10-1)$$

Where k_f is the torque due to friction and k_w the windage constant. These constants can be estimated by line fitting the above expression to the experimental results; k_f is estimated as 0.35Nm whilst k_w is 0.15mNm/rad.s⁻¹. This is shown in Figure 10-22, with the curve fitted data being extrapolated to 10,800rpm.

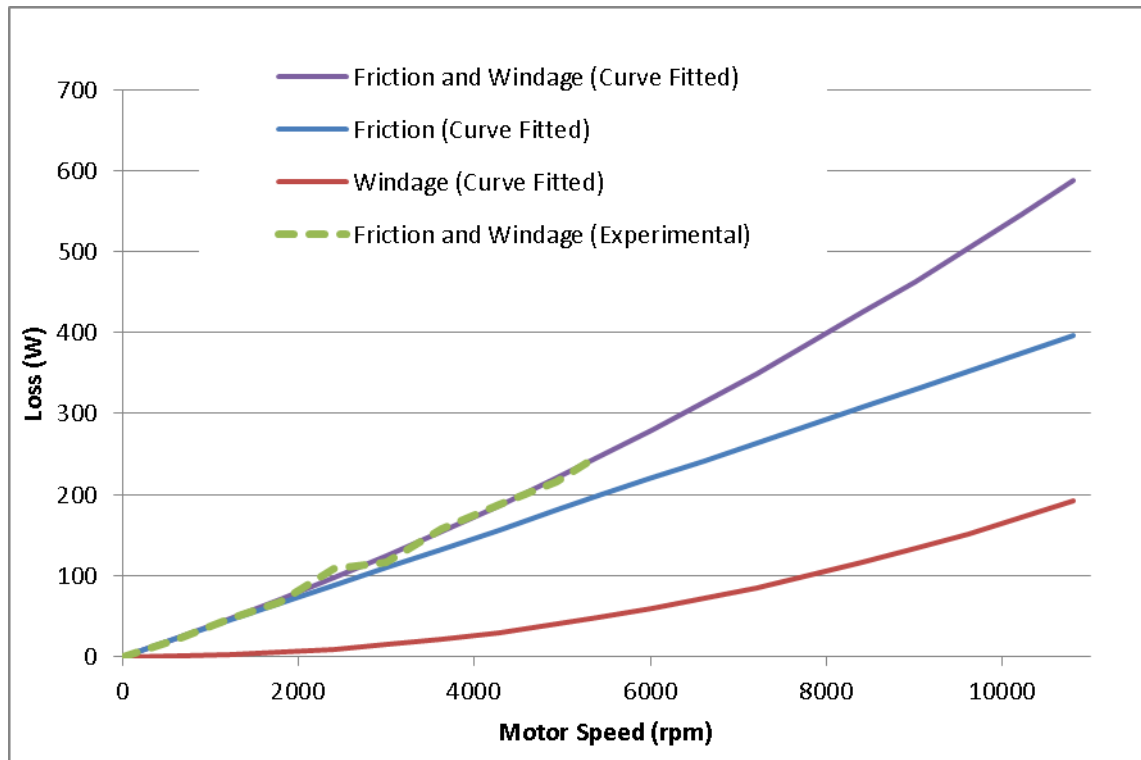


Figure 10-22: Friction and windage from experimental measurement and showing curve fitted estimations of friction and windage components.

Due to the complexity of the rotor design it was unclear what the final windage losses would be at higher motor operating speeds, however this analysis would suggest that windage is low, only 192W at 10,800rpm. This would suggest the current rotor design is acceptable and, from a loss perspective, would need no infilling between rotor segments.

10.7.3 Tests at 3500rpm, 40Nm

Testing was undertaken to confirm the performance of the motor at this key operating point; this however was limited to three runs at the required operating point due, ultimately to converter reliability. As only two converter phases were available, Phase A and C of the motor were driven, with the damaged Phase B being left open circuit. In order to allow a representative test, the torque requirement was reduced by a third to 27Nm. This would mean that the two remaining phases would produce the same torque per phase as would be the case were all three phases operating at 40Nm. Phase currents and voltages along with motor position/speed and torque were recorded on a high bandwidth data logger during the testing, with 100 electrical cycles (10 motor rotations) being measured during each test. Equally the motor temperatures (see Figure 10-7, presented earlier in this Chapter, for thermocouple locations) were continuously logged.

The converter was operated with a 600V DC Link and with a 10kHz Pulse Width Modulation (PWM) frequency. An encoder capable of 4096 lines per revolution was used to provide position control, giving a resolution of better than $1^\circ_{\text{(electrical)}}$. The converter operated under a simple bang-bang control scheme with hard switching (using of both full positive and full negative DC link volts during current control); this control scheme was chosen as it was identical to that used during finite element modelling of the motor. The converter allowed the phase current control level to be set as well as allowing advance and conduction angles to be adjusted individually.

The dynamo was spun to approximately 3500rpm⁷ and, once stabilised, then power was switched to the Segmental Rotor SRM. Initially with advance angle set to zero and conduction angle to 120° , the phase current demand level was slowly raised until the motor entered voltage control; firstly the advance angle and then conduction angle were adjusted so that torque was maximised and finally the demand current set so the desired

⁷ Due to a slight resonance in the coupling to the dynamometer at 3500rpm, the speed was increased slightly to above 3530rpm.

torque (27Nm) was achieved. The final advance angle was 5° (electrical), the conduction angle was 130° (electrical) and the current limit was set to 61A.

Measurements were then taken with the high-bandwidth data logger. This test was repeated three times (on the first two times from cold, and the third after 15 minutes of running). Representative current and voltage waveforms (Test 1) for Phases A and C are shown in Figure 10-23 and Figure 10-24. The two phase currents are compared in Figure 10-25. A plot of flux linkage (calculated as described in Chapter 4) vs phase current, overlaid on the experimentally measured aligned and unaligned flux linkage characteristics (from Figure 10-4), is provided for Phase A in Figure 10-26 and Phase C in Figure 10-27. Table 10-5 summarises the results of the three tests undertaken. As for the testing undertaken in Chapter 6, the accuracy of efficiency measurements is considered to be of the order of $\pm 2\%$.

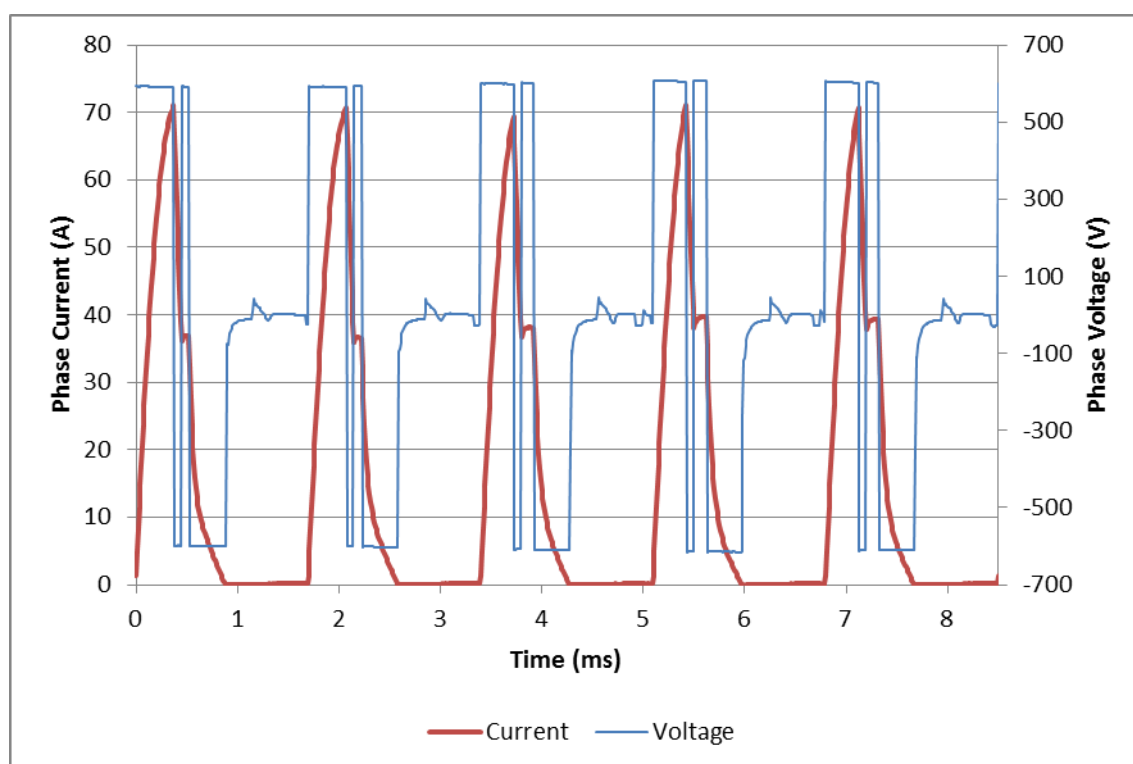


Figure 10-23: Phase A phase voltage and phase current. The motor is operating with a 5° (electrical) advance angle and 130° (electrical) conduction angle and with a 61A current limit.

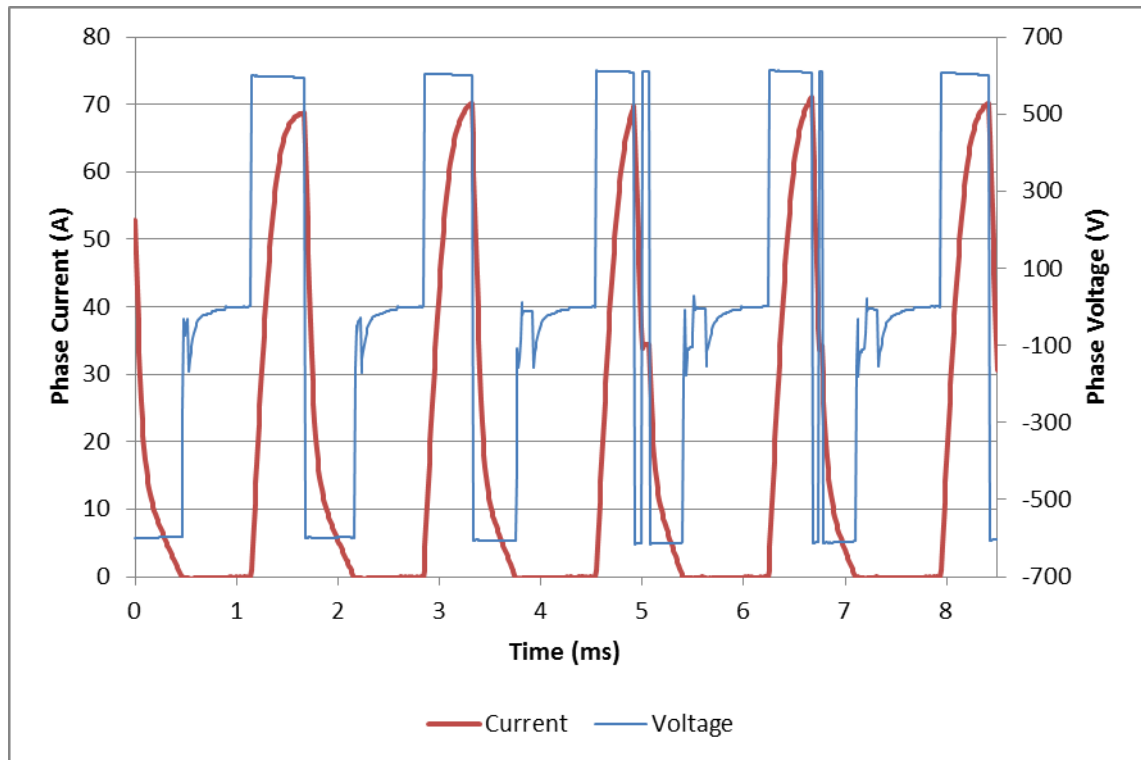


Figure 10-24: Phase C phase voltage and phase current. The motor is operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.

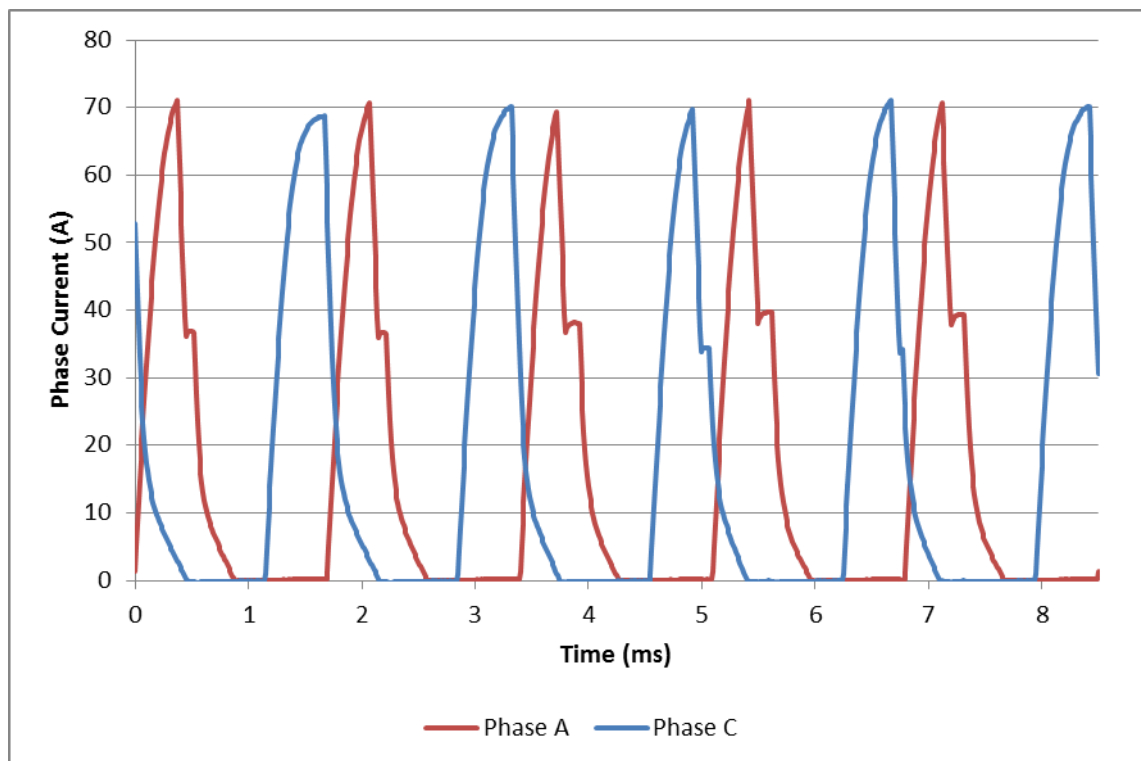


Figure 10-25: Phase A phase current and Phase C phase current. The motor is operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.

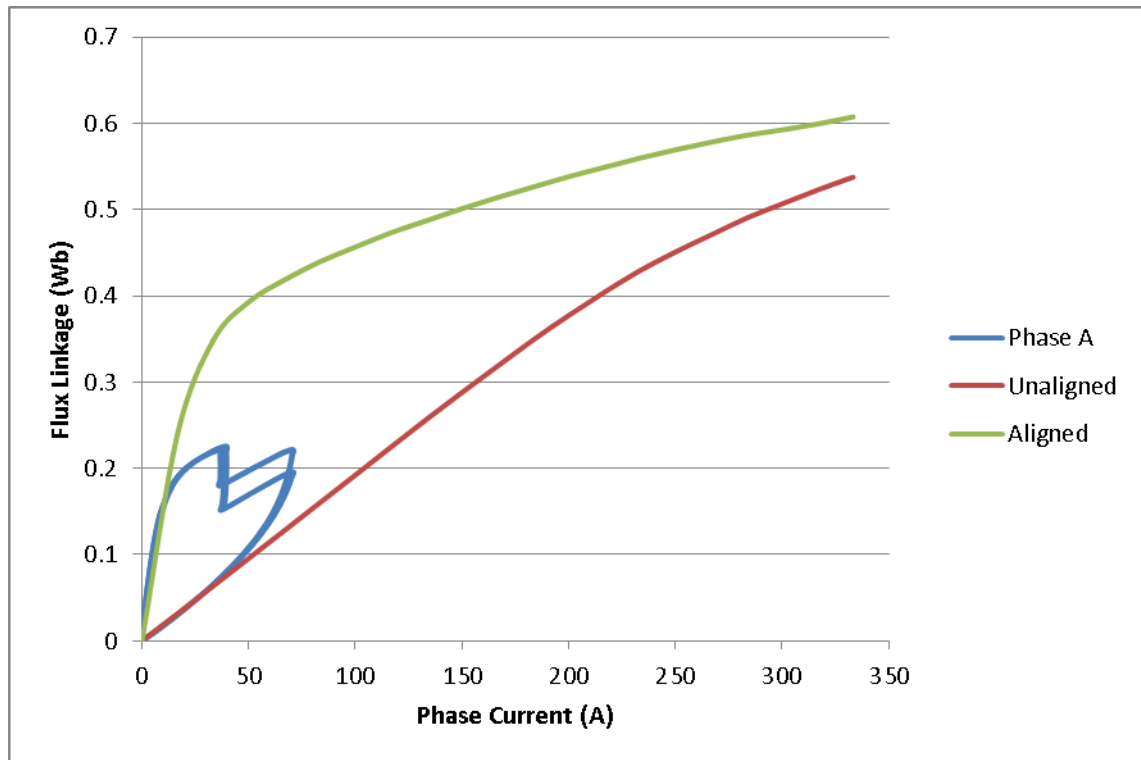


Figure 10-26: Phase A flux linkage versus current (5 electrical cycles) compared to aligned and unaligned flux linkage characteristics; operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.

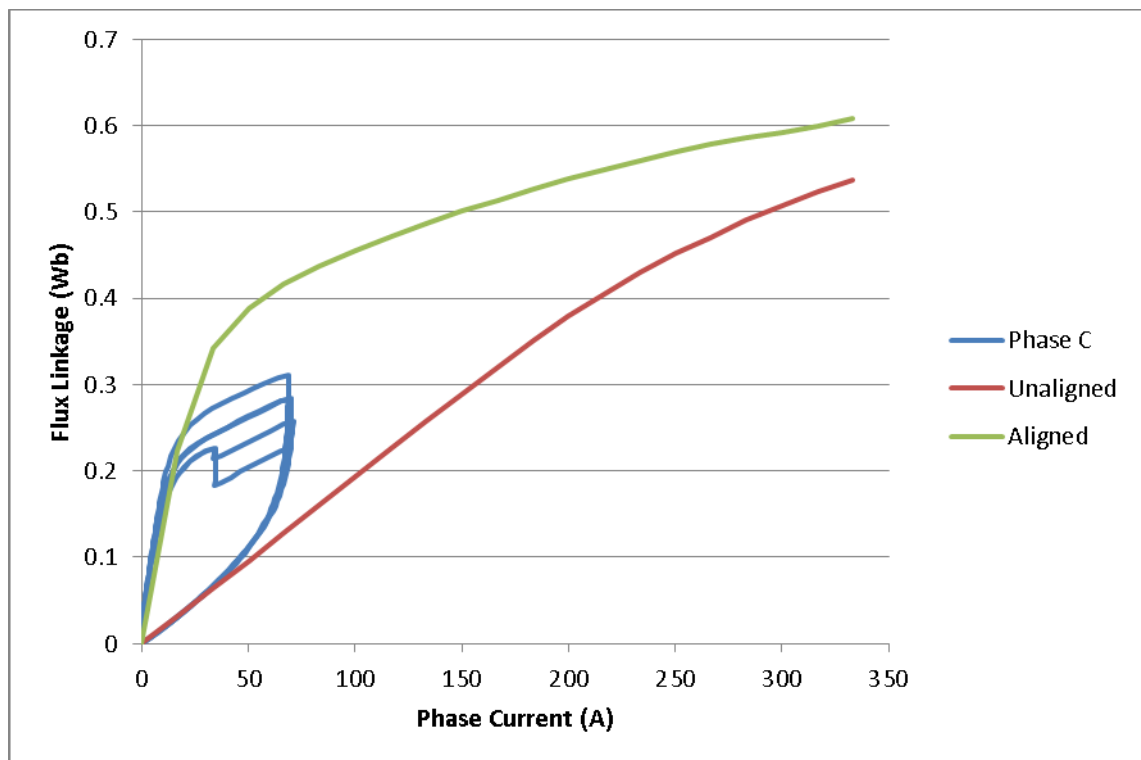


Figure 10-27: Phase C flux linkage versus current (5 electrical cycles) compared to aligned and unaligned flux linkage characteristics; operating with a $5^{\circ}_{(\text{electrical})}$ advance angle and $130^{\circ}_{(\text{electrical})}$ conduction angle and with a 61A current limit.

Table 10-5: Results of Motor Tests at 3500rpm, 40Nm compared with modelling.

	Finite Element Modelled ⁽¹⁾	Experimental Test 1	Experimental Test 2	Experimental Test 3
Running time from cold	Finite Element	~3min	~3min	~15min
Speed	3,500rpm	3,621rpm	3,529rpm	3,529rpm
Torque	26.2Nm	26.6Nm	26.1Nm	27.0Nm
Demand Current	50A	61A	61A	63A
Advance Angle	25°	5°	5°	5°
Conduction Angle	170°	130°	130°	130°
RMS Phase Current	29.5A	26.2 A	29.7 A	29.5A
Mechanical Power⁽²⁾	9,646W	10,088W	9,648W	9,995W
Electrical Power	10,168W	11,338W	10,861W	11,828W
Efficiency	95.0%	88.9%	88.8%	84.5%
Peak Winding Temp (slot)	150°C (assumption)	30.2°C	30.2°C	52.6°C
Peak Winding Temp (end)	150°C (assumption)	26.8°C	26.8°C	35.8°C
DC Winding Loss⁽³⁾	134W	66W	84W	87W
Other Losses⁽⁴⁾	389W	1,185W	1,129W	1,746W

Notes 1: Taken from Chapter 8, Table 8-4, Case 3. Results are revised for two phase operation.

2: Experimental mechanical power is corrected for friction and windage.

3: Copper loss is calculated from RMS current and temperature corrected phase resistance.

4: Including Iron losses, AC winding losses, rotor core eddy current losses.

The RMS currents predicted by modelling and for Tests 2 and 3 are very similar, though the advance and conduction angles are different. Whilst the $25^{\circ}_{(\text{electrical})}$ advance angle was tried with the prototype motor it was not found to operate well. This is likely due to the higher ‘switching frequency’ assumed in the finite element modelling; the model was based on 60 time steps per electrical cycle, with voltage switching being possible at each time step. This is equivalent to a 35kHz PWM frequency, giving much finer control of the current level. With the lower, ‘real world’ 10kHz switching frequency the larger advance angle and longer conduction period proved less efficient than predicted. The 10% lower rms current in Phase A when compared to Phase B (see Figure 10-25) is due to the same issue, with the ‘real world’ voltage switching leading to lower than intended currents in Phase A and an imbalance between the phases .

In terms of winding losses, the modelling assumed a 150°C winding temperature; this high value was selected specifically to allow some safety margin between modelled and experimental winding losses, with modelled losses therefore being 70% higher than the test data. If the finite element modelled winding temperature is corrected to 29°C , much lower than the 150°C assumed during modelling but in line with the winding temperature for the two test cases, then copper losses become 61.4W, more comparable with those measured experimentally. However the 29°C winding temperature is not representative of the system in continuous operation, in particular with the required 85°C coolant inlet temperature. Unfortunately, as will be seen, it was not possible to run the motor continuously until thermal equilibrium was reached and so the likely, maximum steady state winding temperature for this operating condition is unknown.

It is not possible to separate out the other sources of loss in this Segmental Rotor SRM as the same armature field is responsible for iron losses, AC losses in the windings and also any eddy current losses in the aluminium rotor support. These other losses are, however, very significantly higher than had been predicted, being on average 964W higher than modelled. As these losses exclude copper loss, it must therefore be the case that the additional losses are due to one of the following factors: poor experimental measurement accuracy, higher than assumed iron losses, additional losses in the aluminium rotor support, additional AC losses in the windings or other ‘unexpected’ losses elsewhere in the machine.

Poor measurement loss will not be considered further. Whilst this could be in the order of $\pm 200\text{W}$ at this power level, this is not sufficient to explain the discrepancy from modelling. It is not thought that iron losses, at least in the stator, were substantially higher than predicted, with stator temperatures not being unexpectedly high. Other, significant ‘unexpected’ losses will also be discounted as being unlikely.

It is also thought unlikely that the source of this additional loss was related to AC losses in the stator windings. Whilst the temperature rise during testing was higher in the slot (where these AC losses would be most prevalent) than in the end windings, this could already be accounted for. It was predicted by modelling (Chapter 8) that there would be some AC loss in the slot, this being estimated to be circa 14% of the DC copper loss at the test speed. This would lead to increased heating in the slot when compared to the end-windings. This effect was also likely to be compounded through the use of the thermally conductive potting compound encasing the end windings. This potting will have provided both a good thermal interface to transfer heat from the end windings as well as offering a large thermal mass. After only a few minutes of testing, this mass would not have reached thermal equilibrium, also explaining the higher winding temperatures in the slot.

Providing evidence that this additional loss may in fact be traced to eddy currents in the aluminium rotor support, Test 3 is worthy of further investigation. This test stands out as having much lower efficiency than either Test 1 and Test 2. As can be seen in Figure 10-28, which presents the temperature trace relating to Tests 2 and 3, this third test was undertaken just as the temperature of the thermocouple in the middle of the Phase A slot started to rapidly increase in temperature. This was accompanied by increased motor vibration and, as shown in Table 10-5, a decrease in efficiency of 4% (though interestingly the copper loss did not increase significantly). The motor was allowed to run for a further 30-60 seconds before being stopped and an investigation undertaken.

10.7.4 Rotor Expansion into Stator Bore

Once the motor was stopped, it was found that the rotor had jammed in the stator housing. However after a few minutes of cooling it was found to run free once more. This led to the conclusion that the aluminium laminated rotor support had expanded more than had been assumed from the modelling described in Chapter 8. The

aluminium rotor support was suspected over other components due to its novelty and high coefficient of thermal expansion.

The motor was stripped down and inspected; Figure 10-29 shows clear witness marks where the rotor has fouled the stator at around the middle of its axial length. The marks showed both a small level of wear to some rotor segments and the stator bore as well as staining, probably due to high temperatures caused by friction between rotor and stator. The staining was observed around the full periphery of the rotor and around the full bore of the stator. This would explain the response of the thermocouple in the Phase A stator slot; intended to measure coil temperatures in the slot, it was located at the axial mid-point of the stator, towards the slot opening. It is therefore likely that the considerable temperature rise was a direct result of heat transfer from the hot rotor as well as from the friction between stator and rotor. The additional losses in Test 3 are therefore likely to be due to this friction; copper losses perhaps not increasing significantly (as would be expected to provide increased torque to overcome this friction), because the airgap had narrowed, increasing torque density.

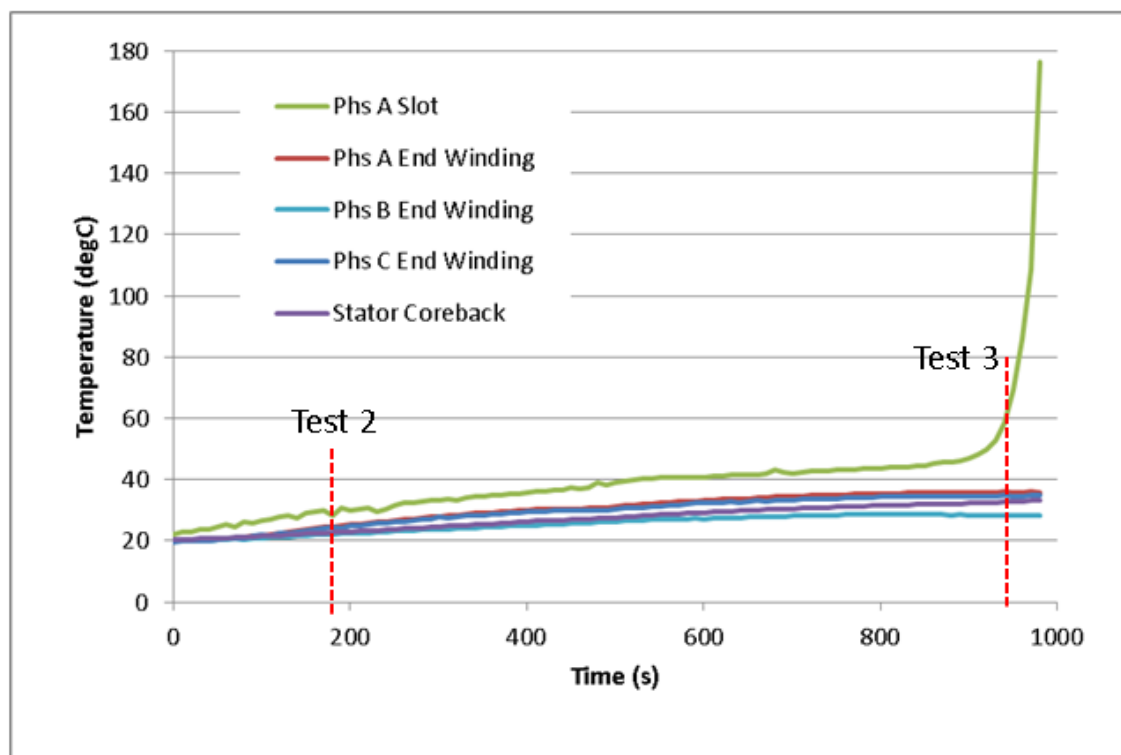


Figure 10-28: Temperature rise observed during Test 2 and Test 3 (see Table 10-5)

It was thought that there were two possible causes of this failure. Firstly it is likely that the temperature and therefore losses in the rotor support were much higher than had been predicted. The additional, 964W of ‘other losses’ (Table 10-5) could potentially be traced to higher than predicted eddy current losses. This is certainly a possibility as the finite element modelling of these losses was based on a simplification of the motor’s operation. As was discussed in Chapter 8, to decrease the solution time, a finite element model of a single coil pitch was considered and the rotor was held fixed in the unaligned position whilst the coil was excited with a representative current waveform. However as only 2W of total eddy current loss in the rotor was estimated at this speed, it is perhaps likely that with such a large increase other factors must also be considered.



Figure 10-29: Witness marks on rotor and stator following Test 3.

As was described in Chapter 9, the aluminium rotor support laminations were insulated using an aerosol based, acrylic lacquer. Whilst this lacquer was advertised as being rated up to 150°C operating temperature, further research has shown that it is likely that 50°C is more realistic. As the thermal testing saw sustained, high temperatures in the motor it is likely that the lacquer coating was broken down and its electrically resistive properties lost. This would therefore have reverted the rotor support to something like a solid form, losing the benefits of lamination and therefore dramatically increasing losses. Unfortunately it is impossible to conclusively prove this without destroying the

rotor, however a visual inspection of the rotor support does confirm that the lacquer coating has indeed been lost from all visible areas.

A second possibility is that the thermal modelling of the rotor support had made one or more invalid assumptions, meaning that there was a larger heat build-up than considered for a given loss. This is again possible as the thermal modelling of the rotor has not been validated. Equally the assumptions in terms of heat loss from the rotor were very approximate, with all heat being lost either by conduction through the shaft or by convection across the airgap. These are perhaps problematic assumptions as there will probably be significant convection axially from the rotor when the machine is operating, with the rotor segments and balancing masses creating a circulating airflow around the case. That the centre of the rotor had expanded more than the axial ends suggested that heat was being retained in the core of the rotor, but lost at the ends; this also suggested that convection cooling could be playing a role in the removal of heat from the rotor. Equally this ‘bowing’ of the rotor, towards its centre, had not been predicted by the modelling, potentially because the modelling software used had not been able to model anisotropic thermal conductivity in the rotor support, where the support would have had lower conductivity axially due to the use of lacquered laminations.

In order to confirm the first possible cause, whether the additional motor losses could alone contribute to the closure of the airgap, the airgap closure modelling was repeated for this condition. This modelling was undertaken in line with the baseline assumptions discussed in Chapter 8, other than being modified for two phase operation and with the thermal conductivity of the slot liner increased as discussed earlier in this chapter. A number of model runs were undertaken to understand the sensitivity of the rotor core to heating within the rotor support as well as, for comparative control purposes, heat transfer out of the rotor support. Table 10-6 summarises the results of these model runs.

It is therefore clear from these results that should the rotor support be experiencing eddy current losses of the levels predicted, then this would result in the closure of the motor’s airgap. It is also clear that doubling the thermal resistance of one of the main heat transfer paths out of the rotor had a lesser effect.

Whilst it seems likely that the use of an inappropriate lacquer may therefore be responsible for this failure, given the safety implications associated with a sudden lock-up of the rotor it is also wise to consider alternative design solutions.

Table 10-6: Airgap closure test cases based on modelling developed in Chapter 8. Design airgap length at 20°C is 0.35mm.

	Baseline	Case 1	Case 2	Case 3
Loss in Rotor Support	2W	964W	2W	964W
Thermal resistance of Rotor shaft and bearings	4.5°C/W	4.5°C/W	10°C/W	10 °C/W
ΔT stator core to rotor support	16°C	162°C	17°C	176°C
Airgap length decrease	0.1 mm	0.34mm	0.10mm	0.35mm

Firstly it would perhaps instead be a better solution to replace the aluminium core with a non-magnetic steel, for example the austenitic stainless steel grade, 316. Table 10-7 compares this material's key features, applicable to its use in the rotor support, with those of aluminium. Its strength (particularly when cold rolled) is twice as high as aluminium, making it suitable for providing the required mechanical support. The conductivity is 26 times lower, reducing eddy current losses proportionally (therefore from 964W to 37W) and therefore also heating. The steel's coefficient of thermal expansion is also 40% lower than for aluminium, this would reduce expansion of the support, even for the same operating temperatures. These advantages are however somewhat offset by 316's thermal conductivity which is about 14 times lower than aluminium, reducing the transfer of heat from the rotor.

Table 10-8 shows how the use of this stainless steel might help to resolve airgap closure: 'Stainless Case 1' represents the expected rotor support eddy current losses if stainless steel were used and 'Stainless Case 2' the difference should the losses remain as per the aluminium rotor support.

Table 10-7: Comparison between the properties of Stainless Steel and Aluminium for use in a Segmental Rotor SRM rotor support [121].

	Stainless Steel (316, cold rolled)	Aluminium (6082-T6)
Ultimate Tensile Strength	620 MPa	310 MPa
Density	8000 kg/m ³	2770 kg/m ³
Electrical Conductivity	1.35e6 S/m	3.53e7 S/m
Thermal Conductivity	16.3 W/m/k	230.0 W/m/K
Coefficient of Thermal Expansion	16.0 $\mu\text{m/m/K}$	23.1 $\mu\text{m/m/K}$

Table 10-8: Airgap closure test cases, contrasting the use of Aluminum and 316 stainless steel in the rotor support. Design airgap length at 20°C is 0.35mm.

	Aluminium Case 1	Stainless Case 1	Stainless Case 2
Loss in Rotor Support	964 W	37 W	964 W
Thermal resistance of Rotor shaft and bearings	4.5°C/W	4.5 °C/W	4.5°C/W
ΔT stator core to rotor support	162 °C	21 °C	197 °C
Airgap length decrease	0.34 mm	0.07 mm	0.30 mm

As a negative, the higher mass density would, however, increase the mass of the motor by 4.4kg, assuming that the rotor support design remained unchanged. However, given the higher strength of the stainless steel it would be possible to minimise this increase through further structural finite element analysis of the fir tree root structure.

A second solution to the problem of airgap closure would be to decrease the thickness of the rotor support laminations, further reducing the eddy current losses. Research indicates that stainless steels, such as 316, can be purchased in very thin sheets, down to thicknesses of 0.1mm or even less, enabling this approach.

10.7.5 Other Qualitative Test Observations

As well as the quantifiable testing already described, a number of qualitative observations were also made during motor testing:

During commissioning testing of the power converter, the motor was operated (three phases functioning) up to 5000rpm, 57Nm (29.9kW), using a 500V DC supply. At this operating point the controller was set to provide 85A peak (though the phase current was lower than this, with the motor operating in voltage control) with a conduction angle of 150° . As discussed previously in the footnote on page 226, it is difficult to know what the real advance angle was, however 65° was selected in the interface. Under these operating conditions, this appeared to be close to the limit of achievable power, however this was due not to the motor but to the DC power supply having reached its current limit at this operating point.

At higher speeds the operation of the motor with a 10kHz Pulse Width Modulation (PWM) frequency became somewhat problematic. It was clear that the advance angle being applied by the controller between different electrical cycles was varying significantly; at 3500rpm the electrical frequency is 583Hz meaning that there would only be ~ 17 PWM cycles per electrical cycle. This in turn led to a maximum quantisation error of $21^\circ_{(\text{electrical})}$, very significant both when the setting of an accurate advance and conduction angle are considered. At 10,500 rpm, where the electrical frequency is 1.75kHz, this would be even more significant, with quantisation errors of $63^\circ_{(\text{electrical})}$. Work is therefore ongoing to resolve this issue by increasing the sampling rate of the drive to 100kHz, whilst still allowing a maximum switching speed of 10kHz. This allows the accuracy of the switch-on angle to be increased to just $2^\circ_{(\text{electrical})}$. At higher speeds (where single pulse voltage control is in operation) this will also resolve the conduction angle quantisation error (the width of the single pulse will be wider than $1/10\text{kHz} = 100\mu\text{s}$, allowing its accurate switch-off). However at lower speeds, where current control is still required, the resolution of the switch-off angle would be reduced to the quantisation error ($100\mu\text{s}$).

Finally the motor was found to be noisy (requiring ear protection in the test cell) under most operating conditions; this would be a real concern when used in an automotive application, where noise, vibration and harshness are a significant concern. However the early experiments implementing the 100kHz sampling controller appeared to result in a

significant reduction in the motor's noise levels, though insufficient testing has been done to reach a conclusive conclusions. Equally no attempt has yet been made to reduce the noise from the motor through the use of control techniques such as these discussed in [122] and [123]; however acoustic noise will clearly remain a significant challenge.

10.8 Conclusions

The validation of the prototype, 80kW Segmental Rotor SRM has allowed a number of valuable conclusions to be drawn as well as suggesting a number of design changes.

Static testing has shown that the motor losses, for a given torque, will be higher than had been anticipated. In order to achieve peak torque (280Nm), the motor will require 11% more current than predicted by modelling. Assuming a phase resistance of $0.046\ \Omega$ at 20°C (as per the rebuilt motor), if this static result is used to scale the predicted motor losses at base speed / peak torque, this would result in an increase in copper loss of 23% at base speed to 9.1kW from the predicted 7.4kW (with these losses assuming a winding temperature of 150°C). On the further assumption that the airgap will close during normal operation to at least the nominal 0.3mm, copper losses would be expected to reduce to 8.2 kW, 11% higher than predicted. This remains a significant reduction in performance. From electromagnetic finite element model validation, it is suggested that the increase in loss is due to a lower level of peak magnetic saturation of the electrical steel than specified in the modelled B-H curves. This is not thought to be attributable to manufacturing effects which, according to information provided by partner Tata Steel, would normally affect losses and permeability rather than saturation. Work is now planned as part of an ongoing, UK Technology Strategy Board funded research project, supported by Tata Steel, to better understand this phenomenon (see Chapter 12 for details).

Partial validation of the thermal model has also been achieved; this has been based on experimental work involving the injection of fixed losses into the motor's windings. This tentatively suggests that, assuming an 85°C coolant temperature, the motor windings would not exceed 200°C if the motor is operated at full power for over 60 seconds in any part of the speed range; this meets the requirement set that peak power be achievable for at least 30 seconds.

Thermal testing also suggests that potting (or some form of active cooling) of the motor end windings may be essential in order to ensure motor reliability. It is also clear that, in general, the design of the winding terminations is critical in an aluminium wound motor; in particular care needs to be taken to ensure that terminations do not oxidise leading to thermal runaway.

Following the thermal failure of the motor, it has been rebuilt and tests undertaken at 3500rpm, 40Nm; the selected operating point for motor optimisation. These tests have shown that the prototype motor was much less efficient than had been predicted. This however has been shown to be most likely related to much higher than expected eddy current losses in the aluminium rotor support; these much increased losses are in turn thought to be due to breakdown of their insulating, acrylic lacquer during thermal test. It has however been proposed that future Segmental Rotor SRMs of this power rating use a non-magnetic, stainless steel rotor supports in place of aluminium. This is to reduce the risk of the rotor becoming jammed in the stator.

Other observations have also been made about the performance of the motor during test. Perhaps the most significant has been to highlight the importance of refining motor control in order to ensure that the Segmental Rotor SRM may be acoustically acceptable for use in an automotive traction application.

Motor testing has been limited in scope due to restrictions in test equipment, failures in the power converter used to drive the machine and due to failures of the motor itself. As such it is not yet possible to draw conclusions about the full performance envelope of the machine. However further prototype work will be undertaken as part of the Technology Strategy Board project discussed above (see Chapter 12 for more details). This will see the construction of further Segmental Rotor SRM prototypes, these will include the changes proposed as part of this chapter.

Chapter 11. Conclusions

This thesis has described research into the use of the Segmental Rotor Switched Reluctance Machine (SRM) topology in a high power, automotive traction application. This development of this has addressed a number of key objectives:

- 1) To eliminate rare-earth magnetic materials and copper, through substitution by aluminium, from the electrical machine, reducing its costs whilst also improving its environmental footprint;
- 2) To explore the suitability of the Segmental Rotor SRM for use in automotive traction;
- 3) To design a motor which takes into account the requirement for cost effective, high volume automotive manufacture;
- 4) To develop, through the use of optimisation techniques, this technology so that it matches as closely as possible today's state-of-the-art traction motors, with the Nissan Leaf's 80kW Interior Permanent Magnet machine as a comparator.

The Segmental Rotor SRM's development has been formed of a number of steps. Firstly the background literature has been reviewed (Chapter 2); this has shown that the Segmental Rotor SRM design has the potential to achieve higher torque densities than standard SRM designs; this is due to its comparatively high magnetic utilisation. It highlighted that whilst there has been only limited literature relating to the development of the Segmental Rotor SRM, much more work has been undertaken with relation to the conventional SRM with, most notably, Akira Chiba in Japan having shown the potential of the conventional SRM for automotive traction. The literature supported the conclusion that a finite element based, stochastic, evolutionary algorithm optimisation approach should be applied to optimise these highly non-linear machines. It also suggested that this process of optimisation could be expected to lead to significant gains. To improve efficiency, the study suggested the use of compressed stator windings to increase fill factor and reduce winding losses. Finally it explored the state of the art in electrical machine design-for-manufacture, suggesting in particular the development of a segmented stator to simplify motor winding.

The optimum design of the Segmental Rotor SRM has then been studied. A process of static finite element optimisation (Chapter 3) has been undertaken to explore the combinations of stator slots and rotor segments which produce maximum torque per

unit loss. This has shown that, for aircooled machines operating at moderate current densities, machines with higher numbers of rotor segments than stator slots are significantly more efficient and offer major gains over conventional SRM designs. A prototype 12 stator slot, 16 rotor segment machine has been constructed and statically tested (Chapter 4) in order to validate the optimisation process. This led to the conclusion that the use of finite element, stochastic optimisation tools is valid and of benefit in developing application tailored Segmental Rotor SRMs. However it also identified limitations with the static optimisation process; these are that dynamic motor performance cannot be assessed and nor can iron losses be readily estimated.

The thesis then goes on to further develop the optimisation approach, with a dynamic, transient-with-motion based optimiser being developed (Chapter 5). Whilst this approach, is in this case, applied to an outer rotor permanent magnet machine, its inclusion is important in explaining the development of the optimisation process from the initial static approach applied in Chapter 3 to its final form, used later in Chapter 7 to optimise an 80kW Segmental Rotor SRM. This outer rotor permanent magnet motor also provided the test bed for the use of pre-compressed aluminium windings in an electrical machine (Chapter 6) and the learning gained from this machine's construction proved vital to inform the later construction of the 80kW Segmental Rotor SRM.

Finally the project has focused on the optimisation (Chapter 7), development (Chapter 8), construction (Chapter 9) and testing (Chapter 10) of an 80kW Segmental Rotor SRM. The optimisation of this machine has built on the lessons learnt in earlier chapters in order to combine features of both static and transient-with-motion optimisation into a 'hybrid' process. This has allowed the motor to be optimised so that its optimum efficiency is achieved at its normal, high residency operating points, whilst also ensuring that it is able to deliver the maximum extents of the torque speed range. An optimised motor design has then been further developed to ensure its mechanical and thermal robustness; this has led to the development of a new fir tree root based interface between the rotor segments and rotor support assembly. This has been shown, through structural finite element modelling, to be sufficiently robust to allow motor operation to 12,500rpm. However, this design has also impacted on the optimised performance of the machine, increasing unaligned leakage flux and reducing torque per unit loss. A segmented stator design has also been developed which has allowed the scaling up of

pre-compressed aluminium windings. The process of development and manufacture of these windings has been further refined and, for the first time, stranded conductors have been used. The 80kW Segmental Rotor SRM has also been thermally modelled with the aim of ensuring that it can perform with the high coolant inlet temperatures required by the automotive industry. As well as considering DC winding losses and iron losses, work has also been undertaken to develop tools to allow the rapid assessment of AC winding losses as well as eddy current losses in the Segmental Rotor SRM's rotor support structure. A motor has been designed which, whilst larger, offers similar performance, has a much lower cost and a similar mass when compared to the Interior Permanent Magnet motor used in the Nissan Leaf.

The motor has been constructed and tested, with important lessons learnt along the way. The rotor manufacturing process proposed was found to be very successful, delivering high levels of rotor concentricity and little ovalisation. Compressed coil construction has been developed so that it produces a repeatable, reliable component. Stator construction has shown the need for further design refinement, with it being difficult to pre-assemble the stator and coils before being fitted into the water jacket. During static testing the constructed motor has been found to have relatively close correlation to 3D modelling, with copper losses at peak torque being 11% higher than predicted. This increase is thought to be due to inaccurate saturation characteristics for the electrical steel used; seemingly a common problem, a further study into this subject forms part of ongoing funded research described in Chapter 12.

Static thermal testing demonstrated the importance of correct termination of aluminium windings and recommendations are made as to design best practice in this area. A level of thermal model validation is also achieved, suggesting that the constructed motor would be capable of operating within thermal limits at the required performance levels. Limited dynamic motor testing has been undertaken at the key optimisation operating point. This has shown that losses in the rotor support were much higher than expected, eventually leading to closure of the motor's airgap. Design changes are proposed to overcome this problem and reduce losses along with the risk of the rotor seizing to an acceptable level.

In final conclusion, this project has done much to investigate the challenges of developing and operating a Segmental Rotor SRM with high power and torque

densities. A motor has been developed which, based on limited testing, offers the potential to provide similar performance to the Nissan Leaf's Interior Permanent magnet motor, but without the use of rare-earth magnets or copper windings. Table 11-1 provides a comparison with the Nissan Leaf.

Table 11-1: Comparison between 80kW Segmental Rotor SRM and the Nissan Leaf's Interior Permanent Magnet Motor.

	80kW Prototype Segmental Rotor SRM	Nissan Leaf Interior Permanent Magnet⁽¹⁾
Max Speed	10,390rpm (TBC)	10,390rpm
DC Voltage	600V	400V
Max Torque	280Nm (200Arms) ⁽²⁾	280Nm (340Arms)
Peak Power	80kW (TBC)	80kW
Motor Efficiency: 3500 rpm 40Nm	95% ⁽³⁾	94%
Motor Outer Diameter: Active / with Jacket	246.1mm / 282mm	200.4mm / 280mm
Length: Active / with Jacket⁽⁴⁾	224.2mm / 283.2mm	231.5mm / 300mm
Volume: Active / with Jacket⁽⁴⁾	10.6l / 17.6l	7.3l / 18.5l
Motor Mass: Active / Complete	32.7kg / 54.2kg	32.0kg / 58.0kg
Power Density: Mass / Volume	2.5kW/kg / 8.4MW/m ³	2.5kW/kg / 11.0MW/m ³
Torque Density: Mass / Volume	8.6Nm/kg / 26.2kNm/m ³	8.8Nm/kg / 48.4kNm/m ³
Mass of NdFeB Magnet	N/A	2.00kg

Notes: 1) Values estimated from [9].

2) From static test.

3) Assumes the use of a 316 stainless steel rotor core.

4) Includes end windings.

Whilst the motor has a larger active volume (45%, also considering end windings) than the Nissan Leaf's, its active mass is only marginally heavier and, based on the available data, would appear to be capable of offering similar performance. Challenges remain; these include the need to iterate the motor design to ensure its reliability and the need to address the issue of acoustic noise. This project, due to its early promise, has now led to a number of follow-on funded research projects which are described in Chapter 12.

Chapter 12. Future Work

This project has suggested a number of avenues for further academic research, as well as leading to three fully funded extensions, all aimed at bringing the Segmental Rotor SRM technology into a production electric or hybrid electric vehicle. This section discusses the objectives and, where appropriate, findings of these projects.

12.1 Further Academic Research

This project has raised a number of academic questions about the operation of segmental rotor SRMs, both when used in automotive traction as well as more generally. To better understand these questions, the author is planning further fundamental research in the following areas:

- **Fundamental Comparison between Segmental Rotor SRMs and Conventional SRMs** – whilst Part 1 of this thesis provides a good comparison between conventional and segmental rotor SRMs, there is still more work to do to characterise these differences; for example to confirm design rules for Segmental Rotor SRMs working in differing applications and to draw further comparisons with conventional SRMs under differing operating conditions;
- **Improved Finite Element Modelling of Segmental Rotor SRMs** – as can be seen in Part 1 and Part 3 of this thesis, there is still more work to be done to enable the robust modelling of segmental rotor SRMs; there are real attractions in the continued use of fast 2D finite element models as the primary analysis tool, in particular during optimisation. However to make this process more reliable, model validity must be improved and all of the real world influences on segmental rotor SRM performance understood (for example, be they 3D effects, rotor support eddy current losses or material variations).
- **Acoustic Noise in Segmental Rotor SRMs** – whilst there is a significant body of work relating to acoustic noise in conventional SRMs, little has yet be done to consider this phenomenon in segmental rotor SRMs. Chapter 10 reported that the 80kW machine constructed in this project was, at least under certain operating conditions, noisy; work should therefore be undertaken to fully understand both the causes and mitigations for acoustic noise in these machines.

12.2 Tata Steel funded Electric Vehicle Motor / Gearbox Project

Now completed, during 2011/12 Tata Steel funded a project to investigate the development of a low cost electrical machine and gearbox for use in a future electric vehicle (Figure 12-1). As well as supporting the development of showcase technologies, this project also sought to investigate the materials which Tata Steel would need to develop in the future in order to meet the needs of the automotive Original Equipment Manufacturers (OEMs). This project was also supported by Jaguar Land Rover who provided the drivetrain specification.

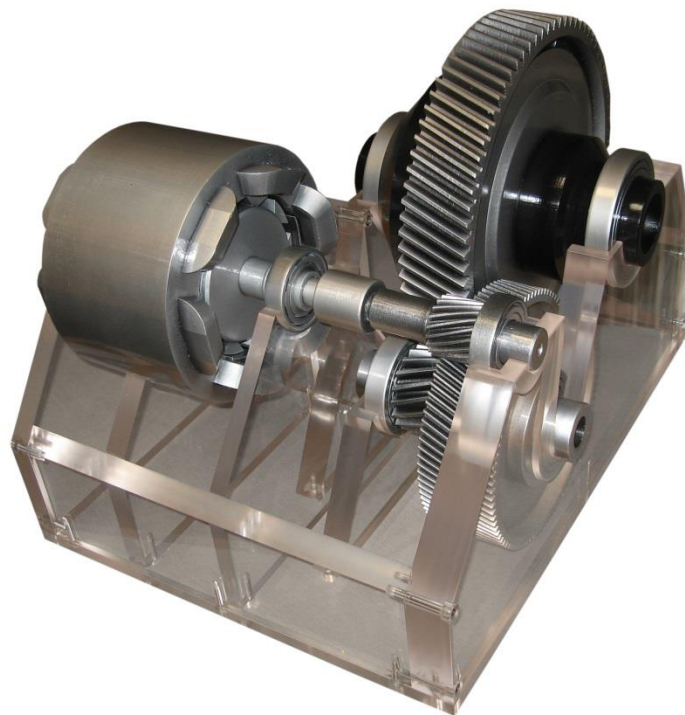


Figure 12-1: Rapid prototype of the Tata Steel Funded 30krpm Segmental Rotor SRM and Gearbox.

This project compared the complete range of electrical machines, with the final decision being between the development of a higher speed Interior Permanent Magnet motor and a very high speed, 30krpm Segmental Rotor SRM. The Segmental Rotor SRM was selected and work undertaken by the author in conjunction with a gear designer, from the University's Design Unit (Gear specialists), to develop this machine and compatible gearbox.

A motor and gearbox was designed using many of the techniques discussed in this PhD including the use of optimisation techniques and fir tree root structures. The project also specified new steel developments, including modified electrical steels as well as

structural and gear steels. The final motor design was predicted to have power densities three times higher than the Nissan Leaf's electrical machine. The motor gearbox assembly was expected to be mass and performance comparable to that resulting from a recent GKN / Evo TSB project [124] which included an Axial Flux Permanent Magnet machine and two speed gearbox; however the Segmental Rotor SRM based design was considered to be significantly lower cost.

12.3 Technology Strategy Board funded Low Cost Electric Drivetrain (LCED) Project

Following on from the Tata Steel project, this project led by Jaguar Land Rover and supported by Sevcon (motor drives), GKN (gearbox) and Tata Steel will develop and construct a prototype high speed Segmental Rotor SRM.

This is a three year project which will complete in mid 2016, with prototype motors being tested by Newcastle University, Sevcon and Jaguar Land Rover. This motor will be designed to meet the requirements of a future Jaguar Land Rover vehicle.

12.4 Technology Strategy Board funded High Density Switched Reluctance Drivetrain System (HDSRDS) Project

This project, again involving motor drive company Sevcon this time partnered with Cummins Generator Technologies, investigates the use of the Segmental Rotor SRM as part of a hybrid truck drivetrain. This project assumes the use of an unusual drive configuration, using a standard 3 Phase Full Bridge Converter via a series of diodes in order to create 6 unipolar phase currents (see Figure 12-2).

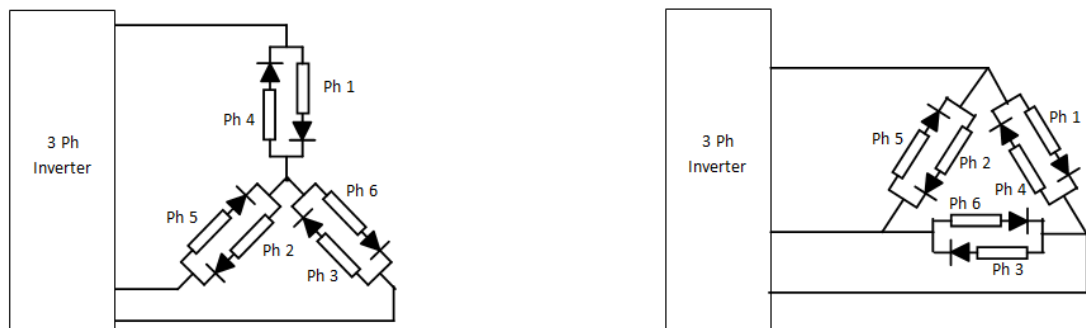


Figure 12-2: 3 Phase Bridge driving a 6 Phase SRM ref [125].

The original intent of this project was to use a Segmental Rotor SRM as the basis for the design, however during the course of the project it was decided instead to develop a conventional toothed SRM design for this application.

Specifically, the project's findings were that when a 6 phase machine is considered the advantages in magnetic loading in the segmental SRM are reduced. The conventional SRM is able to operate a short flux path configuration (Figure 12-3) which improves its torque capability, as previously reported by authors such as Michaelides [68].

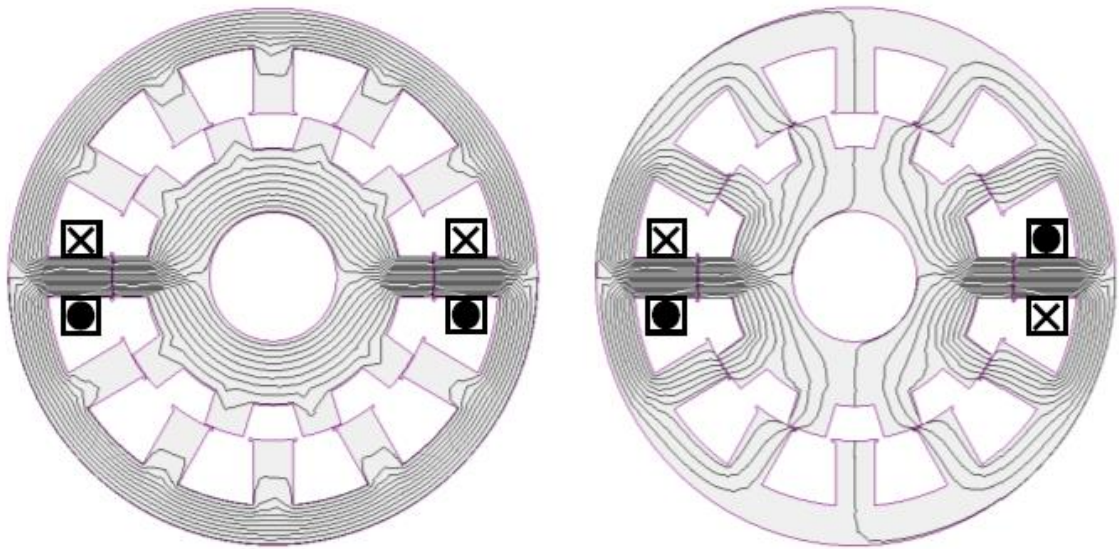


Figure 12-3: Showing the distinction between conventional SRM operation (left) and short flux path operation (right) [126] .

Whilst the Segmental Rotor SRM continues to provide lower copper losses for the same torque, the machine's reactance is much higher than in the case of the conventional machine (as observed in Chapter 3), compromising the constant power region with this particular drive, which is not capable of supporting continuous current operation. However, this problem is not present with a 3 phase machine driven from an asymmetric half bridge converter and so these results are limited just to the novel drive configuration applied in this project.

Appendix 1. Segmental Rotor SRM Parameterisation Script

This appendix contains the Visual Basic script generated in order to build the single tooth wound Segmental Rotor Switched Reluctance Machine in Infolytica MagNet (software version 7.4.1).

A1.1. Script File

```

'*****
'10-03-31 SIR Single Tooth Auto SRM Script v1.2
'*****

'This script file is based on 10-06-10 SIR Even Slot Script v2.5 and is modified to deal
with inner rotor SR-SRMs with single tooth windings
'v0.1 - initial conversion
'v1.0 - working version
'v1.1 - adds changes to allow for new optimisation (mid-range torque based) approach
'v1.2 - code tidy-up and commenting

'*****
'Magnet set-up
'*****

Call SetLocale("en-us")

Call newDocument()
Call getDocument().beginUndoGroup("Set Default Units", true)
Call getDocument().setDefaultLengthUnit("Millimeters")
Call getDocument().endUndoGroup()
Call getDocument().getView().setGridExtent(-60, -60, 60, 60)
Call getDocument().getView().setGridSpacings(2, 2)
Call getDocument().getView().showGrid(false)
'Call getDocument().setParameter("", "MaximumElementSize", "3%mm", infoNumberParameter)
Call
getDocument().setParameter("", "CurvatureRefinementAngle", "3%deg", infoNumberParameter)

'*****
'Variable set-up'
'*****

'Option Explicit

Dim iProbID, adCoordinates(3)
DIM Rinrotor, Routrotor, Rinstator, Routstator, Fluxpath, Slotdepth, Airgap, Phases,
Statorslots, Rotorsegments, Length'define input variables
DIM Statorsection, Rotorsection, Wide, Narrow, Toothgap,
Rsoffset, counter, counter2, counter3 'define internal variables
DIM pi, pi2, Theta, lam, cond 'define constants

'Geometry
Statorslots = 12
Rotorsegments = 10
Airgap = .3
Length = 240
Routstator = 300/2
Fluxpath = 10 'Width in mm of fluxpath
Slotdepth = 20
Tooth_tip_depth = 3
Seg_Fix_Depth = 2
Rotorslope = 3.1

'Windings
Phases = 3
ff = .75
Conductivity = 3.55e7 'Compressed Al Windings Assumed
Turns = 10

```



```

'Magnet Model Setup
Parameterise = TRUE                                'Turns parameterisation on and off
Symslots = 3                                     'Number of slot pairs for rotor symmetry
ActivePhs = 2                                    'Phase to have current simulated
AlignRtr = 2                                     'Only required for machines with even
number of phases
MaxCurDens = 20
lam = "SURA NO20"
cond = "Conductor - Very High Conductivity"
MaxVolts = 500
MaxAmps = 500
PGain = 5
IGain = 1
PWMFreq = 15000
strDirectory = "D:/0 PhD - Auto SRM/12-04 PhD and Tata Optimisations
Revised/leaf_optinet_logs"
strFile = "12-04-01_12-10_Leaf_OptiLog.log"

'sets differing problems covering solareagle spec points as follows:
'1) Stationary
'2) Base Speed
'3) 55mph
'4) Top Speed
Call getDocument().setParameter("", "Index", "4", infoNumberParameter)
Call
getDocument().setParameter("", "spdArray", "[60,60,60,3000,3500,2500,7500]", infoArrayParameter)
Call
getDocument().setParameter("", "NmArray", "[280,280,280,280,10,35,30]", infoArrayParameter)
Call
getDocument().setParameter("", "AdvanceArray", "[0,0,0,90,90,90,90]", infoArrayParameter)
Call
getDocument().setParameter("", "ConductionArray", "[180,180,180,180,180,180,180]", infoArrayParameter)
Call
getDocument().setParameter("", "CurrentOnArray", "[1,1,1,0,1,1,1]", infoArrayParameter)
Call getDocument().setParameter("", "MotionOnArray", "[0,0,0,1,1,1,1]", infoArrayParameter)
Call
getDocument().setParameter("", "StepsArray", "[20,20,20,20,20,20,20]", infoArrayParameter)
Call
getDocument().setParameter("", "CyclesArray", "[1,1,1,1.5,1.5,1.5,1.5]", infoArrayParameter)
Call
getDocument().setParameter("", "StaticAngleArray", "[0,360/%Rotorsegments/4,360/%Rotorsegments/2,0,0,0,0]", infoArrayParameter)
Call getDocument().setParameter("", "CurrentforTgtMaxTorqueArray", "[0,0,0,0,0,0,0]", infoArrayParameter)
Call getDocument().setParameter("", "TRiseArray", "[0,0,0,0,0,0,0]", infoArrayParameter)

'set internal variables
pi = 3.14159265358979323846264338327950288419716939937510
pi2 = pi*2
lam = "Name=" & lam & ""                                'Lamination
cond = "Name=" & cond & ""                                'Conductor
iProbID = 1
RoutSlot=Routstator-Fluxpath
Rinstator = Routslot-Slotdepth-Tooth_tip_depth
Tangrad = Rinstator+Tooth_tip_depth 'radius of tang root
Routrotor = Rinstator-Airgap
Rinrotor = Routrotor-Fluxpath-Seg_Sup_Depth
Statorsection = 360/(Statorslots/2)
Rotorsection = 360/(Rotorsegments)
Rsoffset= Rotorsegments/(Statorslots/Phases/2)-Phases
Wide = .85*Rotorsection
Toothgap = Rotorsection - Wide
Narrow = ((Wide+Toothgap)*(Phases+Rsoffset))/Phases-Wide-2*Toothgap
Theta = pi2*Sylmslots/Statorslots*2
Symsegs = Cint(Rotorsegments*Theta/pi2+.1)

'+++++

CurDens = Slotarea*.4*MaxCurDens*2^.5
CurStep = CurDens/10
RotorStep = Rotorsection/2/10

counter=1

```

```

'offsets rotor if even number of machine phases
if Phases AND 1 then
    offset = "(&Rotorsection*(-120*("&ActivePhs&"-
1)))/360*&MotionOn+&StaticAngleArray[%Index]"
else
    'offset = (Wide-Fluxpath*360/(pi2*Rinstator))/2
    offset= "&(ActivePhs-.5)*&Statorsection-
Rotorsection*&AlignRtr&"+(&Rotorsection*(-120*("&ActivePhs&"-
1)))/360*&MotionOn+&StaticAngleArray[%Index]"
end if

'*****
'set magnet solution parameters
'*****

'Set core parameters - Variables
Call
getDocument().setParameter("", "LogFileLocation", "&strDirectory&", infoTextParameter)
Call getDocument().setParameter("", "LogFileName", "&strFile&", infoTextParameter)
Call getDocument().setParameter("", "Statorslots", "&Statorslots&", infoNumberParameter)
Call
getDocument().setParameter("", "Rotorsegments", "&Rotorsegments&", infoNumberParameter)
Call getDocument().setParameter("", "Airgap", "&Airgap&", infoNumberParameter)
Call getDocument().setParameter("", "la", "&Length&", infoNumberParameter)
Call getDocument().setParameter("", "Routrotor", "&Routrotor+10&", infoNumberParameter)
Call getDocument().setParameter("", "FluxpathNarrow", "&Fluxpath&", infoNumberParameter)
Call getDocument().setParameter("", "FluxpathWide", "&Fluxpath&", infoNumberParameter)
Call getDocument().setParameter("", "SCoreback", "&Fluxpath&", infoNumberParameter)
Call getDocument().setParameter("", "RSegment_height", "&Fluxpath&", infoNumberParameter)
Call getDocument().setParameter("", "Slotdepth", "&Slotdepth&", infoNumberParameter)
Call
getDocument().setParameter("", "Tooth_tip_depth", "&Tooth_tip_depth&", infoNumberParameter)
Call getDocument().setParameter("", "Toothgap", "&Toothgap&", infoNumberParameter)
Call getDocument().setParameter("", "Rotorslope", "&Rotorslope&", infoNumberParameter)
Call getDocument().setParameter("", "Phases", "&Phases&", infoNumberParameter)
Call getDocument().setParameter("", "FillFactor", "&ff&", infoNumberParameter)
Call
getDocument().setParameter("", "Conductivity", "&Conductivity&", infoNumberParameter)
Call getDocument().setParameter("", "Turns", "&Turns&", infoNumberParameter)
Call getDocument().setParameter("", "Symslots", "&Symslots&", infoNumberParameter)
Call getDocument().setParameter("", "Symsegs", "&Symsegs&", infoNumberParameter)
Call getDocument().setParameter("", "MaxVolts", "&MaxVolts&", infoNumberParameter)
Call getDocument().setParameter("", "MaxAmps", "&MaxAmps&", infoNumberParameter)
Call getDocument().setParameter("", "PGain", "&PGain&", infoNumberParameter)
Call getDocument().setParameter("", "IGain", "&IGain&", infoNumberParameter)
Call getDocument().setParameter("", "PWMFreq", "&PWMFreq&", infoNumberParameter)
Call getDocument().setParameter("", "pcMaxAmps", "1", infoNumberParameter)
Call getDocument().setParameter("", "Iteration", "0", infoNumberParameter)
CALL getDocument().setParameter("", "NotSolved", "0", infoNumberParameter)

'Set core parameters - Calculated Variables
Call getDocument().setParameter("", "Steps", "&StepsArray[%Index]", infoNumberParameter)
Call getDocument().setParameter("", "Cycles", "&CyclesArray[%Index]", infoNumberParameter)
Call
getDocument().setParameter("", "StaticAngle", "&StaticAngleArray[%Index]", infoNumberParameter)
Call
getDocument().setParameter("", "CurrentOn", "&CurrentOnArray[%Index]", infoNumberParameter)
Call
getDocument().setParameter("", "MotionOn", "&MotionOnArray[%Index]", infoNumberParameter)
Call getDocument().setParameter("", "CurrentforTgtMaxTorque",
"&CurrentforTgtMaxTorqueArray[%Index]", infoNumberParameter)
Call getDocument().setParameter("", "TRise", "&TRiseArray[%Index]", infoNumberParameter)
Call getDocument().setParameter("", "RotorOSangle", offset, infoNumberParameter)
Call
getDocument().setParameter("", "Routstator", "&Routslot+&SCoreback", infoNumberParameter)
Call
getDocument().setParameter("", "Routslot", "&RoutTang+&Slotdepth", infoNumberParameter)
Call
getDocument().setParameter("", "RoutTang", "&Rinstator+&Tooth_tip_depth", infoNumberParameter)
Call getDocument().setParameter("", "Rinstator", "&Routrotor+&Airgap", infoNumberParameter)
Call getDocument().setParameter("", "Rinrotoractive", "&Routrotor-
&RSegment_height", infoNumberParameter)

```

```

Call getDocument().setParameter("", "Rinrotor", "%Rinrotoractive-
"&Seg_Fix_Depth&"", infoNumberParameter)
Call
getDocument().setParameter("", "Statorsection", "360/(%Statorslots/2)", infoNumberParameter
)
Call
getDocument().setParameter("", "Rotorsection", "360/%Rotorsegments", infoNumberParameter)
Call getDocument().setParameter("", "Rsoffset", "%Rotorsegments/(%Statorslots/%Phases/2)-
%Phases", infoNumberParameter)
Call getDocument().setParameter("", "Rotorstep", "%Rotorsection/2/10", infoNumberParameter)
Call getDocument().setParameter("", "Wide", ""&Rotorsection&"-
%Toothgap", infoNumberParameter)
Call
getDocument().setParameter("", "Narrow", "(%Wide+%Toothgap)*&(Phases+Rsoffset)/Phases&"-
%Wide-2*%Toothgap", infoNumberParameter)
Call
getDocument().setParameter("", "Theta", ""&pi2&"*%Symslots/%Statorslots*2", infoNumberParam
eter)
Call getDocument().setParameter("", "Torque", "%NmArray[%Index]", infoNumberParameter)
Call getDocument().setParameter("", "Speed", "%spdArray[%Index]", infoNumberParameter)
Call
getDocument().setParameter("", "Advance", "%AdvanceArray[%Index]", infoNumberParameter)
Call
getDocument().setParameter("", "Conduction", "%ConductionArray[%Index]", infoNumberParamete
r)
Call
getDocument().setParameter("", "Trot", "60/%Speed*%Rotorsection/360*1000", infoNumberParame
ter)
Call
getDocument().setParameter("", "Sections", "%Statorslots/(%Symslots*2)", infoNumberParamete
r)
Call getDocument().setParameter("", "SolutionSweepDistance", "%la*mm",
infoNumberParameter)
Call getDocument().setParameter("", "Slotarea", "(((%pi*%Routslot^2-
%pi*(%Rinstator)^2)*%Statorsection/360)-(2*%FluxpathWide+%FluxpathNarrow+.4)*(%Routslot-
%Rinstator)-(%RoutTang-%Rinstator)*(2*%pi*%Rinstator*(%Rotorsection-%Toothgap)/360-
2*(%FluxpathWide+.1))/2-(%RoutTang-%Rinstator)*(2*%pi*%Rinstator*%Narrow/360-
(%FluxpathNarrow+.1))/2)/2", infoNumberParameter)
Call
getDocument().setParameter("", "Strandarea", "%Slotarea/%Turns*%FillFactor", infoNumberPara
meter)
Call
getDocument().setParameter("", "Coillength", "(2*%la/1000+2*(%FluxpathWide*2)/1000+4*%Slot
area/1000^2/(%Slotdepth/1000)/2*2*%pi/4)*%Turns", infoNumberParameter)
Call
getDocument().setParameter("", "Rcoil", "%Coillength/(%Strandarea/1000^2*%Conductivity)", i
nfoNumberParameter)
Call getDocument().setParameter("", "Amppeak", "%MaxAmps*%pcMaxAmps", infoNumberParameter)

Call getDocument().setParameter("", "StatorIronMass", "(%pi*%Routstator^2-
%pi*%Rinstator^2-%Slotarea*%Statorslots)*%la/1000^3*7.66e3", infoNumberParameter)
Call getDocument().setParameter("", "RotorIronMass", "(%pi*%Routrotor^2-
%pi*%Rinrotor^2)*(360-((%Toothgap+2*(%Rotorsection-
%Toothgap)/%Rotorslope)/2*%Rotorsegments))/360*%la/1000^3*7.66e3", infoNumberParameter)
Call
getDocument().setParameter("", "CopperMass", "%Coillength*%Strandarea/1000^2*8.954e3*%Stat
orslots/2", infoNumberParameter)
Call
getDocument().setParameter("", "MotorActiveMass", "%StatorIronMass+%RotorIronMass+%CopperM
ass", infoNumberParameter)

'*****
'creates air box for stator, airgap and rotor and makes rotor airboxes rotating
components
'*****

'Select Airgap Boundaries and Parameterise

Call
getDocument().setParameter("", "VertagAX", "%Routrotor+%Airgap/4", infoNumberParameter)
Call getDocument().setParameter("", "VertagAY", "0", infoNumberParameter)
Call getDocument().setParameter("", "VertagBX", "%Rinstator-
%Airgap/4", infoNumberParameter)
Call getDocument().setParameter("", "VertagBY", "0", infoNumberParameter)
Call
getDocument().setParameter("", "VertagCX", "%Routrotor+%Airgap/2", infoNumberParameter)

```

```

Call getDocument().setParameter("", "VertagCY", "0", infoNumberParameter)
Call getDocument().setParameter("", "VertagDX", "%Routstator*1.5", infoNumberParameter)
Call getDocument().setParameter("", "VertagDY", "0", infoNumberParameter)
Call
getDocument().setParameter("", "VertagEX", "cos(%Theta) * (%VertagAX)", infoNumberParameter)
Call
getDocument().setParameter("", "VertagEY", "sin(%Theta) * (%VertagAX)", infoNumberParameter)
Call
getDocument().setParameter("", "VertagFX", "cos(%Theta) * (%VertagBX)", infoNumberParameter)
Call
getDocument().setParameter("", "VertagFY", "sin(%Theta) * (%VertagBX)", infoNumberParameter)
Call
getDocument().setParameter("", "VertagGX", "cos(%Theta) * (%VertagCX)", infoNumberParameter)
Call
getDocument().setParameter("", "VertagGY", "sin(%Theta) * (%VertagCX)", infoNumberParameter)
Call
getDocument().setParameter("", "VertagHX", "cos(%Theta) * (%VertagDX)", infoNumberParameter)
Call
getDocument().setParameter("", "VertagHY", "sin(%Theta) * (%VertagDX)", infoNumberParameter)

Call getDocument().getView().newArc(0,
0, getParam("VertagAX"), getParam("VertagAY"), getParam("VertagEX"), getParam("VertagEY"))
Call getDocument().getView().newArc(0,
0, getParam("VertagBX"), getParam("VertagBY"), getParam("VertagFX"), getParam("VertagFY"))
Call getDocument().getView().newArc(0,
0, getParam("VertagCX"), getParam("VertagCY"), getParam("VertagGX"), getParam("VertagGY"))
Call getDocument().getView().newArc(0,
0, getParam("VertagDX"), getParam("VertagDY"), getParam("VertagHX"), getParam("VertagHY"))
Call
getDocument().getView().newLine(getParam("VertagDX"), getParam("VertagDY"), getParam("VertagHX"), getParam("VertagHY"))

    if pi2/getParam("Theta") <= 2 then
        Call getDocument().getView().newLine(0,0,0, getParam("VertagAX")-.001)
        Call getDocument().getView().selectAt(getParam("VertagAX")-.001, getParam("VertagAY")+0.001, infoSetSelection, Array(infoSliceSurface))

        REDIM ArrayOfValues(0)
        ArrayOfValues(0)= "Rotor Virtual Air"
        Call getDocument().getView().makeComponentInALine(getParam("la"), ArrayOfValues, "Name=Virtual Air", infoMakeComponentUnionSurfaces Or infoMakeComponentIgnoreHoles)
        Call getDocument().setParameter(ArrayOfValues(0), "SweepDistance", "%la%mm", infoNumberParameter)
    else
        if getParam("Rinrotor") < 100 then
            RinAB = getParam("Rinrotor")-5
        else
            RinAB=100
        end if
        Call getDocument().getView().newArc(0, 0, getParam("Rinrotor")-RinAB, 0, cos(getParam("Theta")) * (getParam("Rinrotor")-RinAB), sin(getParam("Theta")) * (getParam("Rinrotor")-RinAB))
        Call getDocument().getView().selectAt(getParam("VertagAX")-.001, getParam("VertagAY")+0.001, infoSetSelection, Array(infoSliceSurface))

        REDIM ArrayOfValues(0)
        ArrayOfValues(0)= "Rotor Virtual Air"
        Call getDocument().getView().makeComponentInALine(getParam("la"), ArrayOfValues, "Name=Virtual Air", infoMakeComponentUnionSurfaces Or infoMakeComponentIgnoreHoles)
        Call getDocument().setParameter(ArrayOfValues(0), "SweepDistance", "%la%mm", infoNumberParameter)
    end if

Call
getDocument().getView().selectAt(getParam("VertagAX")+0.001, getParam("VertagAY")+0.001, infoSetSelection, Array(infoSliceSurface))
REDIM ArrayOfValues(0)
ArrayOfValues(0)= "Rotor Air"
Call getDocument().getView().makeComponentInALine(getParam("la"), ArrayOfValues, "Name=AIR", infoMakeComponentUnionSurfaces Or infoMakeComponentIgnoreHoles Or infoMakeComponentRemoveVertices)
Call getDocument().setParameter(ArrayOfValues(0), "SweepDistance", "%la%mm", infoNumberParameter)

Call getDocument().getView().selectAt(getParam("VertagBX")-.001, getParam("VertagBY")+0.001, infoSetSelection, Array(infoSliceSurface))

```

```

REDIM ArrayOfValues(0)
ArrayOfValues(0)= "Stator Air"
Call getDocument().getView().makeComponentInALine(getParam("la"), ArrayOfValues,
"Name=AIR", infoMakeComponentUnionSurfaces Or infoMakeComponentIgnoreHoles Or
infoMakeComponentRemoveVertices)
Call getDocument().setParameter(ArrayOfValues(0),"SweepDistance","%la%mm",
infoNumberParameter)

Call
getDocument().getView().selectAt(getParam("VertagBX")+.001,getParam("VertagBY")+.001,
infoSetSelection, Array(infoSliceSurface))
REDIM ArrayOfValues(0)
ArrayOfValues(0)= "Stator Virtual Air"
Call getDocument().getView().makeComponentInALine(getParam("la"), ArrayOfValues,
"Name=Virtual Air", infoMakeComponentUnionSurfaces Or infoMakeComponentIgnoreHoles Or
infoMakeComponentRemoveVertices)
Call getDocument().setParameter(ArrayOfValues(0),"SweepDistance","%la%mm",
infoNumberParameter)

'Deletes all construction lines on slice

Call getDocument().getView().selectAll(infoSetSelection, Array(infoSliceLine,
infoSliceArc))
Call getDocument().getView().deleteSelection()

'Parameterise Airgaps

If Parameterise then

    For counter = 1 to 4

        if counter <= 2 then
            adCoordinates(3) = 0
        else
            adCoordinates(3) = getParam("la")
        End if

        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor+10&"" ,infoNumberParameter)
adCoordinates(1) = getParam("VertagAX")
adCoordinates(2) = getParam("VertagAY")
Call
getDocument().setParameter("", "Routrotor", ""&Routrotor&"" ,infoNumberParameter)

        VertexPath = GetVertexPath(iProbID, adCoordinates)

        if Vertexpath <> "No Vertex Found" then
            Call
getDocument().setParameter(""&VertexPath&"" , "Position", "[%VertagAX%mm,%VertagAY%mm]", info
oArrayParameter)
        End if

        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor+10&"" ,infoNumberParameter)
adCoordinates(1) = getParam("VertagBX")
adCoordinates(2) = getParam("VertagBY")
Call
getDocument().setParameter("", "Routrotor", ""&Routrotor&"" ,infoNumberParameter)

        VertexPath = GetVertexPath(iProbID, adCoordinates)

        if Vertexpath <> "No Vertex Found" then
            Call
getDocument().setParameter(""&VertexPath&"" , "Position", "[%VertagBX%mm,%VertagBY%mm]", info
oArrayParameter)
        End if

        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor+10&"" ,infoNumberParameter)
adCoordinates(1) = getParam("VertagCX")
adCoordinates(2) = getParam("VertagCY")
Call
getDocument().setParameter("", "Routrotor", ""&Routrotor&"" ,infoNumberParameter)

        VertexPath = GetVertexPath(iProbID, adCoordinates)

```

```

        if Vertexpath <> "No Vertex Found" then
            Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertagCX%mm,%VertagCY%mm]", info
oArrayParameter)
        End if

        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor+10&", infoNumberParameter)
        adCoordinates(1) = getParam("VertagDX")
        adCoordinates(2) = getParam("VertagDY")
        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor&", infoNumberParameter)

        VertexPath = GetVertexPath(iProbID, adCoordinates)

        if Vertexpath <> "No Vertex Found" then
            Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertagDX%mm,%VertagDY%mm]", info
oArrayParameter)
        End if

        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor+10&", infoNumberParameter)
        adCoordinates(1) = getParam("VertagEX")
        adCoordinates(2) = getParam("VertagEY")
        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor&", infoNumberParameter)

        VertexPath = GetVertexPath(iProbID, adCoordinates)

        if Vertexpath <> "No Vertex Found" then
            Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertagEX%mm,%VertagEY%mm]", info
oArrayParameter)
        End if

        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor+10&", infoNumberParameter)
        adCoordinates(1) = getParam("VertagFX")
        adCoordinates(2) = getParam("VertagFY")
        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor&", infoNumberParameter)

        VertexPath = GetVertexPath(iProbID, adCoordinates)

        if Vertexpath <> "No Vertex Found" then
            Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertagFX%mm,%VertagFY%mm]", info
oArrayParameter)
        End if

        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor+10&", infoNumberParameter)
        adCoordinates(1) = getParam("VertagGX")
        adCoordinates(2) = getParam("VertagGY")
        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor&", infoNumberParameter)

        VertexPath = GetVertexPath(iProbID, adCoordinates)

        if Vertexpath <> "No Vertex Found" then
            Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertagGX%mm,%VertagGY%mm]", info
oArrayParameter)
        End if

        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor+10&", infoNumberParameter)
        adCoordinates(1) = getParam("VertagHX")
        adCoordinates(2) = getParam("VertagHY")
        Call
getDocument().setParameter("", "Routrotor", ""&Routrotor&", infoNumberParameter)

        VertexPath = GetVertexPath(iProbID, adCoordinates)

```

```

        if Vertexpath <> "No Vertex Found" then
            Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertagHX%mm,%VertagHY%mm]", info
oArrayParameter)
            End if

        Next

    End if

counter=1
counter2=1
counter3=1

'+++++
'*****
' Start of code used to design stator teeth.
'*****

Call getDocument().setParameter("", "VertendAX", "%Rinstator", infoNumberParameter)
Call getDocument().setParameter("", "VertendAY", "0", infoNumberParameter)
Call
getDocument().setParameter("", "VertendBX", "cos(%Theta)*%Rinstator", infoNumberParameter)
Call
getDocument().setParameter("", "VertendBY", "sin(%Theta)*%Rinstator", infoNumberParameter)

Call getDocument().setParameter("", "VertendCX", "%Routstator", infoNumberParameter)
Call getDocument().setParameter("", "VertendCY", "0", infoNumberParameter)
Call
getDocument().setParameter("", "VertendDX", "cos(%Theta)*%Routstator", infoNumberParameter)
Call
getDocument().setParameter("", "VertendDY", "sin(%Theta)*%Routstator", infoNumberParameter)

Call getDocument().setParameter("", "VertAX1", "(%Routslot^2-
(FluxpathNarrow/2)^2)^.5", infoNumberParameter)
Call getDocument().setParameter("", "VertAY1", "%FluxpathNarrow/2", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaA", "atan(%VertAY1/%VertAX1)", infoNumberParameter)
Call getDocument().setParameter("", "hypA", "%VertAY1/sin(%ThetaA)", infoNumberParameter)

Call getDocument().setParameter("", "VertWideAX0", "(%Routslot^2-
(FluxpathWide)^2)^.5", infoNumberParameter)
Call getDocument().setParameter("", "VertWideAY0", "%FluxpathWide", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaWideA", "atan(%VertWideAY0/%VertWideAX0)", infoNumberP
arameter)
Call
getDocument().setParameter("", "hypWideA", "%VertWideAY0/sin(%ThetaWideA)", infoNumberParam
eter)

Call getDocument().setParameter("", "VertBX1", "(%RoutTang^2-
(FluxpathNarrow/2)^2)^.5", infoNumberParameter)
Call getDocument().setParameter("", "VertBY1", "%FluxpathNarrow/2", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaB", "atan(%VertBY1/%VertBX1)", infoNumberParameter)
Call getDocument().setParameter("", "hypB", "%VertBY1/sin(%ThetaB)", infoNumberParameter)

Call getDocument().setParameter("", "VertWideBX0", "(%RoutTang^2-
(FluxpathWide)^2)^.5", infoNumberParameter)
Call getDocument().setParameter("", "VertWideBY0", "%FluxpathWide", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaWideB", "atan(%VertWideBY0/%VertWideBX0)", infoNumberP
arameter)
Call
getDocument().setParameter("", "hypWideB", "%VertWideBY0/sin(%ThetaWideB)", infoNumberParam
eter)

Call
getDocument().setParameter("", "VertCX1", "cos(%pi*2*%Narrow/2/360)*%Rinstator", infoNumber
Parameter)
Call
getDocument().setParameter("", "VertCY1", "sin(%pi*2*%Narrow/2/360)*%Rinstator", infoNumber
Parameter)
Call
getDocument().setParameter("", "ThetaC", "atan(%VertCY1/%VertCX1)", infoNumberParameter)

```

```

Call getDocument().setParameter("", "hypC", "%VertCY1/sin(%ThetaC)", infoNumberParameter)

Call
getDocument().setParameter("", "VertWideCX0", "cos(%pi*2*%Wide/2/360)*%Rinstator", infoNumberParameter)
Call
getDocument().setParameter("", "VertWideCY0", "sin(%pi*2*%Wide/2/360)*%Rinstator", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaWideC", "atan(%VertWideCY0/%VertWideCX0)", infoNumberParameter)
Call
getDocument().setParameter("", "hypWideC", "%VertWideCY0/sin(%ThetaWideC)", infoNumberParameter)

For counter = 1 to symslots

    if counter > 1 then

        Call
        getDocument().setParameter("", "VertAX"&counter&"", "%hypA*cos("&(counter-1)&"*%Statorsection*pi/180+%ThetaA)", infoNumberParameter)
        Call
        getDocument().setParameter("", "VertAY"&counter&"", "%hypA*sin("&(counter-1)&"*%Statorsection*pi/180+%ThetaA)", infoNumberParameter)
        Call
        getDocument().setParameter("", "VertBX"&counter&"", "%hypB*cos("&(counter-1)&"*%Statorsection*pi/180+%ThetaB)", infoNumberParameter)
        Call
        getDocument().setParameter("", "VertBY"&counter&"", "%hypB*sin("&(counter-1)&"*%Statorsection*pi/180+%ThetaB)", infoNumberParameter)
        Call
        getDocument().setParameter("", "VertCX"&counter&"", "%hypC*cos("&(counter-1)&"*%Statorsection*pi/180+%ThetaC)", infoNumberParameter)
        Call
        getDocument().setParameter("", "VertCY"&counter&"", "%hypC*sin("&(counter-1)&"*%Statorsection*pi/180+%ThetaC)", infoNumberParameter)

    End if

    Call
    getDocument().setParameter("", "VertWideAX"&counter&"", "%hypWideA*cos("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180-%ThetaWideA)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertWideAY"&counter&"", "%hypWideA*sin("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180-%ThetaWideA)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertWideBX"&counter&"", "%hypWideB*cos("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180-%ThetaWideB)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertWideBY"&counter&"", "%hypWideB*sin("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180-%ThetaWideB)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertWideCX"&counter&"", "%hypWideC*cos("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180-%ThetaWideC)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertWideCY"&counter&"", "%hypWideC*sin("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180-%ThetaWideC)", infoNumberParameter)

    Call
    getDocument().setParameter("", "VertDX"&counter&"", "%hypA*cos("&(counter)&"*%Statorsection*pi/180-%ThetaA)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertDY"&counter&"", "%hypA*sin("&(counter)&"*%Statorsection*pi/180-%ThetaA)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertEX"&counter&"", "%hypB*cos("&(counter)&"*%Statorsection*pi/180-%ThetaB)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertEY"&counter&"", "%hypB*sin("&(counter)&"*%Statorsection*pi/180-%ThetaB)", infoNumberParameter)
    Call
    getDocument().setParameter("", "VertFX"&counter&"", "%hypC*cos("&(counter)&"*%Statorsection*pi/180-%ThetaC)", infoNumberParameter)

```



```

        Call
getDocument().setParameter("", "VertFY"&counter&"", "%hypC*sin("&(counter)&"*%Statorsection*%pi/180-%ThetaC)", infoNumberParameter)

        Call
getDocument().setParameter("", "VertWideDX"&counter&"", "%hypWideA*cos("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180+%ThetaWideA)", infoNumberParameter)
        Call
getDocument().setParameter("", "VertWideDY"&counter&"", "%hypWideA*sin("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180+%ThetaWideA)", infoNumberParameter)
        Call
getDocument().setParameter("", "VertWideEX"&counter&"", "%hypWideB*cos("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180+%ThetaWideB)", infoNumberParameter)
        Call
getDocument().setParameter("", "VertWideEY"&counter&"", "%hypWideB*sin("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180+%ThetaWideB)", infoNumberParameter)
        Call
getDocument().setParameter("", "VertWideFX"&counter&"", "%hypWideC*cos("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180+%ThetaWideC)", infoNumberParameter)
        Call
getDocument().setParameter("", "VertWideFY"&counter&"", "%hypWideC*sin("&(counter-1)&"*%Statorsection+%Statorsection/2)*%pi/180+%ThetaWideC)", infoNumberParameter)

        Call getDocument().getView().newLine(getParam("VertAX"&counter&"",
getParam("VertAY"&counter&"", getParam("VertBX"&counter&"",
getParam("VertBY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertBX"&counter&"",
getParam("VertBY"&counter&"", getParam("VertCX"&counter&"",
getParam("VertCY"&counter&""))
        Call getDocument().getView().newArc(0, 0, getParam("VertAX"&counter&"",
getParam("VertAY"&counter&"", getParam("VertWideAX"&counter&"",
getParam("VertWideAY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertWideAX"&counter&"",
getParam("VertWideAY"&counter&"", getParam("VertWideBX"&counter&"",
getParam("VertWideBY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertWideBX"&counter&"",
getParam("VertWideBY"&counter&"", getParam("VertWideCX"&counter&"",
getParam("VertWideCY"&counter&""))

        Call getDocument().getView().newLine(getParam("VertDX"&counter&"",
getParam("VertDY"&counter&"", getParam("VertEX"&counter&"",
getParam("VertEY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertEX"&counter&"",
getParam("VertEY"&counter&"", getParam("VertFX"&counter&"",
getParam("VertFY"&counter&""))
        Call getDocument().getView().newArc(0, 0, getParam("VertWideDX"&counter&"",
getParam("VertWideDY"&counter&"", getParam("VertDX"&counter&"",
getParam("VertDY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertWideDX"&counter&"",
getParam("VertWideDY"&counter&"", getParam("VertWideEX"&counter&"",
getParam("VertWideEY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertWideEX"&counter&"",
getParam("VertWideEY"&counter&"", getParam("VertWideFX"&counter&"",
getParam("VertWideFY"&counter&""))

Next

Call getDocument().getView().newArc(0, 0, getParam("VertendAX"), getParam("VertendAY"),
getParam("VertendBX"), getParam("VertendBY"))
Call getDocument().getView().newArc(0, 0, getParam("VertendCX"), getParam("VertendCY"),
getParam("VertendDX"), getParam("VertendDY"))
Call getDocument().getView().newLine(getParam("VertendCX"), getParam("VertendCY"),
getParam("VertendDX"), getParam("VertendDY"))

'create Stator Part

REDIM ArrayOfValues(0)
ArrayOfValues(0)= "Stator"
Call getDocument().getView().selectAt(getParam("VertendAX")+.001,
getParam("VertendAY")+.001, infoSetSelection, Array(infoSliceSurface))
Call getDocument().getView().makeComponentInALine(getParam("la"), ArrayOfValues, lam,
infoMakeComponentUnionSurfaces Or infoMakeComponentRemoveVertices)
Call getDocument().setParameter(ArrayOfValues(0), "SweepDistance", "%la%mm",
infoNumberParameter)

'Deletes all construction lines on slice

```

```

Call getDocument().getView().selectAll(infoSetSelection, Array(infoSliceLine,
infoSliceArc))
Call getDocument().getView().deleteSelection()

'*****
'Select Stator Slot Vertices and Parameterise
'*****

If Parameterise then

    For counter1 = 1 to 2

        Select Case counter1
            Case 1
                adCoordinates(3) = 0
            Case 2
                adCoordinates(3) = getParam("la")
        End Select

        adCoordinates(1) = getParam("VertendAX")
        adCoordinates(2) = getParam("VertendAY")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertendAX%mm,%VertendAY%mm]", i
nfoArrayParameter)

        adCoordinates(1) = getParam("VertendBX")
        adCoordinates(2) = getParam("VertendBY")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertendBX%mm,%VertendBY%mm]", i
nfoArrayParameter)

        adCoordinates(1) = getParam("VertendCX")
        adCoordinates(2) = getParam("VertendCY")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertendCX%mm,%VertendCY%mm]", i
nfoArrayParameter)

        adCoordinates(1) = getParam("VertendDX")
        adCoordinates(2) = getParam("VertendDY")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertendDX%mm,%VertendDY%mm]", i
nfoArrayParameter)

    Next

    For counter = 1 to symslots

        For counter1 = 1 to 2

            Select Case counter1
                Case 1
                    adCoordinates(3) = 0
                Case 2
                    adCoordinates(3) = getParam("la")
            End Select

            adCoordinates(1) = getParam("VertAX"&counter&")
            adCoordinates(2) = getParam("VertAY"&counter&")
            VertexPath = GetVertexPath(iProbID, adCoordinates)
            Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertAX"&counter&"%mm,%VertAY"&
counter&"%mm]", infoArrayParameter)

            adCoordinates(1) = getParam("VertBX"&counter&")
            adCoordinates(2) = getParam("VertBY"&counter&")
            VertexPath = GetVertexPath(iProbID, adCoordinates)
            Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertBX"&counter&"%mm,%VertBY"&
counter&"%mm]", infoArrayParameter)

```

```

        adCoordinates(1) = getParam("VertCX"&counter&"")
        adCoordinates(2) = getParam("VertCY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertCX"&counter&"%mm,%VertCY"&
counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertDX"&counter&"")
        adCoordinates(2) = getParam("VertDY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertDX"&counter&"%mm,%VertDY"&
counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertEX"&counter&"")
        adCoordinates(2) = getParam("VertEY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertEX"&counter&"%mm,%VertEY"&
counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertFX"&counter&"")
        adCoordinates(2) = getParam("VertFY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertFX"&counter&"%mm,%VertFY"&
counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertWideAX"&counter&"")
        adCoordinates(2) = getParam("VertWideAY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertWideAX"&counter&"%mm,%Vert
WideAY"&counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertWideBX"&counter&"")
        adCoordinates(2) = getParam("VertWideBY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertWideBX"&counter&"%mm,%Vert
WideBY"&counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertWideCX"&counter&"")
        adCoordinates(2) = getParam("VertWideCY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertWideCX"&counter&"%mm,%Vert
WideCY"&counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertWideDX"&counter&"")
        adCoordinates(2) = getParam("VertWideDY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertWideDX"&counter&"%mm,%Vert
WideDY"&counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertWideEX"&counter&"")
        adCoordinates(2) = getParam("VertWideEY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertWideEX"&counter&"%mm,%Vert
WideEY"&counter&"%mm]",infoArrayParameter)

        adCoordinates(1) = getParam("VertWideFX"&counter&"")
        adCoordinates(2) = getParam("VertWideFY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertWideFX"&counter&"%mm,%Vert
WideFY"&counter&"%mm]",infoArrayParameter)

```

Next

Next

End if

```

*****
' Start of code for winding Design.
*****

Call getDocument().setParameter("", "VertClAX1", "( (%Routslot-.1)^2-
(%FluxpathNarrow/2+.1)^2)^.5", infoNumberParameter)
Call
getDocument().setParameter("", "VertClAY1", "%FluxpathNarrow/2+.1", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaClA", "atan(%VertClAY1/%VertClAX1)", infoNumberParameter)
Call
getDocument().setParameter("", "hypClA", "%VertClAY1/sin(%ThetaClA)", infoNumberParameter)

Call getDocument().setParameter("", "VertWideClAX0", "( (%Routslot-.1)^2-
(%FluxpathWide+.1)^2)^.5", infoNumberParameter)
Call
getDocument().setParameter("", "VertWideClAY0", "%FluxpathWide+.1", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaWideClA", "atan(%VertWideClAY0/%VertWideClAX0)", infoNumberParameter)
Call
getDocument().setParameter("", "hypWideClA", "%VertWideClAY0/sin(%ThetaWideClA)", infoNumberParameter)

Call getDocument().setParameter("", "VertClBX1", "( (%RoutTang+.1)^2-
(%FluxpathNarrow/2+.1)^2)^.5", infoNumberParameter)
Call
getDocument().setParameter("", "VertClBY1", "%FluxpathNarrow/2+.1", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaClB", "atan(%VertClBY1/%VertClBX1)", infoNumberParameter)
Call
getDocument().setParameter("", "hypClB", "%VertClBY1/sin(%ThetaClB)", infoNumberParameter)

Call getDocument().setParameter("", "VertWideClBX0", "( (%RoutTang+.1)^2-
(%FluxpathWide+.1)^2)^.5", infoNumberParameter)
Call
getDocument().setParameter("", "VertWideClBY0", "%FluxpathWide+.1", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaWideClB", "atan(%VertWideClBY0/%VertWideClBX0)", infoNumberParameter)
Call
getDocument().setParameter("", "hypWideClB", "%VertWideClBY0/sin(%ThetaWideClB)", infoNumberParameter)

Call
getDocument().setParameter("", "VertClCX1", "cos(%pi*2*(%Narrow/2+.2)/360)*%Rinstator", infoNumberParameter)
Call
getDocument().setParameter("", "VertClCY1", "sin(%pi*2*(%Narrow/2+.2)/360)*%Rinstator", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaClC", "atan(%VertClCY1/%VertClCX1)", infoNumberParameter)
Call
getDocument().setParameter("", "hypClC", "%VertClCY1/sin(%ThetaClC)", infoNumberParameter)

Call
getDocument().setParameter("", "VertWideClCX0", "cos(%pi*2*(%Wide/2+.2)/360)*%Rinstator", infoNumberParameter)
Call
getDocument().setParameter("", "VertWideClCY0", "sin(%pi*2*(%Wide/2+.2)/360)*%Rinstator", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaWideClC", "atan(%VertWideClCY0/%VertWideClCX0)", infoNumberParameter)
Call
getDocument().setParameter("", "hypWideClC", "%VertWideClCY0/sin(%ThetaWideClC)", infoNumberParameter)

For counter = 1 to symslots

    if counter > 1 then

```



```

Call
getDocument().setParameter("", "VertWideClFY"&counter&"", "%hypWideClC*sin((&(counter-
1)&"%Statorsection+%Statorsection/2)*%pi/180+%ThetaWideClC)", infoNumberParameter)

Call getDocument().getView().newLine(getParam("VertClAX"&counter&""),
getParam("VertClAY"&counter&""), getParam("VertClBX"&counter&""),
getParam("VertClBY"&counter&""))
Call getDocument().getView().newLine(getParam("VertClBX"&counter&""),
getParam("VertClBY"&counter&""), getParam("VertClCX"&counter&""),
getParam("VertClCY"&counter&""))
Call getDocument().getView().newArc(0, 0, getParam("VertClAX"&counter&""),
getParam("VertClAY"&counter&""), getParam("VertWideClAX"&counter&""),
getParam("VertWideClAY"&counter&""))
Call getDocument().getView().newLine(getParam("VertWideClAX"&counter&""),
getParam("VertWideClAY"&counter&""), getParam("VertWideClBX"&counter&""),
getParam("VertWideClBY"&counter&""))
Call getDocument().getView().newLine(getParam("VertWideClBX"&counter&""),
getParam("VertWideClBY"&counter&""), getParam("VertWideClCX"&counter&""),
getParam("VertWideClCY"&counter&""))
Call getDocument().getView().newArc(0, 0, getParam("VertClCX"&counter&""),
getParam("VertClCY"&counter&""), getParam("VertWideClCX"&counter&""),
getParam("VertWideClCY"&counter&""))

Call getDocument().getView().newLine(getParam("VertClDX"&counter&""),
getParam("VertClDY"&counter&""), getParam("VertClEX"&counter&""),
getParam("VertClEY"&counter&""))
Call getDocument().getView().newLine(getParam("VertClEX"&counter&""),
getParam("VertClEY"&counter&""), getParam("VertClFX"&counter&""),
getParam("VertClFY"&counter&""))
Call getDocument().getView().newArc(0, 0, getParam("VertWideClDX"&counter&""),
getParam("VertWideClDY"&counter&""), getParam("VertClDX"&counter&""),
getParam("VertClDY"&counter&""))
Call getDocument().getView().newLine(getParam("VertWideClDX"&counter&""),
getParam("VertWideClDY"&counter&""), getParam("VertWideClEX"&counter&""),
getParam("VertWideClEY"&counter&""))
Call getDocument().getView().newLine(getParam("VertWideClEX"&counter&""),
getParam("VertWideClEY"&counter&""), getParam("VertWideClFX"&counter&""),
getParam("VertWideClFY"&counter&""))
Call getDocument().getView().newArc(0, 0, getParam("VertClFX"&counter&""),
getParam("VertClFY"&counter&""), getParam("VertWideClFX"&counter&""),
getParam("VertWideClFY"&counter&""))

Next

' Make copper conductors

For counter = 1 to symslots

    Backcounter = symslots-counter+1 'reverse the order of conductors

    For coil = 1 to 2
        REDIM ArrayOfValues(0)
        ArrayOfValues(0) = "Copper" & Cstr(Backcounter) &"-"& Cstr(coil)

        If coil = 1 then

            Call
getDocument().getView().selectAt((getParam("VertClAX"&counter&"")+getParam("VertWideClBX
"&counter&""))/2, (getParam("VertClAY"&counter&"")+getParam("VertWideClBY"&counter&""))/2
, infoSetSelection, Array(infoSliceSurface))

            else

            Call
getDocument().getView().selectAt((getParam("VertClDX"&counter&"")+getParam("VertWideClEX
"&counter&""))/2, (getParam("VertClDY"&counter&"")+getParam("VertWideClEY"&counter&""))/2
, infoSetSelection, Array(infoSliceSurface))

            End if

            Call getDocument().getView().makeComponentInALine(getParam("la"),
ArrayOfValues, cond, infoMakeComponentUnionSurfaces Or infoMakeComponentRemoveVertices)
            Call
getDocument().setParameter(ArrayOfValues(0), "SweepDistance", "%la%mm",
infoNumberParameter)

```

Next

Next

```
'Set up coil pairs in correct orientation
For counter = 1 to symslots
```

```
    if counter AND 1 then
        if counter2 AND 1 then
            odd = 1
        else
            odd = 0
        end if
    else
        if counter2 AND 1 then
            odd = 0
        else
            odd = 1
        end if
    end if
```

```
    REDIM ArrayOfValues(3)
    ArrayOfValues(0)= "Copper"&Cstr(counter)&"-1,Face#"&Cstr(2-odd)
    ArrayOfValues(1)= "Copper"&Cstr(counter)&"-1,Face#"&Cstr(1+odd)
    ArrayOfValues(2)= "Copper"&Cstr(counter)&"-2,Face#"&Cstr(1+odd)
    ArrayOfValues(3)= "Copper"&Cstr(counter)&"-2,Face#"&Cstr(2-odd)
```

```
    Call getDocument().makeSimpleCoil(1, ArrayOfValues)
    Call getDocument().setParameter("Coil#"&counter&"", "NumberOfTurns", "%Turns",
infoNumberParameter)
```

Next

```
'Deletes all construction lines on slice
Call getDocument().getView().selectAll(infoSetSelection, Array(infoSliceLine,
infoSliceArc))
Call getDocument().getView().deleteSelection()
```

```
*****
'Select Coil Vertices and Parameterise
*****
```

If Parameterise then

```
    For counter = 1 to Symslots
        For counter1 = 1 to 2
```

```
            Select Case counter1
                Case 1
                    adCoordinates(3) = 0
                Case 2
                    adCoordinates(3) = getParam("la")
            End Select
```

```
            adCoordinates(1) = getParam("VertClAX"&counter&")
            adCoordinates(2) = getParam("VertClAY"&counter&")
            VertexPath = GetVertexPath(iProbID, adCoordinates)
            Call
getDocument().setParameter("&VertexPath&""", "Position", "[%VertClAX"&counter&"%mm,%VertCl
AY"&counter&"%mm]", infoArrayParameter)
```

```
            adCoordinates(1) = getParam("VertClBX"&counter&")
            adCoordinates(2) = getParam("VertClBY"&counter&")
            VertexPath = GetVertexPath(iProbID, adCoordinates)
            Call
getDocument().setParameter("&VertexPath&""", "Position", "[%VertClBX"&counter&"%mm,%VertCl
BY"&counter&"%mm]", infoArrayParameter)
```

```
            adCoordinates(1) = getParam("VertClCX"&counter&")
            adCoordinates(2) = getParam("VertClCY"&counter&")
            VertexPath = GetVertexPath(iProbID, adCoordinates)
```

```

        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertClCX"&counter&"%mm,%VertCl
CY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertClDX"&counter&"")
        adCoordinates(2) = getParam("VertClDY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertClDX"&counter&"%mm,%VertCl
DY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertClEX"&counter&"")
        adCoordinates(2) = getParam("VertClEY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertClEX"&counter&"%mm,%VertCl
EY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertClFX"&counter&"")
        adCoordinates(2) = getParam("VertClFY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertClFX"&counter&"%mm,%VertCl
FY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertWideClAX"&counter&"")
        adCoordinates(2) = getParam("VertWideClAY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertWideClAX"&counter&"%mm,%Ve
rtWideClAY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertWideClBX"&counter&"")
        adCoordinates(2) = getParam("VertWideClBY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertWideClBX"&counter&"%mm,%Ve
rtWideClBY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertWideClCX"&counter&"")
        adCoordinates(2) = getParam("VertWideClCY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertWideClCX"&counter&"%mm,%Ve
rtWideClCY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertWideClDX"&counter&"")
        adCoordinates(2) = getParam("VertWideClDY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertWideClDX"&counter&"%mm,%Ve
rtWideClDY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertWideClEX"&counter&"")
        adCoordinates(2) = getParam("VertWideClEY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertWideClEX"&counter&"%mm,%Ve
rtWideClEY"&counter&"%mm]", infoArrayParameter)

        adCoordinates(1) = getParam("VertWideClFX"&counter&"")
        adCoordinates(2) = getParam("VertWideClFY"&counter&"")
        VertexPath = GetVertexPath(iProbID, adCoordinates)
        Call
getDocument().setParameter("&VertexPath&", "Position", "[%VertWideClFX"&counter&"%mm,%Ve
rtWideClFY"&counter&"%mm]", infoArrayParameter)

Next

Next

End if

' *****
' Start of code for Rotor Design.
' *****

```



```

Call
getDocument().setParameter("", "VertRSAX", "cos(%pi*2*(%Toothgap/2+.2)/360)*%Routrotor", infoNumberParameter)
Call
getDocument().setParameter("", "VertRSAY", "sin(%pi*2*(%Toothgap/2+.2)/360)*%Routrotor", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaRSA", "atan(%VertRSAY/%VertRSAX)", infoNumberParameter)
Call
getDocument().setParameter("", "hypRSA", "%VertRSAY/sin(%ThetaRSA)", infoNumberParameter)

Call getDocument().setParameter("", "VertRSBX", "cos(%pi*2*(%Rotorsection-
%Toothgap)/%Rotorslope+%Toothgap/2)/360)*%Rinrotoractive", infoNumberParameter)
Call getDocument().setParameter("", "VertRSBY", "sin(%pi*2*(%Rotorsection-
%Toothgap)/%Rotorslope+%Toothgap/2)/360)*%Rinrotoractive", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaRSB", "atan(%VertRSBY/%VertRSBX)", infoNumberParameter)
Call
getDocument().setParameter("", "hypRSB", "%VertRSBY/sin(%ThetaRSB)", infoNumberParameter)

Call getDocument().setParameter("", "VertRSCX", "cos(%pi*2*(%Rotorsection-
%Toothgap)/%Rotorslope+%Toothgap/2)/360-1.5/(%Rinrotoractive+ (%Rinrotoractive-
%Rinrotor))* (%Rinrotoractive)", infoNumberParameter)
Call getDocument().setParameter("", "VertRSCY", "sin(%pi*2*(%Rotorsection-
%Toothgap)/%Rotorslope+%Toothgap/2)/360-1.5/(%Rinrotoractive+ (%Rinrotoractive-
%Rinrotor))* (%Rinrotoractive)", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaRSC", "atan(%VertRSCY/%VertRSCX)", infoNumberParameter)
Call
getDocument().setParameter("", "hypRSC", "%VertRSCY/sin(%ThetaRSC)", infoNumberParameter)

Call getDocument().setParameter("", "VertRSDX", "cos(%pi*2*(%Rotorsection-
%Toothgap)/%Rotorslope+%Toothgap/2)/360-1.5/(%Rinrotoractive+ (%Rinrotoractive-
%Rinrotor))* (%Rinrotor)", infoNumberParameter)
Call getDocument().setParameter("", "VertRSDY", "sin(%pi*2*(%Rotorsection-
%Toothgap)/%Rotorslope+%Toothgap/2)/360-1.5/(%Rinrotoractive+ (%Rinrotoractive-
%Rinrotor))* (%Rinrotor)", infoNumberParameter)
Call
getDocument().setParameter("", "ThetaRSD", "atan(%VertRSDY/%VertRSDX)", infoNumberParameter)
Call
getDocument().setParameter("", "hypRSD", "%VertRSDY/sin(%ThetaRSD)", infoNumberParameter)

For counter = 1 to Symsegs

    Call getDocument().setParameter("", "VertRSAX"&counter&"", "%hypRSA*cos("&(counter-
1)&"**Rotorsection*pi/180+%ThetaRSA)", infoNumberParameter)
    Call getDocument().setParameter("", "VertRSAY"&counter&"", "%hypRSA*sin("&(counter-
1)&"**Rotorsection*pi/180+%ThetaRSA)", infoNumberParameter)

    Call getDocument().setParameter("", "VertRSBX"&counter&"", "%hypRSB*cos("&(counter-
1)&"**Rotorsection*pi/180+%ThetaRSB)", infoNumberParameter)
    Call getDocument().setParameter("", "VertRSBY"&counter&"", "%hypRSB*sin("&(counter-
1)&"**Rotorsection*pi/180+%ThetaRSB)", infoNumberParameter)

    Call getDocument().setParameter("", "VertRSCX"&counter&"", "%hypRSC*cos("&(counter-
1)&"**Rotorsection*pi/180+%ThetaRSC)", infoNumberParameter)
    Call getDocument().setParameter("", "VertRSCY"&counter&"", "%hypRSC*sin("&(counter-
1)&"**Rotorsection*pi/180+%ThetaRSC)", infoNumberParameter)

    Call getDocument().setParameter("", "VertRSDX"&counter&"", "%hypRSD*cos("&(counter-
1)&"**Rotorsection*pi/180+%ThetaRSD)", infoNumberParameter)
    Call getDocument().setParameter("", "VertRSDY"&counter&"", "%hypRSD*sin("&(counter-
1)&"**Rotorsection*pi/180+%ThetaRSD)", infoNumberParameter)

    Call
getDocument().setParameter("", "VertRSEX"&counter&"", "%hypRSA*cos("&counter&"**Rotorsecti
on*pi/180-%ThetaRSA)", infoNumberParameter)
    Call
getDocument().setParameter("", "VertRSEY"&counter&"", "%hypRSA*sin("&counter&"**Rotorsecti
on*pi/180-%ThetaRSA)", infoNumberParameter)

```

```

        Call
getDocument().setParameter("", "VertRSFX"&counter&"", "%hypRSB*cos("&counter&"*%Rotorsecti
on*%pi/180-%ThetaRSB)", infoNumberParameter)
        Call
getDocument().setParameter("", "VertRSFY"&counter&"", "%hypRSB*sin("&counter&"*%Rotorsecti
on*%pi/180-%ThetaRSB)", infoNumberParameter)

        Call
getDocument().setParameter("", "VertRSGX"&counter&"", "%hypRSC*cos("&counter&"*%Rotorsecti
on*%pi/180-%ThetaRSC)", infoNumberParameter)
        Call
getDocument().setParameter("", "VertRSGY"&counter&"", "%hypRSC*sin("&counter&"*%Rotorsecti
on*%pi/180-%ThetaRSC)", infoNumberParameter)

        Call
getDocument().setParameter("", "VertRSHX"&counter&"", "%hypRSD*cos("&counter&"*%Rotorsecti
on*%pi/180-%ThetaRSD)", infoNumberParameter)
        Call
getDocument().setParameter("", "VertRSHY"&counter&"", "%hypRSD*sin("&counter&"*%Rotorsecti
on*%pi/180-%ThetaRSD)", infoNumberParameter)

        Call getDocument().getView().newLine(getParam("VertRSAX"&counter&""),
getParam("VertRSAY"&counter&""), getParam("VertRSBX"&counter&""),
getParam("VertRSBY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertRSBX"&counter&""),
getParam("VertRSBY"&counter&""), getParam("VertRSCX"&counter&""),
getParam("VertRSCY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertRSCX"&counter&""),
getParam("VertRSCY"&counter&""), getParam("VertRSDX"&counter&""),
getParam("VertRSDY"&counter&""))

        Call getDocument().getView().newLine(getParam("VertRSEX"&counter&""),
getParam("VertRSEY"&counter&""), getParam("VertRSFX"&counter&""),
getParam("VertRSFY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertRSFX"&counter&""),
getParam("VertRSFY"&counter&""), getParam("VertRSGX"&counter&""),
getParam("VertRSGY"&counter&""))
        Call getDocument().getView().newLine(getParam("VertRSGX"&counter&""),
getParam("VertRSGY"&counter&""), getParam("VertRSHX"&counter&""),
getParam("VertRSHY"&counter&""))

        Call getDocument().getView().newArc(0, 0, getParam("VertRSAX"&counter&""),
getParam("VertRSAY"&counter&""), getParam("VertRSEX"&counter&""),
getParam("VertRSEY"&counter&""))
        Call getDocument().getView().newArc(0, 0, getParam("VertRSDX"&counter&""),
getParam("VertRSDY"&counter&""), getParam("VertRSHX"&counter&""),
getParam("VertRSHY"&counter&""))

        'Create Rotor Segement
        REDIM ArrayOfValues(0)
        ArrayOfValues(0)= "Rotor"&Cstr(counter)
        Call
getDocument().getView().selectAt((getParam("VertRSAX"&counter&"")+getParam("VertRSFX"&co
unter&""))/2,(getParam("VertRSAY"&counter&"")+getParam("VertRSFY"&counter&""))/2,
infoSetSelection, Array(infoSliceSurface))
        Call getDocument().getView().makeComponentInALine(getParam("la"), ArrayOfValues,
lam, infoMakeComponentUnionSurfaces Or infoMakeComponentRemoveVertices)
        Call getDocument().setParameter(ArrayOfValues(0), "SweepDistance", "%la%mm",
infoNumberParameter)

Next

'Deletes all construction lines on slice
Call getDocument().getView().selectAll(infoSetSelection, Array(infoSliceLine,
infoSliceArc))
Call getDocument().getView().deleteSelection()

*****
'Select Rotor Vertices and Parameterise
*****

If Parameterise then

        For counter = 1 to Symsegs

```

```

For counter1 = 1 to 2

    Select Case counter1
        Case 1
            adCoordinates(3) = 0
        Case 2
            adCoordinates(3) = getParam("1a")
    End Select

    adCoordinates(1) = getParam("VertRSAX"&counter&"")
    adCoordinates(2) = getParam("VertRSAY"&counter&"")
    VertexPath = GetVertexPath(iProbID, adCoordinates)
    Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertRSAX"&counter&"%mm,%VertRS
    AY"&counter&"%mm]", infoArrayParameter)

    adCoordinates(1) = getParam("VertRSBX"&counter&"")
    adCoordinates(2) = getParam("VertRSBY"&counter&"")
    VertexPath = GetVertexPath(iProbID, adCoordinates)
    Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertRSBX"&counter&"%mm,%VertRS
    BY"&counter&"%mm]", infoArrayParameter)

    adCoordinates(1) = getParam("VertRSCX"&counter&"")
    adCoordinates(2) = getParam("VertRSCY"&counter&"")
    VertexPath = GetVertexPath(iProbID, adCoordinates)
    Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertRSCX"&counter&"%mm,%VertRS
    CY"&counter&"%mm]", infoArrayParameter)

    adCoordinates(1) = getParam("VertRSDX"&counter&"")
    adCoordinates(2) = getParam("VertRSDY"&counter&"")
    VertexPath = GetVertexPath(iProbID, adCoordinates)
    Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertRSDX"&counter&"%mm,%VertRS
    DY"&counter&"%mm]", infoArrayParameter)

    adCoordinates(1) = getParam("VertRSEX"&counter&"")
    adCoordinates(2) = getParam("VertRSEY"&counter&"")
    VertexPath = GetVertexPath(iProbID, adCoordinates)
    Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertRSEX"&counter&"%mm,%VertRS
    EY"&counter&"%mm]", infoArrayParameter)

    adCoordinates(1) = getParam("VertRSFX"&counter&"")
    adCoordinates(2) = getParam("VertRSFY"&counter&"")
    VertexPath = GetVertexPath(iProbID, adCoordinates)
    Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertRSFX"&counter&"%mm,%VertRS
    FY"&counter&"%mm]", infoArrayParameter)

    adCoordinates(1) = getParam("VertRSGX"&counter&"")
    adCoordinates(2) = getParam("VertRSGY"&counter&"")
    VertexPath = GetVertexPath(iProbID, adCoordinates)
    Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertRSGX"&counter&"%mm,%VertRS
    GY"&counter&"%mm]", infoArrayParameter)

    adCoordinates(1) = getParam("VertRSHX"&counter&"")
    adCoordinates(2) = getParam("VertRSHY"&counter&"")
    VertexPath = GetVertexPath(iProbID, adCoordinates)
    Call
    getDocument().setParameter("&VertexPath&", "Position", "[%VertRSHX"&counter&"%mm,%VertRS
    HY"&counter&"%mm]", infoArrayParameter)

Next

Next

'set all curve centre-points to 0,0
Call FixCentre(iProbID)

End if

'*****
'Implement Circuit Winding and Transient Analysis

```

```

*****

'Insert current sources into circuit diagramme

For count=1 to Phases
    Call getDocument().getCircuit().insertVoltageSource(100,count*200)
    Call getDocument().getCircuit().insertSwitch(200,count*200)
    Call getDocument().getCircuit().insertDiode(300,count*200)
    Call getDocument().getCircuit().insertCurrentSource(400,count*200+75)
    Call getDocument().getCircuit().insertResistor(400,count*200)
next

'Insert windings into circuit diagramme

For count=1 to Symslots/Phases
    PhsCount = (count-1)*Phases
    For count1=1 to Phases
        CALL getDocument().getCircuit().insertCoil("Coil#"&Phscount+count1&"",
400+(Phscount+1)*100, count1*200)
    next
next

'Store locations of terminals in arrays for Current Sources and Windings respectively

ReDim VSourceTermArray(3,4)

For count=1 to Phases
CALL getDocument().getCircuit().getPositionOfTerminal ("V"&count&","T1",t1x,t1y)
CALL getDocument().getCircuit().getPositionOfTerminal ("V"&count&","T2",t2x,t2y)

        VSourceTermArray(count, 1)= t1x
        VSourceTermArray(count, 2)= t1y
        VSourceTermArray(count, 3)= t2x
        VSourceTermArray(count, 4)= t2y

next

ReDim SwitchATermArray(3,4)

For count=1 to Phases
CALL getDocument().getCircuit().getPositionOfTerminal ("S"&count&","T1",t1x,t1y)
CALL getDocument().getCircuit().getPositionOfTerminal ("S"&count&","T2",t2x,t2y)

        SwitchATermArray(count, 1)= t1x
        SwitchATermArray(count, 2)= t1y
        SwitchATermArray(count, 3)= t2x
        SwitchATermArray(count, 4)= t2y

next

ReDim CSourceTermArray(3,4)

For count=1 to Phases
CALL getDocument().getCircuit().getPositionOfTerminal ("I"&count&","T1",t1x,t1y)
CALL getDocument().getCircuit().getPositionOfTerminal ("I"&count&","T2",t2x,t2y)

        CSourceTermArray(count, 1)= t1x
        CSourceTermArray(count, 2)= t1y
        CSourceTermArray(count, 3)= t2x
        CSourceTermArray(count, 4)= t2y

next

ReDim DiodeTermArray(3,4)

For count=1 to Phases
CALL getDocument().getCircuit().getPositionOfTerminal ("D"&count&","T1",t1x,t1y)
CALL getDocument().getCircuit().getPositionOfTerminal ("D"&count&","T2",t2x,t2y)

        DiodeTermArray(count, 1)= t1x
        DiodeTermArray(count, 2)= t1y
        DiodeTermArray(count, 3)= t2x
        DiodeTermArray(count, 4)= t2y

next

```

```

ReDim ResistorTermArray(3,4)

For count=1 to Phases
CALL getDocument().getCircuit().getPositionOfTerminal ("R"&count&","T1",t1x,t1y)
CALL getDocument().getCircuit().getPositionOfTerminal ("R"&count&","T2",t2x,t2y)

    ResistorTermArray(count, 1)= t1x
    ResistorTermArray(count, 2)= t1y
    ResistorTermArray(count, 3)= t2x
    ResistorTermArray(count, 4)= t2y

next

ReDIM CoilTermArray(SymSlots, 4)

for count=1 to SymSlots
    CALL getDocument().getCircuit().getPositionOfTerminal
("Coil#"&count&","T1",ct1x,ct1y)
    CALL getDocument().getCircuit().getPositionOfTerminal
("Coil#"&count&","T2",ct2x,ct2y)

    CoilTermArray(count, 1)= ct1x
    CoilTermArray(count, 2)= ct1y
    CoilTermArray(count, 3)= ct2x
    CoilTermArray(count, 4)= ct2y

next

For count=1 to Phases
    REDIM XArrayOfValues(3)
    XArrayOfValues(0)= VSourceTermArray(count,1)
    XArrayOfValues(1)= VSourceTermArray(count,1)
    XArrayOfValues(2)= SwitchATermArray(count,1)
    XArrayOfValues(3)= SwitchATermArray(count,1)
    REDIM YArrayOfValues(3)
    YArrayOfValues(0)= VSourceTermArray(count,2)
    YArrayOfValues(1)= VSourceTermArray(count,2)+75
    YArrayOfValues(2)= SwitchATermArray(count,2)+75
    YArrayOfValues(3)= SwitchATermArray(count,2)
    CALL getDocument().getCircuit().insertConnection(XArrayOfValues, YArrayOfValues)

    REDIM XArrayOfValues(1)
    XArrayOfValues(0)= SwitchATermArray(count,3)
    XArrayOfValues(1)= DiodeTermArray(count,1)
    REDIM YArrayOfValues(1)
    YArrayOfValues(0)= SwitchATermArray(count,4)
    YArrayOfValues(1)= DiodeTermArray(count,2)
    CALL getDocument().getCircuit().insertConnection(XArrayOfValues, YArrayOfValues)

    REDIM XArrayOfValues(1)
    XArrayOfValues(0)= DiodeTermArray(count,3)
    XArrayOfValues(1)= ResistorTermArray(count,1)
    REDIM YArrayOfValues(1)
    YArrayOfValues(0)= DiodeTermArray(count,4)
    YArrayOfValues(1)= ResistorTermArray(count,2)
    CALL getDocument().getCircuit().insertConnection(XArrayOfValues, YArrayOfValues)

    REDIM XArrayOfValues(1)
    XArrayOfValues(0)= ResistorTermArray(count,3)
    XArrayOfValues(1)= CoilTermArray(count,1)
    REDIM YArrayOfValues(1)
    YArrayOfValues(0)= ResistorTermArray(count,4)
    YArrayOfValues(1)= CoilTermArray(count,2)
    CALL getDocument().getCircuit().insertConnection(XArrayOfValues, YArrayOfValues)

    If Sysmlots > Phases then
        For count1=1 to Phases
            PhsCount = (count-1)*Phases
            REDIM XArrayOfValues(1)
            XArrayOfValues(0)= CoilTermArray(Phscount+count1,3)
            XArrayOfValues(1)= CoilTermArray(Phscount+count1,1)
            REDIM YArrayOfValues(1)
            YArrayOfValues(0)= CoilTermArray(Phscount+count1+1,4)
            YArrayOfValues(1)= CoilTermArray(Phscount+count1+1,2)
            CALL getDocument().getCircuit().insertConnection(XArrayOfValues,
YArrayOfValues)

```

```

        next
    end if

    REDIM XArrayOfValues(2)
    XArrayOfValues(0) = CoilTermArray(Phscount+count,3)
    XArrayOfValues(1) = CoilTermArray(Phscount+count,3)
    XArrayOfValues(2) = CSourceTermArray(count,3)
    REDIM YArrayOfValues(2)
    YArrayOfValues(0) = CoilTermArray(Phscount+count,4)
    YArrayOfValues(1) = CoilTermArray(Phscount+count,4)+75
    YArrayOfValues(2) = CSourceTermArray(count,4)
    CALL getDocument().getCircuit().insertConnection(XArrayOfValues, YArrayOfValues)

    REDIM XArrayOfValues(2)
    XArrayOfValues(0) = CSourceTermArray(count,1)
    XArrayOfValues(1) = DiodeTermArray(count,3)
    XArrayOfValues(2) = DiodeTermArray(count,3)
    REDIM YArrayOfValues(2)
    YArrayOfValues(0) = CSourceTermArray(count,2)
    YArrayOfValues(1) = DiodeTermArray(count,2)+75
    YArrayOfValues(2) = DiodeTermArray(count,2)
    CALL getDocument().getCircuit().insertConnection(XArrayOfValues, YArrayOfValues)

    REDIM XArrayOfValues(3)
    XArrayOfValues(0) = CoilTermArray(Phscount+count,3)
    XArrayOfValues(1) = CoilTermArray(Phscount+count,3)
    XArrayOfValues(2) = VSourceTermArray(count,3)
    XArrayOfValues(3) = VSourceTermArray(count,3)
    REDIM YArrayOfValues(3)
    YArrayOfValues(0) = CoilTermArray(Phscount+count,4)
    YArrayOfValues(1) = CoilTermArray(Phscount+count,4)-75
    YArrayOfValues(2) = VSourceTermArray(count,4)-75
    YArrayOfValues(3) = VSourceTermArray(count,4)
    CALL getDocument().getCircuit().insertConnection(XArrayOfValues, YArrayOfValues)

next

'set Current Source Phase Current and angle

For count=1 to Phases
    Call getDocument().setParameter("V"&count&"", "WaveFormType", "PULSE",
infoTextParameter)
    Call getDocument().setParameter("V"&count&"", "WaveFormValues", "[ -
%MaxVolts/%Sections*(1-%CurrentOn), %MaxVolts/%Sections*(1-%CurrentOn), ((0-
%Advance+("&count-1"*120))/%Rotorsegments)/360*1/(%Speed/60), 0,0,
((%Conduction)/%Rotorsegments)/360*1/(%Speed/60), 1/%Rotorsegments*1/(%Speed/60)]",
infoArrayParameter)
    Call getDocument().setParameter("D"&count&"", "OffResistance", "10000000",
infoNumberParameter)
    Call getDocument().setParameter("D"&count&"", "OnResistance", ".0001",
infoNumberParameter)
    Call getDocument().setParameter("R"&count&"", "Value",
"%Rcoil*%Symslots/%Phases", infoNumberParameter)
    Call getDocument().setParameter("S"&count&"", "SwitchTimes",
"[(%Trot%ms*%Cycles+%Trot/%Steps/2)*%CurrentOn]", infoArrayParameter)
next

Call getDocument().setParameter("I1", "WaveFormType", "PWL", infoTextParameter)
Call getDocument().setParameter("I1", "WaveFormValues", "[0,0,%Trot%ms*%Cycles,-
%MaxAmps*%CurrentOn]", infoArrayParameter)

Call getDocument().setParameter("", "PhaseAdvance", ""& PhaseAdvance
&"", infoNumberParameter)

'Sets the Solver options
Call getDocument().beginUndoGroup("Set Solver Options", true)
Call getDocument().setPolynomialOrder("", 2)
Call getDocument().endUndoGroup()

'Set adaption
Call getDocument().setAdaptionTolerance(0.001)
Call getDocument().setHAdaptionRefinement(0.25)

'Set Motion Component

```

```

REDIM ArrayOfValues(1+Symsegs)
ArrayOfValues(0)= "Rotor Air"
ArrayOfValues(1)= "Rotor Virtual Air"

for count=1 to Symsegs
    ArrayOfValues(1 + count)= "Rotor"&count&"
next

Call getDocument().makeMotionComponent(ArrayOfValues)

CALL getDocument().setMotionSourceType("Motion#1", infoVelocityDriven)

Call getDocument().setParameter("", "TimeSteps", "[0%ms, (%Trot/%Steps)%ms,
%Trot%ms*%Cycles]", infoArrayParameter)
Call getDocument().setParameter("Motion#1", "PositionVsTime", "[0%ms, 0%deg, %Trot%ms,
%Rotorsection%deg*(%MotionOn)]", infoArrayParameter)

'set intial rotor angle

Call getDocument().setParameter("Rotor
Air", "RotationAngle", "%RotorOSangle%deg", infoNumberParameter)
Call getDocument().setParameter("Rotor Virtual
Air", "RotationAngle", "%RotorOSangle%deg", infoNumberParameter)

for count = 1 to Symsegs
    Call
getDocument().setParameter("Rotor"&count&"", "RotationAngle", "%RotorOSangle%deg", infoNumb
erParameter)
next

'sets boundary(even periodic)
REDIM ArrayOfValues(4)
ArrayOfValues(0)= "Stator Virtual Air,Face#5"
ArrayOfValues(1)= "Stator Air,Face#5"
ArrayOfValues(2)= "Rotor Air,Face#5"
ArrayOfValues(3)= "Rotor Virtual Air,Face#4"
ArrayOfValues(4)= "Stator Air,Face#4"
Call getDocument().createBoundaryCondition(ArrayOfValues, "BoundaryCondition#1")
REDIM RotationAxis(2)
RotationAxis(0)= 0
RotationAxis(1)= 0
RotationAxis(2)= 1
REDIM Center(2)
Center(0)= 0
Center(1)= 0
Center(2)= 0
Call getDocument().setOddPeriodic("BoundaryCondition#1", Null, 180, RotationAxis, Null,
Null, Center)
Call
getDocument().setParameter("BoundaryCondition#1", "RotationAngle", "%Theta", infoNumberPara
meter)
Call getDocument().endUndoGroup()

Call getDocument().getView().rotateToAxis(infoPositiveZAxis)
Call getDocument().getView().setScaledToFit(True)
Call getDocument().newCircuitWindow()
Call getDocument().setCurrentView(1)

'*****
'Calls the result for the Parameter Name 'ParaName' from Magnet
'*****

Function getParam(ParamName)

    Call getDocument().getProblem(1).getParameter("", ""&ParamName&"", value)
    getParam = value

End Function

'*****
'Set All centre-point parameters to [0,0]
'*****

```

```

Function FixCentre(iProbID) 'FixComponentCentre(iProbID, sComponentName, adCoordinates,
dEps)

    Const dEps = 2.5

    Dim oPrb, sComponentSurfaceName, sEdgeName, sVertexName, iCounterSurface,
iCounterEdge, _
        iCounterVertex, vX, vY, vZ, sComponentName, iNumberOfComponents,
iComponentVertexIndex, _
        adCoordinates(3), VertexPath, test, test2, testarray(200),teststring, counter

    Set oPrb = getDocument().getProblem(iProbID)

    VertexPath = "No Vertex Found"

    test = 1
    test2 = 1
    counter =1

    adCoordinates(1) = 0
    adCoordinates(2) = 0
    adCoordinates(3) = 0

    iNumberOfComponents = getDocument().getNumberOfComponents()

    For counter = 1 to 2
        For iComponentVertexIndex = 1 To iNumberOfComponents
            sComponentName = getDocument().getPathOfComponent(iComponentVertexIndex)

            iCounterSurface = 1
            Do

                sComponentSurfaceName = sComponentName & ",Face#" & iCounterSurface
                If oPrb.isSurface(sComponentSurfaceName) Then

                    iCounterEdge = 1
                    Do

                        sEdgeName = sComponentSurfaceName & ",Edge#" & iCounterEdge
                        If oPrb.isEdge(sEdgeName) Then

                            iCounterVertex = 1
                            Do
                                sVertexName = sEdgeName & ",Vertex#" & iCounterVertex
                                If oPrb.isVertex(sVertexName) Then

                                    oPrb.getVertexGlobalPosition sVertexName, vX, vY, vZ
                                    If abs(adCoordinates(1) - vX) <= dEps And
abs(adCoordinates(2) - vY) <= dEps And _
abs(adCoordinates(3) - vZ) <= dEps Then
                                        Call
getDocument().setParameter("&sVertexName&", "Position", "[0,0]",infoArrayParameter)
                                        End If 'location correct
                                    Else
                                        Exit Do
                                    End If 'isVertex

                                    iCounterVertex = iCounterVertex + 1

                                Loop ' On edge vertices

                            Else
                                Exit Do
                            End If 'isEdge

                            iCounterEdge = iCounterEdge + 1

                        Loop ' On surface edges

                    Else
                        Exit Do
                    End If 'isSurface

                    iCounterSurface = iCounterSurface + 1

                Loop ' On component surfaces

```



```

        Next 'iNumberOfComponents

adCoordinates(3) = Length

Next 'Counter

End Function

'*****
'Returns the vertex path corresponding to the specified vertex global coordinates.
'*****

Function GetVertexPath(iProbID, adCoordinates)

    Const dEps = 0.001
    Dim sComponentName, iNumberOfComponents, iComponentVertexIndex
    iNumberOfComponents = getDocument().getNumberOfComponents()
    For iComponentVertexIndex = 1 To iNumberOfComponents
        sComponentName = getDocument().getPathOfComponent(iComponentVertexIndex)
        GetVertexPath = GetComponentVertexPath(iProbID, sComponentName, adCoordinates,
dEps)
        If GetVertexPath <> "No Vertex Found" Then: Exit For
    Next

End Function

Function GetComponentVertexPath(iProbID, sComponentName, adCoordinates, dEps)

    Dim oPrb, sComponentSurfaceName, sEdgeName, sVertexName, iCounterSurface,
iCounterEdge, _
        iCounterVertex, vX, vY, vZ

    Set oPrb = getDocument().getProblem(iProbID)

    GetComponentVertexPath = "No Vertex Found"

    iCounterSurface = 1
    Do

        sComponentSurfaceName = sComponentName & ",Face#" & iCounterSurface
        If oPrb.isSurface(sComponentSurfaceName) Then

            iCounterEdge = 1
            Do

                sEdgeName = sComponentSurfaceName & ",Edge#" & iCounterEdge
                If oPrb.isEdge(sEdgeName) Then

                    iCounterVertex = 1
                    Do

                        sVertexName = sEdgeName & ",Vertex#" & iCounterVertex
                        If oPrb.isVertex(sVertexName) Then

                            oPrb.getVertexGlobalPosition sVertexName, vX, vY, vZ
                            If abs(adCoordinates(1) - vX) <= dEps And
abs(adCoordinates(2) - vY) <= dEps And _
                                abs(adCoordinates(3) - vZ) <= dEps Then
                                GetComponentVertexPath = sVertexName
                                Exit Function
                            End If
                        Else
                            Exit Do
                        End If

                        iCounterVertex = iCounterVertex + 1

                    Loop ' On edge vertices

                Else
                    Exit Do
                End If

                iCounterEdge = iCounterEdge + 1

            Loop ' On edge vertices

        Else
            Exit Do
        End If

        iCounterSurface = iCounterSurface + 1

    Do


```

```
        Loop ' On surface edges

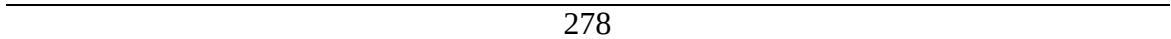
Else
    Exit Function
End If

iCounterSurface = iCounterSurface + 1

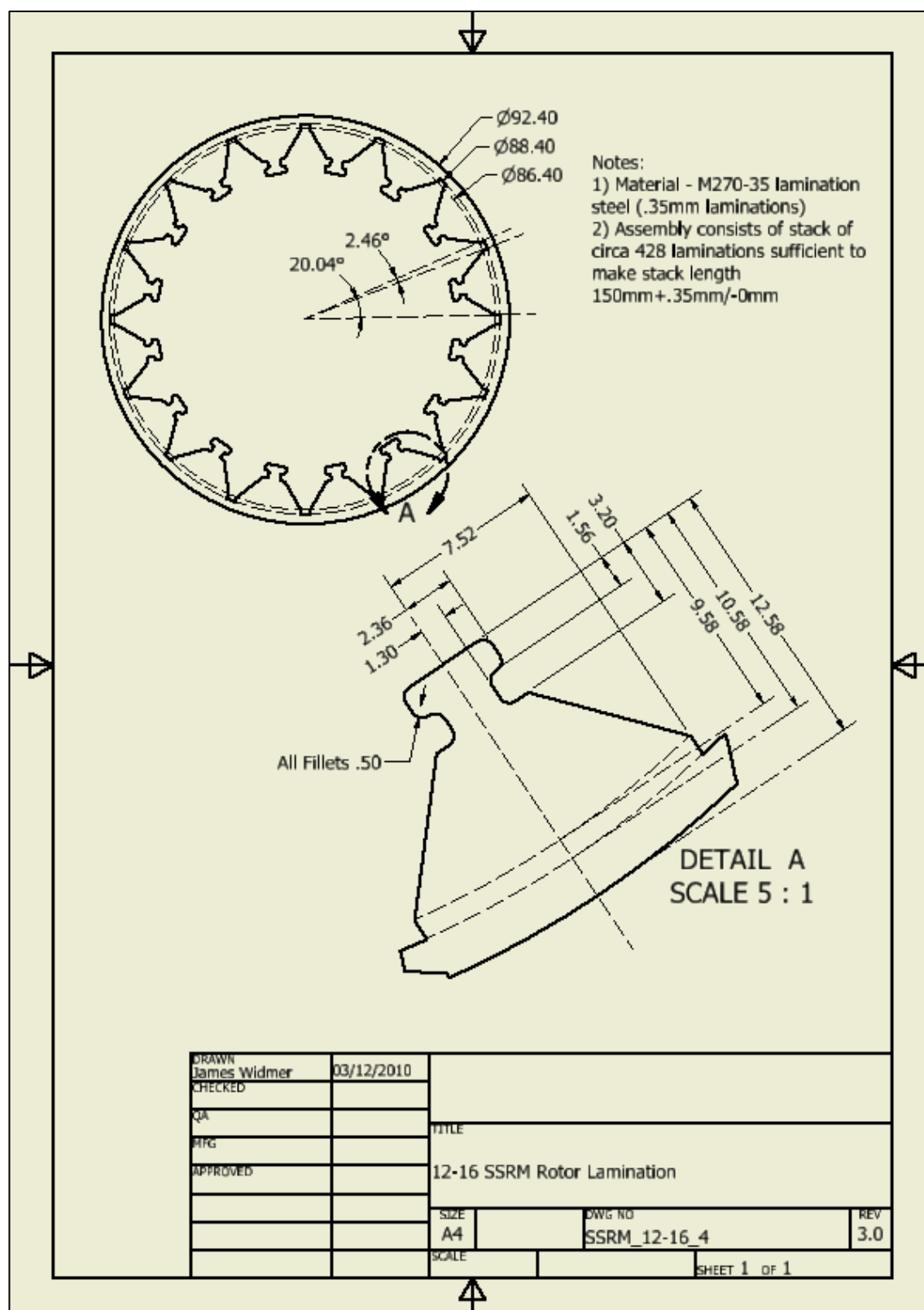
Loop ' On component surfaces

End Function
```

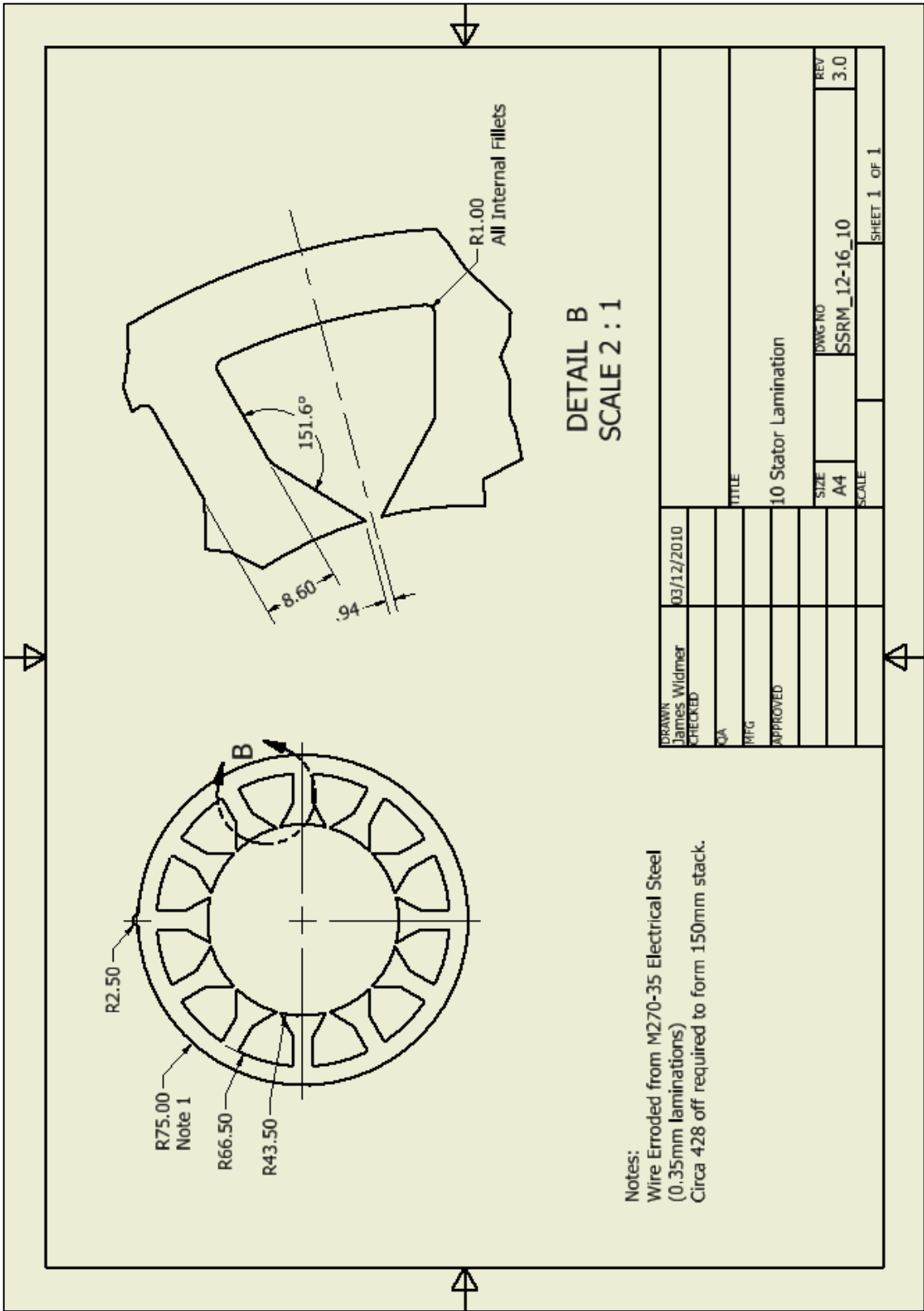
This appendix provides drawings of the key active components of the 12-16 Segmental Rotor SRM with fully pitched windings constructed in Chapter 4.



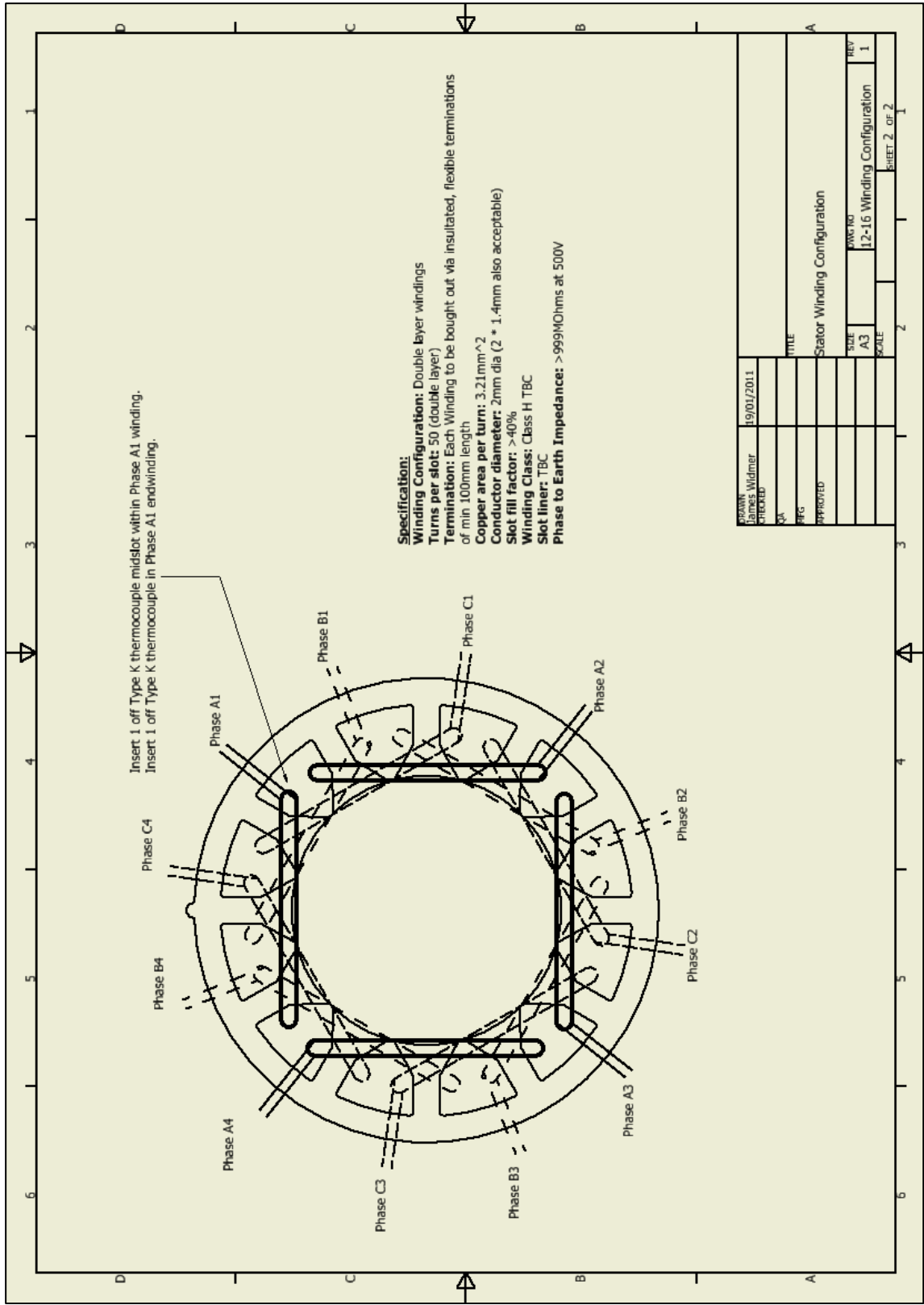
A2.2. Rotor Laminations



A2.4. Stator Laminations



A2.5. Winding Scheme



Appendix 3. Motor Run-down Testing

This appendix provides details of the motor run-down test used to characterise friction, windage and iron losses in the Outer Rotor Permanent Magnet Machine described in Chapter 5.

A3.1. Friction and Windage Loss Estimation

In this test the motor stator is replaced by a dummy plastic unit. This allows the measurement of friction and windage; the removal of the laminated stator means that the magnets do not link flux with the stator and therefore no iron losses are induced, with the only forces acting being those associated with bearing friction and rotor windage. The plastic dummy rotor is fitted with a search coil to allow the accurate measurement of speed. It is known that friction and windage losses apply breaking torque in accordance with the following expression:

$$T_{fw} = T_f + k_w \cdot \omega \quad (\text{A3-1})$$

where T_{fw} is the torque due to friction and winding, T_f is the torque due to friction, k_f the windage coefficient and ω the angular velocity of the rotor.

The kinetic energy due to the inertia of the rotor is given by:

$$KE = \frac{1}{2} \cdot J \cdot \omega^2 \quad (\text{A3-2})$$

where J is the angular moment of inertia and ω the angular velocity of the rotor.

Therefore as the energy of the rotating rotor is dissipated by the friction and windage losses such that:

$$\frac{d}{dt} \left(\frac{1}{2} \cdot J \cdot \omega^2 \right) = -(T_f \cdot \omega + k_w \cdot \omega^2) \quad (\text{A3-3})$$

and therefore (for speeds greater than zero):

$$\omega(t) = \omega_0 \cdot e^{-\frac{k_w}{J} \cdot t} + \frac{T_f}{k_w} \cdot (e^{-\frac{k_w}{J} \cdot t} - 1) \quad (\text{A3-4})$$

with it therefore being possible to fit this curve to the experimental data, by varying the coefficients k_w and T_f , and therefore calculate the values of the friction constant and windage coefficient.

A3.2. Hysteresis and Lamination Eddy Current Loss Estimation

A second test is then undertaken, this time with the laminated stator fitted.

With magnet losses assumed to be zero, in a similar way to the estimation of friction and windage losses, iron losses can be estimated through the Steinmetz equation. Iron losses produce a drag torque which can be approximated to:

$$P_{iron} = k_h \cdot B^\beta \cdot \omega^\alpha + k_e \cdot B^2 \cdot \omega^2 \quad (A3-5)$$

where P_{iron} is the iron losses and, at a single operating point, $k_h \cdot B^\beta$ and $k_e \cdot B^2$ can be assumed to be constants (with B being the flux density, k_h and k_e hysteresis and eddy current loss constants respectively).

If it is assumed that α is 1 (generally it is greater than 1, however this simplifies the mathematics) then these constants can be calculated in the same way as friction and windage such that:

$$\omega(t) = w_0 \cdot e^{-\frac{(k_w + k_e \cdot B^2)}{J} \cdot t} + \frac{(T_f + k_h \cdot B^\beta)}{(k_w + k_e \cdot B^2)} \cdot (e^{-\frac{(k_w + k_e \cdot B^2)}{J} \cdot t} - 1) \quad (A3-6)$$

As k_w and T_f are known, it is then possible to curve fit the coefficients (including flux density terms) for hysteresis loss ($k_h \cdot B^\beta$) and eddy current loss ($k_e \cdot B^2$). A judgment can be made with respect to the magnitude of the flux density terms in these coefficients based on the known, peak airgap flux density; however this would assume a sinusoidal flux density which is unlikely in a machine with fractional slot windings.

Appendix 4. Base Speed / Peak Torque Estimation Script

This Visual Basic script interfaces with Infolytica MagNet (software version 7.4.1) to estimate whether a given Segmental Rotor SRM geometry can achieve the required torque at base speed. It also sets up transient current source models in MagNet to allow efficiency to be estimated at the operating point around which the motor will be optimised.

A4.1. Script File

```

'*****
'13-04-01 SR-SRM Base Speed Peak Torque Check v4
'*****

'v1 - first working version
'v2 - improved script with bug fixes
'v3 - script modified in response to BCM comments
'v4 - code tidy-up and commenting

'*****
'Script Set-Up
'*****

Call getDocument().setNumberOfMultiCoreSolveThreads(3)

'Set Logfile Location
Call getDocument().getProblem(1).getParameter("", "LogFileName", strDirectory)
Call getDocument().getProblem(1).getParameter("", "LogFileName", strFile)

Main()

'Set Iteration Number variable in Magnet
Call getDocument().getParameter("", "Iteration", Iteration)
CALL getDocument().setParameter("", "Iteration", "" & Iteration + 1 & "",
infoNumberParameter)

'*****
'Main Script Sub-Routine
'*****

Sub Main()

    'Static Index - 1: Unaligned, 2: Max Torque, 3: Aligned Postion
    MaxTIndex = 2
    UnalIndex = 1

    'Set initial number of turns
    InitTurns = 50

    'Set problems to solve during optimisation
    DynamicArraySize = 1
    Redim DynamicIndexArray(DynamicArraySize)
    DynamicIndexArray(0) = 5
    'DynamicIndexArray(1) = 6
    'DynamicIndexArray(2) = 7

    'TgtTorque = 140
    kRipple = .65 'assumed torque ripple level at base speed / peak torque
    kOffset = 1.05 'torque ripple asymetry around average torque
    UnalIndScale = 1.15 'unaligned inductance multiplication factor to allow for 3D
effects
    TorqueScale = 1.05 'required torque multiplication factor to allow for 3D and
build effects
    TgtSpeed = 3000 'target base speed

    pi = 3.14159265358979323846264338327950288419716939937510

```

```

Call getDocument().getParameter("", "Iteration", Iteration)

'Write Logfile Titles
Call Writelog(Now,strDirectory , strFile, vbCrLf _
&" *****NEW OPTINET
CYCLE*****"& vbCrLf _
&" OptiNet Solution ID: "& Iteration & vbCrLf)

' Call Parameters from Magnet
Call getDocument().setParameter("", "Index", ""&MaxTIndex&"" ,
infoNumberParameter)
Call getDocument().setParameter("", "Turns", ""&InitTurns&"" ,
infoNumberParameter)
CALL getDocument().setParameter("", "NotSolved", "1", infoNumberParameter)
Call getDocument().getProblem(1).getParameter("", "Sections", Sections)
Call getDocument().getProblem(1).getParameter("", "Rotorsegments", Rotorsegments)
Call getDocument().getProblem(1).getParameter("", "MaxVolts", MaxVolts)
Call getDocument().getProblem(1).getParameter("", "MaxAmps", MaxCurrent)
Call getDocument().getProblem(1).getParameter("", "Torque", TgtTorque)
'Call getDocument().getProblem(1).getParameter("", "Speed", TgtSpeed)
Call getDocument().getProblem(1).getParameter("", "Phases", Phases)
Call getDocument().getProblem(1).getParameter("", "Toothgap", Toothgap) :
Toothgap = Rotorsegments * Toothgap

'Set up Magnet to undertake 'static' analysis in Phase B (linear rising current)
'This uses transient solver with very slow current rise time
Call getDocument().setParameter("I1", "WaveFormType", "PWL", infoTextParameter)
Call getDocument().setParameter("I1", "WaveFormValues",
"[0,0,%Trot%ms*Cycles,0]", infoArrayParameter)

Call getDocument().setParameter("I2", "WaveFormType", "PWL", infoTextParameter)
Call getDocument().setParameter("I2", "WaveFormValues", "[0,-
1*%CurrentOn,%Trot%ms*Cycles,-%MaxAmps*CurrentOn]", infoArrayParameter)

For phs = 3 to Phases

    Call getDocument().setParameter("I"&phs&"" , "WaveFormType", "PWL",
infoTextParameter)
    Call getDocument().setParameter("I"&phs&"" , "WaveFormValues",
"[0,0,%Trot%ms*Cycles,0]", infoArrayParameter)

Next

'*****
Delay 2

CALL getDocument().solveTransient2d()

Delay 2
'*****

'Extract Torque, Current and Fluxlinkage values from Magnet

TimeInstants = getDocument().getSolution().getFieldSolutionTimeInstants(1,Steps)
MaxTorque = 0
REDIM ArrayofValues(2)
REDIM ArrayofTorques(2,TimeInstants)
REDIM ArrayofMMFs(2,TimeInstants)
REDIM ArrayofFluxLinkage(2,TimeInstants)
ArrayofValues(0) = 1 'ProblemID
REM ArrayofValues(0) = 2 'ProblemID

For i = 0 to TimeInstants-1

    ArrayofValues(1) = Steps(i)

    Call
getDocument().getSolution().getTorqueAboutOriginOnBody(ArrayofValues, "Rotor Virtual
Air", torque_x, torque_y, torque_z)

    ArrayofTorques(1,i) = ABS(torque_z) * Sections

    If ArrayofTorques(1,i) > MaxTorque then
        MaxTorque = ArrayofTorques(1,i)
    End if

```

```

Call
getDocument().getSolution().getCurrentThroughCoil(ArrayofValues,"Coil#2", magnitude,
phase)

ArrayofMMFs(1,i) = ABS(magnitude)*InitTurns

CALL
getDocument().getSolution().getFluxLinkageThroughCoil(ArrayofValues,"Coil#2", magnitude,
phase)

ArrayofFluxLinkage(1,i) = magnitude*Sections

Next

'Present results in log file

REDIM TxtFileArray(TimeInstants)

For i = 0 to TimeInstants-1: TxtFileArray(i) = Round(ArrayofMMFs(1,i),2): Next:
MMFs = Join(TxtFileArray," ")
For i = 0 to TimeInstants-1: TxtFileArray(i) = Round(ArrayofTorques(1,i),2):
Next: Torques = Join(TxtFileArray," ")
For i = 0 to TimeInstants-1: TxtFileArray(i) = Round(ArrayofFluxLinkage(1,i),3):
Next: FluxLinkage = Join(TxtFileArray," ")

Call Writelog(Now,strDirectory , strFile, vbCrLf
&" MaxTorque MMFs = "& MMFs & vbCrLf
&" MaxTorque Torques = "& Torques & vbCrLf
&" MaxTorque FluxLinkage = "& FluxLinkage & vbCrLf)

'Calculate the target maximum torque - this is an estimate of the peak torque
required to achieve
' the required average torque based on assumptions about torque ripple
magnitude. This is also
' multiplied up by TorqueScale to allow for 3D and build effects.

TgtMaxTorque = kOffset*TgtTorque*(1 + kRipple/2)*TorqueScale

'Reject any machine that can not produce max torque with InitTurns number of
turns per coil

If MaxTorque < TgtMaxTorque then

CALL getDocument().setParameter("", "NotSolved", "1",
infoNumberParameter)
Call Writelog(Now,strDirectory , strFile, vbCrLf
&" *** REJECTED DESIGN: Motor can not reach required torque:
TgtMaxTorque = "& TgtMaxTorque &" > MaxTorque = "&Round(MaxTorque,2) &" for Turns = "&
InitTurns & vbCrLf)
Exit Sub

End if

REDIM ArrayofCurrents(2,TimeInstants)

'Select number of turns which will generate required Target Peak Torque for
maximum supply current

For turns = 1 to InitTurns

'Set up array containing phase current values for each step given
number of turns

For i = 0 to TimeInstants-1

ArrayofCurrents(1,i) = ArrayofMMFs(1,i)/turns

if ArrayofCurrents(1,i) < MaxCurrent then
x = i
End if

Next

'Interpolate the max torque which can be produced for a given
supply current and number of turns

```

```

        If x < TimeInstants-1 then
            TurnsMaxTorque = (ArrayofTorques(1,x+1)-
            ArrayofTorques(1,x)) * (MaxCurrent-ArrayofCurrents(1,x)) / (ArrayofCurrents(1,x+1)-
            ArrayofCurrents(1,x)) + ArrayofTorques(1,x)
            Else
                TurnsMaxTorque = (ArrayofTorques(1,x)-
                ArrayofTorques(1,x-1)) * (MaxCurrent-ArrayofCurrents(1,x-1)) / (ArrayofCurrents(1,x)-
                ArrayofCurrents(1,x-1)) + ArrayofTorques(1,x-1)
            End if

        'As soon as TurnsMaxTorque is greater than the requirement, fix
        the optimum number of turns and calculate the current required to deliver that torque

        If TurnsMaxTorque > TgtMaxTorque then

            OptTurns = turns

            i = TimeInstants-1
            turns = InitTurns

            If x < TimeInstants-1 then
                CurrentforTgtMaxTorque =
                (ArrayofCurrents(1,x+1)-ArrayofCurrents(1,x)) * (TgtMaxTorque-
                ArrayofTorques(1,x)) / (ArrayofTorques(1,x+1)-ArrayofTorques(1,x)) + ArrayofCurrents(1,x)
                Else
                    CurrentforTgtMaxTorque =
                    (ArrayofCurrents(1,x)-ArrayofCurrents(1,x-1)) * (TgtMaxTorque-ArrayofTorques(1,x-
                    1)) / (ArrayofTorques(1,x)-ArrayofTorques(1,x-1)) + ArrayofCurrents(1,x-1)
                End if

            End if

        End if

    Next

    'Write results to log file

    Call Writelog(Now,strDirectory , strFile, vbCrLf _
    &"
    &"            Target Peak Torque ="& Round(TgtMaxTorque,2) & vbCrLf _
    &"            For Turns ="& OptTurns &" with Max Supply Current ="&
    Round(MaxCurrent,2) &"A => Maximum Torque ="& Round(TurnsMaxTorque,2) &"Nm"& vbCrLf _
    &"            For Turns ="& OptTurns &" at rqd Peak Torque ="&
    Round(TgtMaxTorque,2) &"Nm => Current ="& Round(CurrentforTgtMaxTorque,2) &"A"& vbCrLf)

    'Set new turns number in Magnet

    If OptTurns > 0 then
        Call getDocument().setParameter("", "Turns", ""& OptTurns &"",
        infoNumberParameter)
    Else
        MsgBox "Error"
        Exit Sub
    End if

    'Rerun 'static' analysis in Magnet

    Call getDocument().setParameter("", "Index", ""&UnalIndex&","&MaxTIndex&"" ,
    infoNumberParameter)

    '*****
    Delay 2

    CALL getDocument().solveTransient2d()

    Delay 2
    '*****

    'Extract Unaligned and Aligned Flux linkage from Magnet

    For ID = 1 to 2 'ProblemIDs for Unaligned and MaxT Positions

        ArrayofValues(0) = ID

        For i = 0 to TimeInstants-1

```

```

        ArrayofValues(1) = Steps(i)

        Call
        getDocument().getSolution().getCurrentThroughCoil(ArrayofValues,"Coil#2", magnitude,
        phase)

        ArrayofCurrents(ID-1,i) = magnitude
        ArrayofMMFs(ID-1,i) = magnitude * OptTurns

        CALL
        getDocument().getSolution().getFluxLinkageThroughCoil(ArrayofValues,"Coil#2", magnitude,
        phase)

        ArrayofFluxLinkage(ID-1,i) = magnitude * Sections

        Call
        getDocument().getSolution().getTorqueAboutOriginOnBody(ArrayofValues, "Rotor Virtual
        Air", torque_x, torque_y, torque_z)

        ArrayofTorques(ID-1,i) = ABS(torque_z) * Sections

    Next

Next

'Output results to Log File

REDIM TxtFileArray(TimeInstants)

MMFs = ""
FluxLinkage = ""

    For i = 0 to TimeInstants-1: TxtFileArray(i) = Round(ArrayofMMFs(0,i),2): Next:
MMFs = Join(TxtFileArray," ")
    For i = 0 to TimeInstants-1: TxtFileArray(i) = Round(ArrayofCurrents(0,i),2):
Next: Currents = Join(TxtFileArray," ")
    For i = 0 to TimeInstants-1: TxtFileArray(i) = Round(ArrayofTorques(1,i),2):
Next: Torques = Join(TxtFileArray," ")
    For i = 0 to TimeInstants-1: TxtFileArray(i) = Round(ArrayofFluxLinkage(0,i),3):
Next: FluxLinkage = Join(TxtFileArray," ")
    For i = 0 to TimeInstants-1: TxtFileArray(i) = Round(ArrayofFluxLinkage(1,i),3):
Next: FluxLinkage1 = Join(TxtFileArray," ")

    Call Writelog(Now,strDirectory , strFile, vbCrLf _
        &"          Unaligned / MaxT MMFs          = "& MMFs & vbCrLf _
        &"          Unaligned / MaxT Currents = "& Currents & vbCrLf _
        &"          MaxTorque Torques          = "& Torques & vbCrLf _

        &"          Unaligned FluxLinkage      = "& FluxLinkage & vbCrLf _
        &"          MaxT Postion FluxLinkage     = "& FluxLinkage1 & vbCrLf)

'Sets-up script to calculate current rise time

MaxRiseTime = 30/(Rotorsegments*TgtSpeed) 'Max time available to rise to required
current for required torque

For i = 0 to TimeInstants-1
    if ArrayofCurrents(0,i) > CurrentforTgtMaxTorque then
        x = i-1
        i = TimeInstants-1
    End if
Next

'Interpolates flux linkage in the MaxT postion for target torque and then
calculates current rise time from this flux linkage

FluxLinkforTgtMaxTorque = ArrayofFluxLinkage(1,x) + ((ArrayofFluxLinkage(1,x+1)-
ArrayofFluxLinkage(1,x))*(CurrentforTgtMaxTorque -
ArrayofCurrents(0,x))/(ArrayofCurrents(0,x+1)- ArrayofCurrents(0,x)))

TRise = FluxLinkforTgtMaxTorque/MaxVolts

'Writes to log file

Call Writelog(Now,strDirectory , strFile, vbCrLf _

```

```

&" Max Supply Voltage = "&
Round(MaxVolts,2) &"V"& vbCrLf _
&" Selected Mechanical Speed = "&
Round(TgtSpeed,2) &"rpm"& vbCrLf _
&" Maximum Current Rise Time at selected speed = "&
Round(MaxRiseTime*1000^2,2) &"us"& vbCrLf _
&" Rise Time to reach Achieved Current = "&
Round(Trise*1000^2,2) &"us"& vbCrLf)

'Reject designs where current will not rise high enough to deliver required
torque.

If TRiseCum > MaxRiseTime then
    CALL getDocument().setParameter("", "NotSolved", "1",
infoNumberParameter)
    Call Writelog(Now,strDirectory , strFile, vbCrLf _
&" *** REJECTED DESIGN: Motor cannot reach required base
speed / torque conditions: Required Current for Peak Torque = "&
Round(CurrentforTgtMaxTorque,2) &" > Achieved Current = "& Round(IRise,2) &" for Turns =
"& OptTurns & vbCrLf)

    Call getDocument().setParameter("", "Index", ""&UnalIndex&"",
infoNumberParameter)

    Exit Sub

Else

    CALL getDocument().setParameter("", "NotSolved", "0",
infoNumberParameter)
    Call Writelog(Now,strDirectory , strFile, vbCrLf _
&" *****& vbCrLf _
&" ACCEPTED DESIGN: Motor can reach required base
speed / torque conditions: Required Current for Peak Torque = "&
Round(CurrentforTgtMaxTorque,2) &" achieved in Time = "& Round(Trise*1000^2,2) &" us for
Turns = "& OptTurns & vbCrLf _
&" *****&
vbCrLf)

End if

'Constructs Current Waveforms for Dynamic FE Analysis.

Redim CurrentforTgtMaxTorqueArray(DynamicArraySize)
Redim TRiseArray(DynamicArraySize)
Redim TFallArray(DynamicArraySize)

'Sets up arrays which will tranfer current waveform data to Magnet

CurrentforTgtMaxTorqueString = "["
TRiseString = "["
TFallString = "["

For i = 1 to DynamicIndexArray(0)-1
    CurrentforTgtMaxTorqueString = CurrentforTgtMaxTorqueString &"0,"
    TRiseString = TRiseString &"0,"
    TFallString = TFallString &"0,"
Next

'Gets dynamic model run setting from Magnet

For count = 0 to DynamicArraySize-1

    Call getDocument().setParameter("", "Index", ""& DynamicIndexArray(count)
&"", infoNumberParameter)

    Call getDocument().getProblem(1).getParameter("", "Torque", TgtTorque) :
TgtMaxTorque = kOffset*TgtTorque*(1 + kRipple/2)
    Call getDocument().getProblem(1).getParameter("", "Speed", TgtSpeed)

    For i = 0 to TimeInstants-1
        if ArrayofTorques(1,i) > TgtMaxTorque then
            x = i
            i = TimeInstants-1
        End if
    
```

```

Next

CurrentforTgtMaxTorque = (ArrayofCurrents(1,x)-ArrayofCurrents(1,x-1)) * (TgtMaxTorque-ArrayofTorques(1,x-1)) / (ArrayofTorques(1,x)-ArrayofTorques(1,x-1))+ArrayofCurrents(1,x-1)

'Calculate flux linkage in unaligned position at required current and therefore derive current rise time to achieve tgt torque

FluxLinkforTRise = ArrayofFluxLinkage(0,x-1) + ((ArrayofFluxLinkage(0,x)-ArrayofFluxLinkage(0,x-1)) * (TgtMaxTorque-ArrayofTorques(1,x-1)) / (ArrayofTorques(1,x)-ArrayofTorques(1,x-1)))

TRise = FluxLinkforTRise/MaxVolts

'To calculate current fall time, first extrapolate flux linkage into aligned position and then calculate current fall time

FluxLinkforTFallUnal = ArrayofFluxLinkage(0,x-1) + ((ArrayofFluxLinkage(0,x)-ArrayofFluxLinkage(0,x-1)) * (TgtMaxTorque-ArrayofTorques(1,x-1)) / (ArrayofTorques(1,x)-ArrayofTorques(1,x-1)))

FluxLinkforTFallMaxT = ArrayofFluxLinkage(1,x-1) + ((ArrayofFluxLinkage(1,x)-ArrayofFluxLinkage(1,x-1)) * (TgtMaxTorque-ArrayofTorques(1,x-1)) / (ArrayofTorques(1,x)-ArrayofTorques(1,x-1)))

FluxLinkforTFallAlign = FluxLinkforTFallUnal + (FluxLinkforTFallMaxT - FluxLinkforTFallUnal) * 180/90 'MaxT position being at 90 degrees and aligned at 180degrees

TFall = -FluxLinkforTFallAlign/-MaxVolts

'Calculate current on-time at target speed

OnTime = (180/Rotorsegments)/360*1/(TgtSpeed/60)

'Write to log file

Call Writelog(Now,strDirectory , strFile, vbcrLf _
&"          Index Number                                = "&
DynamicIndexArray(count) & vbcrLf _
&"          Target Average Torque                        = "&
Round(TgtTorque,2) &"Nm"& vbcrLf _
&"          Target Peak Torque                          = "&
Round(TgtMaxTorque,2) &"Nm"& vbcrLf _
&"          Target Speed                                = "&
Round(TgtSpeed,2) &"rpm"& vbcrLf _
&"          Current to achieve Target Torque            = "&
Round(CurrentforTgtMaxTorque,2) &"A"& vbcrLf _
&"          Rise Flux Linkage for Tgt Speed / Current   = "&
Round(FluxLinkforTFallUnal*1000,2) &"mWb"& vbcrLf _
&"          Fall Flux Linkage for Tgt Speed / Current   = "&
Round(FluxLinkforTFallAlign*1000,2) &"mWb"& vbcrLf _
&"          On Time                                      = "&
Round(OnTime*1000^2,2) &"us"& vbcrLf _
&"          Estimated Current Rise Time                = "&
Round(Trise*1000^2,2) &"us"& vbcrLf _
&"          Estimated Current Fall Time                = "&
Round(Tfall*1000^2,2) &"us"& vbcrLf _
&"          TRise / OnTime (problem if >50%)            = "&
Round(Trise/OnTime*100,2) &"%"& vbcrLf)

CurrentforTgtMaxTorqueArray(count) = CurrentforTgtMaxTorque
TRiseArray(count) = Trise
TFallArray(count) = Tfall

CurrentforTgtMaxTorqueString = CurrentforTgtMaxTorqueString &
CurrentforTgtMaxTorqueArray(count)
TRiseString = TRiseString & TRiseArray(count)
TFallString = TFallString & TFallArray(count)

if count < DynamicArraySize-1 then
CurrentforTgtMaxTorqueString =
CurrentforTgtMaxTorqueString & ","
TRiseString = TRiseString & ","
TFallString = TFallString & ","

```



```

End if

Next

'Set-up Magnet for transient with motion studies

CurrentforTgtMaxTorqueString = CurrentforTgtMaxTorqueString & "]"
TRiseString = TRiseString & "]"
TFallString = TFallString & "]"

Call getDocument().setParameter("", "CurrentforTgtMaxTorqueArray",
""&CurrentforTgtMaxTorqueString&"", infoArrayParameter)
Call getDocument().setParameter("", "TRiseArray", ""&TRiseString&"",
infoArrayParameter)
Call getDocument().setParameter("", "TFallArray", ""&TFallString&"",
infoArrayParameter)

Call getDocument().setParameter("", "CurrentforTgtMaxTorque",
"%CurrentforTgtMaxTorqueArray[%Index]", infoNumberParameter)
Call getDocument().setParameter("", "TRise", "%TRiseArray[%Index]",
infoNumberParameter)
Call getDocument().setParameter("", "TFall", "%TFallArray[%Index]",
infoNumberParameter)

For phs = 1 to Phases

Call getDocument().setParameter("I"&phs&"", "WaveFormType",
"PULSE", infoTextParameter)

Call getDocument().setParameter("I"&phs&"", "WaveFormValues",
"[0,%CurrentforTgtMaxTorque*%CurrentOn, ((0+("&phs-
1&"*120))/%Rotorsegments)/360*1/((%Speed/60), %TRise,%TFall,
(%Conduction/%Rotorsegments)/360*1/((%Speed/60)-%TRise, 1/%Rotorsegments*1/((%Speed/60)]",
infoArrayParameter)

Next

DynamicArrayString = ""

For count = 0 to DynamicArraySize-1
DynamicArrayString = DynamicArrayString & DynamicIndexArray(count)

if count < DynamicArraySize-1 then
DynamicArrayString = DynamicArrayString & ","
End if

Next

Call getDocument().setParameter("", "Index", ""& DynamicArrayString &"",
infoNumberParameter)

End Sub

'*****
'Function to allow use to break out on ESC key press
'*****

Function IsSolveStopped()
IsSolveStopped= isKeyPressed(infoEscapeKey)
If (IsSolveStopped) Then IsSolveStopped= CBool(getApplication().MsgBox("Do you want
to stop the solve?", vbYesNo) = vbYes)
End Function

'*****
'Sets up delay to allow Magnet time to complete processing
'*****

Sub Delay(iNumberOfSeconds)
Dim StartTime
StartTime = Timer
While Timer - StartTime < iNumberOfSeconds
Wend
End Sub

```

```

*****
'Function to set-up and write to log file
*****

Sub WriteLog(TimeDate, strDirectory, strFile,Message)

    'Msgbox strDirectory

    strDirectory = Replace(strDirectory,"/","\")

    'Msgbox strDirectory

    'Option Explicit
    Dim objFSO, objFolder, objShell, objTextFile, objFile
    Dim strText, curPath

    ' Create the File System Object
    Set objFSO = CreateObject("Scripting.FileSystemObject")

    ' Check that the strDirectory folder exists
    If objFSO.FolderExists(strDirectory) Then
        Set objFolder = objFSO.GetFolder(strDirectory)
    Else
        Set objFolder = objFSO.CreateFolder(strDirectory)
        'Wscript.Echo "Just created " & strDirectory
    End If

    If objFSO.FileExists(strDirectory & "\" & strFile) Then
        Set objFolder = objFSO.GetFolder(strDirectory)
    Else
        Set objFile = objFSO.CreateTextFile(strDirectory & "\" & strFile)
        'Wscript.Echo "Just created " & strDirectory & strFile
    End If

    set objFile = nothing
    set objFolder = nothing
    ' OpenTextFile Method needs a Const value
    ' ForAppending = 8 ForReading = 1, ForWriting = 2
    Const ForAppending = 8

    Set objTextFile = objFSO.OpenTextFile _
        (strDirectory & "\" & strFile, ForAppending, True)

    ' Writes strText every time you run this VBScript
    objTextFile.WriteLine "[" & TimeDate & "]" & "Message: " & Message)
    objTextFile.Close

End Sub

```

Appendix 5. Derivation of Airgap Heat Transfer Coefficient

This appendix details the derivation of the airgap heat transfer coefficient for use in motor thermal modeling.

A5.1. Derivation

Staton [127] provides a methodology for the calculation of heat transfer across a motor airgap. This initially assumed that the rotor is an unbroken cylinder – clearly not the case with a Segmental Rotor SRM – however later proposes some correction factors to be applied.

Reynolds Number may be estimated from:

$$Re = \frac{\rho \cdot l_g \cdot v}{\mu} \quad (\text{A5-1})$$

where:

ρ is the fluid density (kg/m^3)

l_g the airgap length (m)

v the velocity of the outer surface of the rotor (m/s)

And μ is the viscosity of air (kg/(m.s))

The Taylor number can then be estimated from:

$$Ta = Re \cdot \sqrt{\frac{l_g}{R_r}} \quad (\text{A5-2})$$

where R_r is the rotor radius (m).

The Taylor number then defines differing flow conditions which in turn can be used to calculate the Nusselt Number; this number defines the ratio of convection to conduction heat transfer or in effect the efficiency of convection across the airgap. Therefore with:

- $Ta < 41$ meaning that flow is laminar and the Nusselt number, $Nu = 2$.
- $41 < Ta < 100$ then the flow includes vortices and the Nusslet Number is increased, with:

$$Nu = 0.212 \cdot Ta^{0.63} \cdot Pr^{0.27} \quad (\text{A5-3})$$

- $Ta > 100$ then the flow become turbulent and the Nusselt number increases to:

$$Nu = 0.386 \cdot Ta^{0.5} \cdot Pr^{0.27} \quad (\text{A5-4})$$

Finally the heat transfer coefficient, for heat transfer across the airgap, can be calculated from:

$$h = Nu \cdot \frac{k}{l_g} \quad (\text{A5-5})$$

where k is the thermal conductivity of air.

From these expressions, the heat transfer across the airgap of the Segmental Rotor SRM can then be calculated for differing rotor speeds; the results are summarised in Table A5-2. In this table it is assumed that the airgap is at arbitrarily temperature of 127°C (400K) at all times.

Table A5-2: Calculated Airgap Heat Transfer Coefficients

Condition	2750rpm	10,500rpm	3,500rpm	Units
Rotor Velocity (v)	2.24E+01	8.55E+01	2.85E+01	m/s
Density of Air (ρ)	0.524	0.524	0.524	kg/m ³
Viscosity of Air (μ)	229e-3	229e-3	229e-3	kg/(m.s)
Rotor Radius (R_r)	77.8e-3	77.8e-3	77.8e-3	m
Thermal Conductivity of Air (k)	51.5e-3	51.5e-3	51.5e-3	W/(m.K)
Prandtl Number of Air (Pr)	0.68	0.68	0.68	
Reynolds Number (Re)	154.1	588.3	196.1	
Taylor Number (Ta)	6.8	25.8	8.6	
Nusselt Number (Nu)	2	2	2	
Heat Transfer Coefficient (h)	171.7	171.7	171.7	W/(m ² .K)

As can be seen from the table, in each case the air is estimated to demonstrate laminar flow (the worst case in terms of heat transfer) and therefore the heat transfer coefficient (at this temperature) is estimated to be 171.7W/(m².K).

Staton suggests that in the case of a motor where the rotor is salient, a correction factor of 0.9 should be applied to this estimate; this allows for the large gaps between rotor teeth. Where the stator is also salient then a factor of 0.8 should be applied.

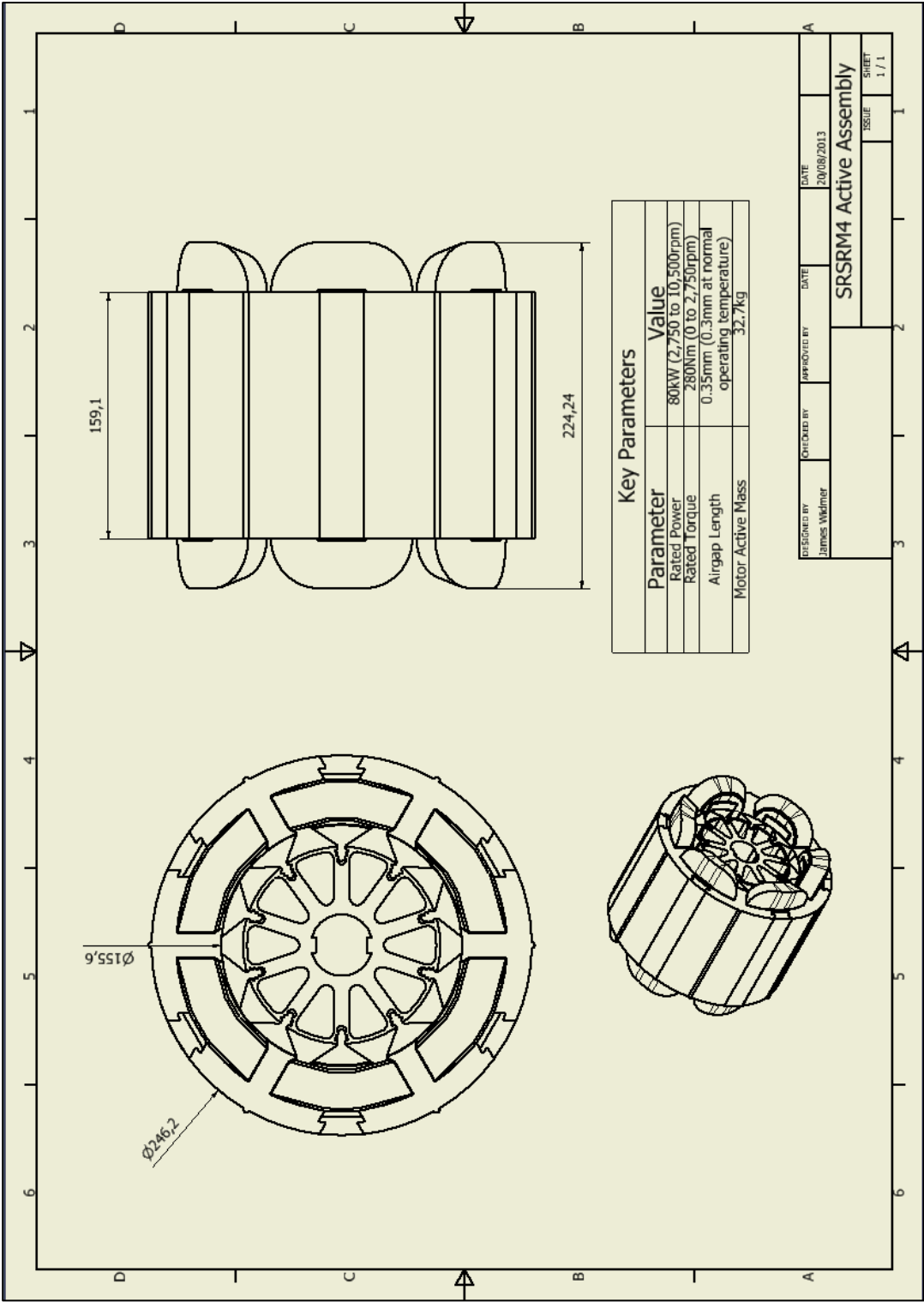
In the case of the Segmental Rotor SRM it was decided to take the mid-point between these two values; whilst the stator is salient it has semi-closed gaps, perhaps making it half way case.

The resulting heat transfer coefficient assumed in modeling is therefore $146\text{W}/(\text{m}^2.\text{K})$.

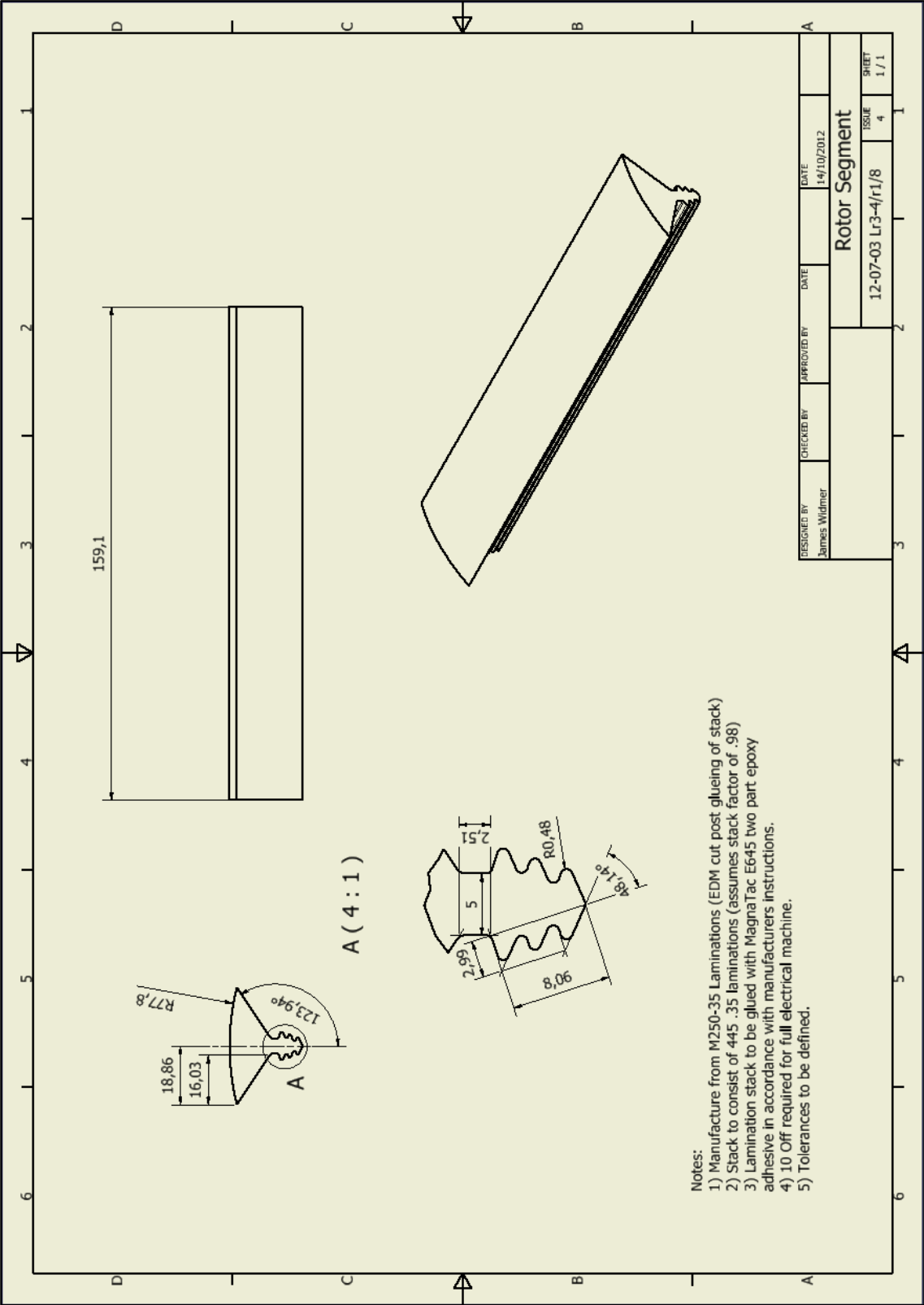
Appendix 6. SRSRM4 Motor Drawings

This appendix provides drawings of the key active components of the SRSRM4 Segmental Rotor SRM final motor design, as constructed in Chapter 9.

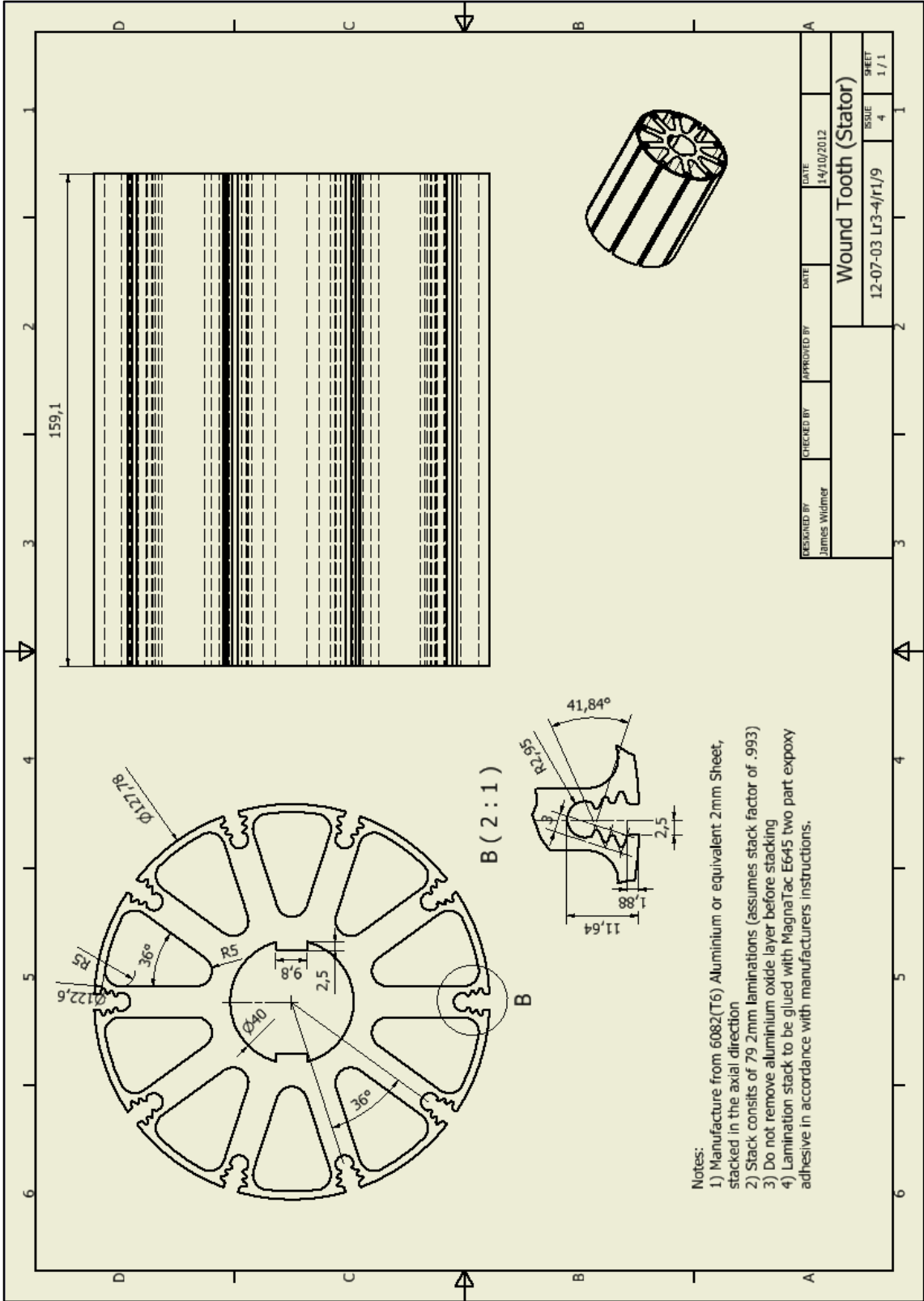
A6.1. Motor Active Assembly



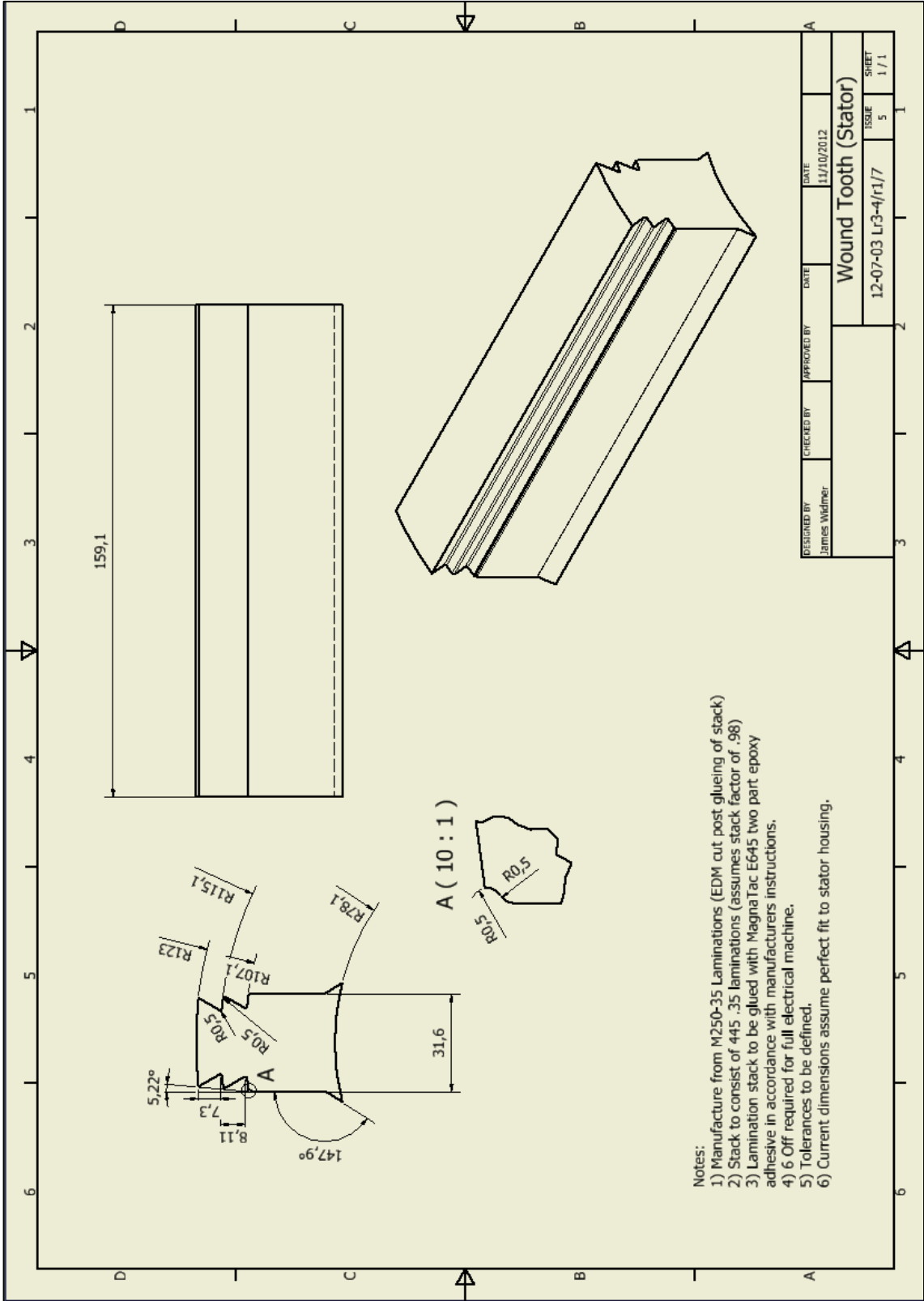
A6.2. Rotor Segment



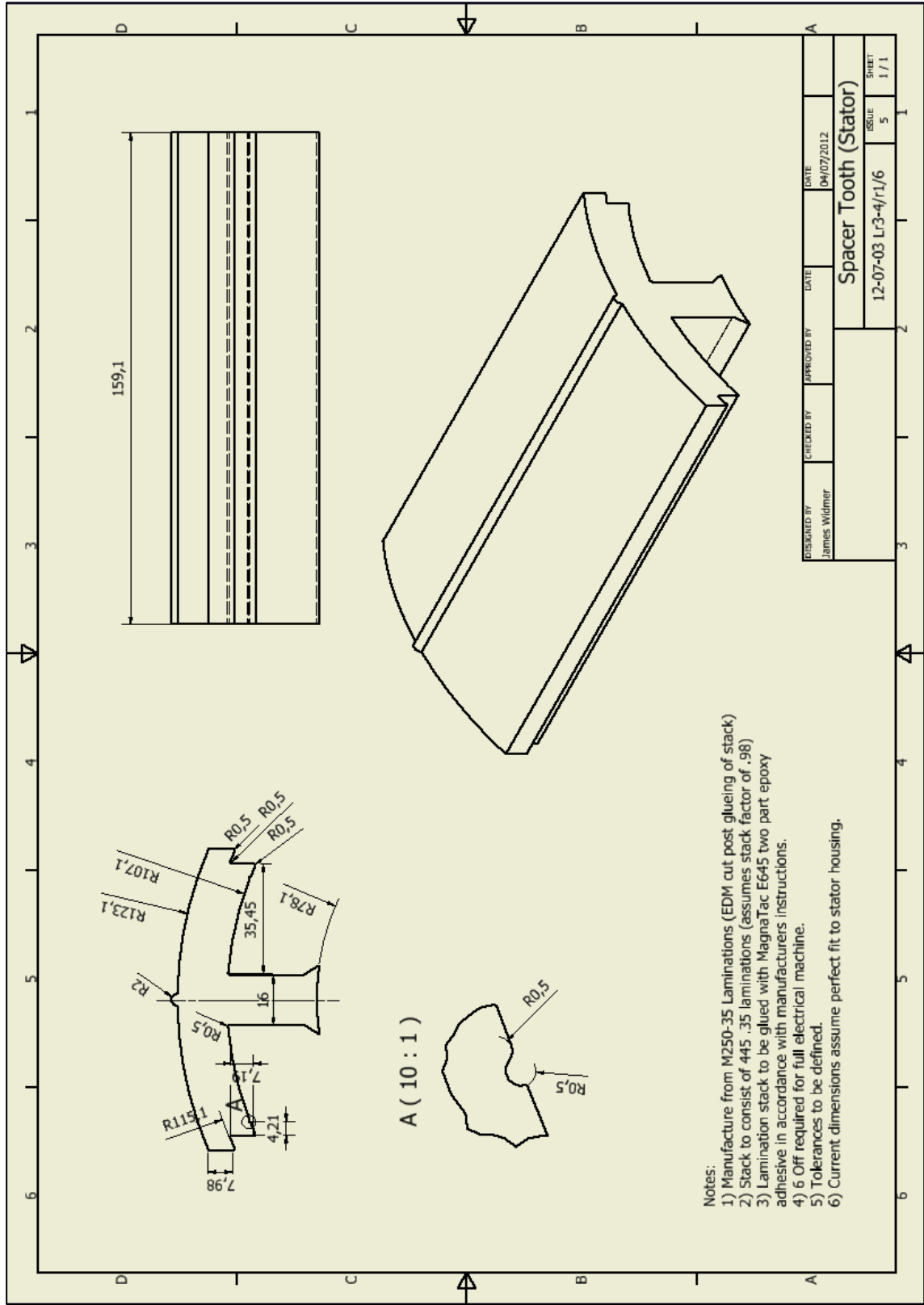
A6.3. Rotor Support



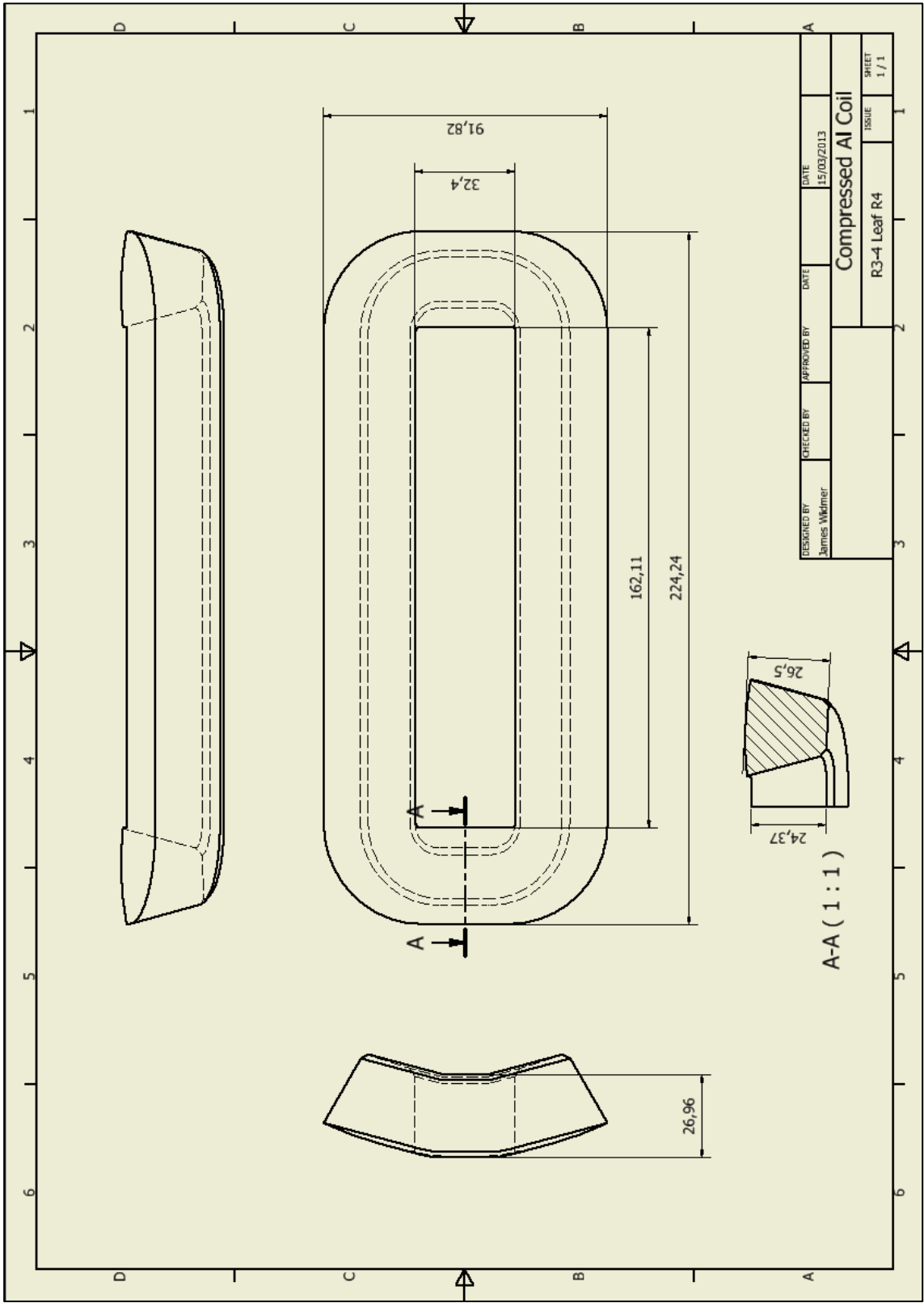
A6.4. Stator Wound Tooth



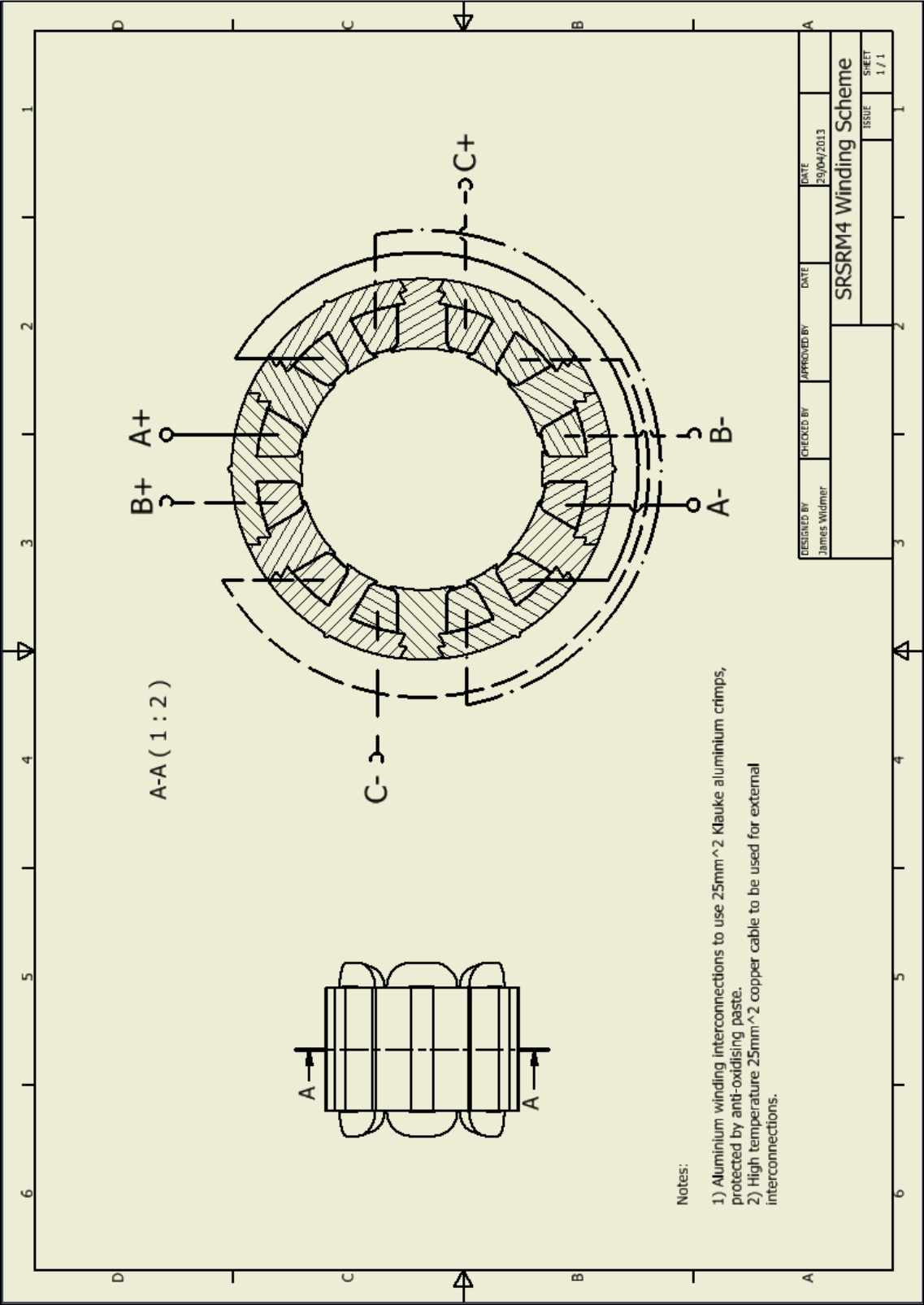
A6.5. Stator Intermediate Tooth



A6.6. Aluminium Compressed Coil



A6.7. Winding Scheme



References

- [1] P. Waide and C. Brunner, "Energy-efficiency policy opportunities for electric motor-driven systems," International Energy Agency OECD, 2011.
- [2] *Energy Conservation Program: Energy Conservation Standards for Small Electric Motors; Final Rule*, US Department of Energy, 2010.
- [3] *Implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors*, European Union, 2009.
- [4] *Electric Vehicles 2010-2020*, IDTechEx, 2010.
- [5] Anon. (2011, 27/12/12). *2011 Production Statistics*. Available: <http://oica.net/category/production-statistics/>
- [6] X. D. Xue, K. W. E Cheng and N. C. Cheung, "Selection of Electric Motor Drives for Electric Vehicles," in *Australasian Universities Power Engineering Conference, AUPEC'08*, 2008.
- [7] S. M. Lukic and A. Emado, "Modeling of electric machines for automotive applications using efficiency maps," in *Proc. Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Technology Conference*, 2003, pp. 543-550.
- [8] Anon. (2012, 28 December). *About the Size of a Watermelon with a Lot More Juice*. Available: <http://www.teslamotors.com/roadster/technology/motor>
- [9] I. S. Sato Y., Okubo T., Abe M. and Tamai K., "Development of High Response Motor and Inverter System for the Nissan LEAF Electric Vehicle," in *SAE 2011 World Congress & Exhibition*, Detroit, Michigan, United States, 2011.
- [10] K. Rahman, Anwar, M., Schulz, S., Kaiser, E. et al., "The Voltec 4ET50 Electric Drive System," *SAE International Journal of Engines*, vol. 4, pp. 323-337, 2011.
- [11] Anon. (2012, 28 December). *A 100% Electric Car*. Available: <http://www.renault.com/en/vehicules/aujourd-hui/renault-vehicules-electriques/pages/fluence-ze.aspx>
- [12] Anon. (2007, 28/12/12). *Hybrid family car uses CSIRO technology*. Available: <http://www.csiro.au/en/Outcomes/Climate/Reducing-GHG/ECOMmodore.aspx>
- [13] Anon. (2009, 28 December). *Jaguar C-X75 Concept*. Available: <http://www.jaguar-cx75.com/jaguar-c-x75-concept>
- [14] H. Neudorfer, et al., "Comparison of three different electric powertrains for the use in hybrid electric vehicles," in *4th IET Conference on Power Electronics, Machines and Drives, PEMD*, 2008, pp. 510-514.
- [15] M. Zeraouila, et al., "Electric motor drive selection issues for HEV propulsion systems: a comparative study," in *IEEE Conf. Vehicle Power and Propulsion*, 2005, p. 8 pp.
- [16] Z. Q. Zhu and C. C. Chan, "Electrical machine topologies and technologies for electric, hybrid, and fuel cell vehicles," in *IEEE Conf. Vehicle Power and Propulsion Conference, VPPC '08*, 2008, pp. 1-6.
- [17] Z. Q. Zhu and D. Howe, "Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles," *Proceedings of the IEEE*, vol. 95, pp. 746-765, 2007.
- [18] D. G. Dorrell, et al., "Comparison of different motor design drives for hybrid electric vehicles," in *IEEE Energy Conversion Congress and Exposition, ECCE*, 2010, pp. 3352-3359.

-
- [19] D. G. Dorrell, *et al.*, "Comparison of permanent magnet drive motor with a cage induction motor design for a hybrid electric vehicle," in *International Power Electronics Conference, IPEC*, 2010, pp. 1807-1813.
 - [20] J. Hsu, *et al.*, "REPORT ON TOYOTA/PRIUS MOTOR DESIGN AND MANUFACTURING ASSESSMENT," Oak Ridge National Laboratory.
 - [21] A. M. El-Refaie, *et al.*, "Scalable, low-cost, high performance IPM Motor for Hybrid Vehicles," in *XIX Int. Conf. on Electrical Machines ,ICEM*, 2010, pp. 1-6.
 - [22] Anon. (2012, 17 November 2012) Reluctant heroes: An electric motor that does not need expensive rare-earth magnets. *The Economist*. Available: <http://www.economist.com/news/science-and-technology/21566613-electric-motor-does-not-need-expensive-rare-earth-magnets-reluctant-heroes/comments#comments>
 - [23] "Resource Security Action Plan: Making the most of Valuable Materials," UK BIS and DEFRA, Ed., ed. London, 2012.
 - [24] Anon, "Rare-earth mining in China comes at a heavy cost for local villages," in *Guardian*, ed. London, 2012.
 - [25] S. Parry and E. Douglas, "In China, the true cost of Britain's clean, green wind power experiment: Pollution on a disastrous scale," in *Daily Mail*, ed. London, 2011.
 - [26] "Material Security: Ensuring resource availability for the UK economy," ed: Resource Efficiency Knowledge Transfer Network, 2008.
 - [27] B. C. Mecrow, *et al.*, "Segmental rotor switched reluctance motors with single-tooth windings," *IEE Proc. Electric Power Applications*, vol. 150, pp. 591-599, 2003.
 - [28] E. A. El-Kharashi, "Segmented Rotor Switched Reluctance Machines," Doctor of Philosophy, Electrical, Electronic and Computer Engineering, Newcastle University, Newcatle Upon Tyne, 2003.
 - [29] B. C. Mecrow, *et al.*, "Preliminary performance evaluation of switched reluctance motors with segmental rotors," *IEEE Trans. Energy Conversion*, vol. 19, pp. 679-686, 2004.
 - [30] B. C. Mecrow, *et al.*, "Switched reluctance motors with segmental rotors," *IEE Proc. Electric Power Applications*, vol. 149, pp. 245-254, 2002.
 - [31] T. Burress, "Benchmarking of Compitative Technologies," Oak Ridge National Laboratory, 2012.
 - [32] R. Staunton, *et al.*, "EVALUATION OF 2005 HONDA ACCORD HYBRID ELECTRIC DRIVE SYSTEM," Oak Ridge National Laboratory, 2006.
 - [33] (2012, 28/12/12). *The Rise of the Machines*. Available: <http://www.popsoci.com/content/computing>
 - [34] T. J. E. Miller, *Switched Reluctance Motors and their Control*. Oxford: Magna Physics Publications - Oxford University Press, 1993.
 - [35] S. A. Nasar, "DC Switched Reluctance Motor," *IEE Proceedings*, vol. Vol 116, pp. 1048-9, 1969.
 - [36] P. J. Lawrenson, *et al.*, "Variable-speed switched reluctance motors," *IEE Proc. B Electric Power Applications*, , vol. 127, pp. 253-265, 1980.
 - [37] J. V. Byrne and J. G. Lacy, "Characteristics of saturable stepper and reluctance motors," *IEE Conference Publication 136, Small Electrical Machines*, pp. 93-99, 1976.
 - [38] G. A. HORST, "Isolated segmental switched reluctance motor," United States Patent, 1992.
-

- [39] J. Oyama, *et al.*, "The fundamental characteristics of novel switched reluctance motor with segment core embedded in aluminum rotor block," in *Proc. Int. Conf. Electrical Machines and Systems, ICEMS*, 2005, pp. 515-519 Vol. 1.
- [40] T. Higuchi, *et al.*, "Torque ripple reduction of novel segment type Switched reluctance motor by increasing phase number," in *Proc. Int. Conf. Electrical Machines and Systems, ICEMS*, 2009, pp. 1-4.
- [41] T. Higuchi, *et al.*, "Torque ripple reduction control of a novel segment type SRM with 2-steps slide rotor," in *Int. Power Electronics Conference, IPEC*, 2010, pp. 2175-2180.
- [42] R. Hall, *et al.*, "Design and initial testing of an outer rotating segmented rotor switched reluctance machine for an aero-engine shaft-line-embedded starter/generator," in *IEEE Int. Conf. on Electric Machines and Drives*, 2005, pp. 1870-1877.
- [43] S. P. Nikam, *et al.*, "A High-Torque-Density Permanent-Magnet Free Motor for in-Wheel Electric Vehicle Application," *IEEE Transactions on Industry Applications*, vol. 48, pp. 2287-2295, 2012.
- [44] X. Chen, *et al.*, "Comparison of two switched reluctance motors with bipolar excitation," in *5th IET Int. Conf. on Power Electronics, Machines and Drives, PEMD*, Brighton, UK, 2010, pp. 1-6.
- [45] X. Chen, *et al.*, "New designs of switched reluctance motors with segmental rotors," in *5th IET Int. Conf. on Power Electronics, Machines and Drives, PEMD*, Brighton, UK, 2010.
- [46] R. Vandana, *et al.*, "A Novel High Power Density Segmented Switched Reluctance Machine," in *Industry Applications Society Annual Meeting, 2008. IAS '08. IEEE*, 2008, pp. 1-7.
- [47] N. Vattikuti, *et al.*, "A novel high torque and low weight segmented switched reluctance motor," in *IEEE Power Electronics Specialists Conference, PESC*, 2008, pp. 1223-1228.
- [48] Autospeed. (2009). *Holden's Green Car*. Available: http://autospeed.com/cms/title_Holdens-Green-Car/A_111326/article.html
- [49] Y. Takano, *et al.*, "Design and analysis of a switched reluctance motor for next generation hybrid vehicle without PM materials," in *Int. Power Electronics Conference, IPEC*, 2010, pp. 1801-1806.
- [50] A. Labak and N. C. Kar, "A novel five-phase pancake shaped switched reluctance motor for hybrid electric vehicles," in *IEEE Vehicle Power and Propulsion Conference, VPPC '09*, 2009, pp. 494-499.
- [51] H. Goto, *et al.*, "A multipolar SR motor and its application in EV," *Journal of Magnetism and Magnetic Materials*, vol. 290-291, pp. 1338-1342, 2005.
- [52] M. D. Hennen and R. W. De Doncker, "Comparison of Outer- and Inner-Rotor Switched Reluctance Machines," in *7th Int. Conf. on Power Electronics and Drive Systems, PEDS '07*, 2007, pp. 702-706.
- [53] L. Jiongkang, *et al.*, "Experimental investigation of in-wheel switched reluctance motor driving system for future electric vehicles," in *3rd Int. Conf. on Power Electronics Systems and Applications, PESA '09*, 2009, pp. 1-6.
- [54] K. Nakamura, *et al.*, "Design of outer-rotor type multipolar SR motor for electric vehicle," *Journal of Magnetism and Magnetic Materials*, vol. 290-291, pp. 1334-1337, 2005.
- [55] F. Satoshi, *et al.*, "Design of outer-rotor-type multipolar switched reluctance motor for electric vehicle," 2006, p. 08R324.

-
- [56] Y. Takano, *et al.*, "Torque density and efficiency improvements of a Switched Reluctance Motor without rare earth material for hybrid vehicles," in *IEEE Energy Conversion Congress and Exposition, ECCE*, 2010, pp. 2653-2659.
 - [57] Q. Zhan, *et al.*, "Design of a 50 kW switched reluctance machine for HEV propulsion system," in *IEEE 58th Vehicular Technology Conference, VTC*, 2003, pp. 3207-3211 Vol.5.
 - [58] S. Aida, *et al.*, "Basic characteristics of electric vehicle using 40kW switched reluctance motor," in *Int. Conf. Electrical Machines and Systems, ICEMS*, 2008, pp. 3358-3361.
 - [59] J. Faiz and J. W. Finch, "Aspects of design optimisation for switched reluctance motors," *IEEE Transactions on Energy Conversion*, vol. 8, pp. 704-713, 1993.
 - [60] S. Brisset and P. Brochet, "Optimization of switched reluctance motors using deterministic methods with static and dynamic finite element simulations," *IEEE Transactions on Magnetics*, vol. 34, pp. 2853-2856, 1998.
 - [61] X. D. Xue, *et al.*, "Multi-Objective Optimization Design of In-Wheel Switched Reluctance Motors in Electric Vehicles," *IEEE Transactions on Industrial Electronics*, vol. 57, pp. 2980-2987, 2010.
 - [62] W. Wei, *et al.*, "Design optimization of a switched reluctance motor by electromagnetic and thermal finite-element analysis," *Magnetics, IEEE Transactions on*, vol. 39, pp. 3334-3336, 2003.
 - [63] A. M. Omekanda, "Robust torque and torque-per-inertia optimization of a switched reluctance motor using the Taguchi methods," *IEEE Transactions on Industry Applications*, vol. 42, pp. 473-478, 2006.
 - [64] H. Sahraoui, *et al.*, "Switched Reluctance Motor Design Using Neural-Network Method With Static Finite-Element Simulation," *IEEE Transactions on Magnetics*, vol. 43, pp. 4089-4095, 2007.
 - [65] R. T. Naayagi and V. Kamaraj, "A Comparative Study of Shape Optimization of SRM using Genetic Algorithm and Simulated Annealing," in *IEEE INDICON*, 2005, pp. 596-599.
 - [66] W. Phuangmalai, *et al.*, "A design study of 4/2 switched reluctance motor using particle swarm optimization," in *9th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, ECTI-CON*, 2012, pp. 1-4.
 - [67] P. Neittaanmaki, *et al.*, *Inverse Problem and Optimal Design in Electricity and Magnetism*: Oxford University Press, 1996.
 - [68] A. M. Michaelides and C. Pollock, "A new magnetic flux pattern to improve the efficiency of the switched reluctance motor," in *Conference Record of the 1992 IEEE Industry Applications Society Annual Meeting*, 1992, pp. 226-233 vol.1.
 - [69] C. Pollock and A. Michaelides, "Switched reluctance drives: a comparative evaluation," *Power Engineering Journal*, vol. 9, pp. 257-266, 1995.
 - [70] B. C. Mecrow, "New winding configurations for doubly salient reluctance machines," *IEEE Transactions on Industry Applications*, vol. 32, pp. 1348-1356, 1996.
 - [71] L. Jun-Young, *et al.*, "A performance of single phase switched reluctance motor having both radial and axial air gap," in *Proc. of the 24th Annu. Conf. IEEE Industrial Electronics Society, IECON '98*, 1998, pp. 905-910 vol.2.
 - [72] T. Higuchi, *et al.*, "Clyindrical Type Switched Reluctance Motor," *Journal of the Japan Society of Applied Electromagnetics*, vol. 3, pp. 66-72, March 1995.
-

-
- [73] R. Hamdy, *et al.*, "High-speed performance improvements of a two-phase switched reluctance machine utilizing rotor-conducting screens," *IEEE Transactions on Energy Conversion*, vol. 17, pp. 500-506, 2002.
 - [74] H. Hayashi, *et al.*, "Efficiency Improvements of Switched Reluctance Motors With High-Quality Iron Steel and Enhanced Conductor Slot Fill," *IEEE Transactions on Energy Conversion*, vol. 24, pp. 819-825, 2009.
 - [75] H. M. Amreiz, *et al.*, "Switched reluctance machines with simple hoop windings," in *Int. Conf. on Power Electronics, Machines and Drives*, 2002, pp. 522-527.
 - [76] A. G. Jack, *et al.*, "Permanent magnet machines with powdered iron cores and pre-pressed windings," in *Conf. Rec. . IEEE Industry Applications Conf.*, 1999, pp. 97-103 vol.1.
 - [77] Y. Hasegawa, *et al.*, "Optimization of a Switched Reluctance Motor Made of Permendur," *IEEE Transactions on Magnetics*, vol. 46, pp. 1311-1314, 2010.
 - [78] Goodfellow. (2013, August 2013). *Permendur 49 (Co49/Fe49/V2)*. Available: <http://www.goodfellow.com/E/Permendur-49.html>
 - [79] L. M. Exchange. (2013, August 2013). *Metals*. Available: <http://www.lme.com/metals/>
 - [80] N. S. Lobo, *et al.*, "M-Phase N-Segment Flux-Reversal-Free Stator Switched Reluctance Machines," in *IEEE Industry Applications Society Annual Meeting, IAS '08*, 2008, pp. 1-8.
 - [81] A. Chiba, *et al.*, "Test Results of an SRM Made From a Layered Block of Heat-Treated Amorphous Alloys," *IEEE Transactions on Industry Applications*, vol. 44, pp. 699-706, 2008.
 - [82] Ishizuka, "Stator for Dynamoelectric Machine and Method of Manufacture Same," US Patent US 8,179,013, 2012.
 - [83] Foulsham, "Coil Tooth Assembly to Facilitate Winding," UK Patent Application GB 2475732, 2009.
 - [84] Protean, "Stator with Radially Mounted Teeth," WIPO Patent 2011/095945, 2011.
 - [85] T. Yamada, Kawamara, T. Mizutani, N. Sato, T., Miyaoka, K, Mochizuki, M., "Stator for Dynamoelectric machine and method for making the same," European Patent EP 0 871 282, 1998.
 - [86] B. C. Mecrow, *et al.*, "Simplifying the manufacturing process for electrical machines," in *Int. Conf. Power Electronics, Machines and Drives, PEMD*, 2004, pp. 169-174 Vol.1.
 - [87] J. D. Widmer and B. C. Mecrow, "Optimised Segmental Rotor Switched Reluctance Machines with a Greater Number of Rotor Segments than Stator Slots," *IEEE Transactions on Industry Applications*, vol.49, no.4, pp.1491,1498, July-Aug. 2013.
 - [88] P. A. Hargreaves, *et al.*, "Calculation of Iron Loss in Electrical Generators Using Finite-Element Analysis," *IEEE Transactions on Industry Applications*, vol. 48, pp. 1460-1466, 2012.
 - [89] H. Hannoun, *et al.*, "Design of an SRM Speed Control Strategy for a Wide Range of Operating Speeds," *IEEE Transactions on Industrial Electronics*, vol. 57, pp. 2911-2921, 2010.
 - [90] E. A. El-Kharashi, "Segmented Rotor Switched Reluctance Machines," PhD Thesis, Electrical, Electronic and Computer Engineering, Newcastle University, Newcatle Upon Tyne, 2003.
-

-
- [91] A. Zulu, "Flux Switching Machines using Segmental Rotors," PhD Thesis, Electrical and Electronic Engineering, Newcastle University, 2010.
 - [92] T. Celik, "Segmental Rotor Switched Reluctance Drives," PhD Thesis, Electrical and Electronic Engineering, Newcastle University, 2011.
 - [93] J. Amos. (2010, 16th July) Zephyr solar plane flies 7 days non-stop. *BBC News*. Available: <http://www.bbc.co.uk/news/science-environment-10664362>
 - [94] Anon. (2012, 6th June) Giant solar plane completes Spain-Morocco flight. *BBC News*. Available: <http://www.bbc.co.uk/news/science-environment-18330009>
 - [95] B. C. Mecrow, *et al.*, "Drive Topologies for Solar-Powered Aircraft," *IEEE Transactions on Industrial Electronics*, vol. 57, pp. 457-464, 2010.
 - [96] R. Hall, "The Design of High Temperature Electrical Machines for Aerospace Applications," PhD Thesis, School of Electrical, Electronic and Computer Engineering, Newcastle University, 2005.
 - [97] J. D. Widmer, C. Spargo *et al.*, "Solar Plane Propulsion Motors With Precompressed Aluminum Stator Windings," *Energy Conversion, IEEE Transactions on*, vol. 29, pp. 681-688, 2014.
 - [98] L. M. Exchange. (2013, 15th February). *Settlement prices*. Available: <http://www.lme.com/home.asp>
 - [99] K. Björn and J. Jan-Ove, "Recycling of electrical motors by automatic disassembly," *Measurement Science and Technology*, vol. 11, p. 350, 2000.
 - [100] *End of Life Vehicles*, The European Parliament and the Council of the European Union, 2000/53/EC, 2000.
 - [101] J. Aronstein, "Reducing the Fire Hazard in Aluminium Wired Homes," presented at the Electrical Safety Conference - Electrical Fires, University of Wisconsin, 1982.
 - [102] Yabumoto, *et al.*, "Nippon Steel Technical Report No 88," 2003.
 - [103] P. Pulnikov, de Wulf & Melkebeek, "Measuring setup for the investigation of the influence of mechanical stresses on magnetic properties of electrical steel," *Journal of Magnetism and Magnetic Materials*, vol. 254-255, pp. 94-96, 2003.
 - [104] Sowter, "Cold Pressure Welding," US Patent 2522408, 1950.
 - [105] B. S. Institute, "BS EN 60317-0-1:2008 Specifications for particular types of winding wires. General requirements. Enamelled round copper wire.," ed, 2008.
 - [106] C. L. Choy, "Thermal conductivity of polymers," *Polymer*, vol. 18, pp. 984-1004, 1977.
 - [107] J. D. Widmer, R. Martin and B.C. Mecrow, "Optimisation of an 80kW Segmental Rotor Switched Reluctance Machine for Automotive Traction," in *IEMDC 2013*, Chicago, 2013.
 - [108] M. Ehsani, *et al.*, "Propulsion system design of electric and hybrid vehicles," *IEEE Transactions on Industrial Electronics*, vol. 44, pp. 19-27, 1997.
 - [109] M. André, "The ARTEMIS European driving cycles for measuring car pollutant emissions," *Science of The Total Environment*, vol. 334-335, pp. 73-84, 2004.
 - [110] J. Widmer, "Rotor Manufacturing Challenges: 80kW Segmental Rotor Switched Reluctance Machine," presented at the UKMagSoc Advances in Machine Manufacture, Newcastle-upon-Tyne, 2013.
 - [111] T. Lisle, "A Finite Element Approach for Validating Gear Contract and Bending Stress," PhD Thesis, School of Mechanical Engineering, Newcastle University, 2013.
 - [112] C. Steel. (2012). *Typical data for SURA M270-35A*. Available: [http://www.sura.se/Sura/hp_products.nsf/vOpendocument/03A8B2433FAE16C4C1256AA8002280E6/\\$FILE/270-35.pdf?OpenElement](http://www.sura.se/Sura/hp_products.nsf/vOpendocument/03A8B2433FAE16C4C1256AA8002280E6/$FILE/270-35.pdf?OpenElement)
-

-
- [113] Matweb. (2012). *Aluminum 6082-T6*. Available: <http://www.matweb.com/search/datasheet.aspx?matguid=fad29be6e64d4e95a241690f1f6e1eb7&ckck=1>
- [114] A. K. Wenbin Song, Janet Rees, Atul Bhaskar, Steven Bagnall, "Turbine blade fir-tree root design optimisation using intelligent CAD and finite element analysis," *Computers and Structures*, vol. 80, pp. 1853–1867, 2002.
- [115] C. R. Sullivan, "Computationally efficient winding loss calculation with multiple windings, arbitrary waveforms, and two-dimensional or three-dimensional field geometry," *IEEE Transactions on Power Electronics*, vol. 16, pp. 142-150, 2001.
- [116] Matweb. (2013). *Material Property Data*. Available: www.matweb.com
- [117] Dupont. (2013). *Nomex Datasheet*. Available: http://www2.dupont.com/Nomex/en_US/assets/downloads/energy_solutions/410.pdf
- [118] Anon. (2012). *SKF Static Motor Analyzer Baker AWA-IV*. Available: <http://www.skf.com/binary/12-121157/6753-EN-Baker-AWAIV-brochure-V5.pdf>
- [119] Klauke, "Compression cable lugs and connectors for aluminium-copper connections.," ed, 2013.
- [120] Intertronics. (2013, 18th August). *Polyurethane Potting Compound*. Available: <http://www.intertronics.co.uk/products/irs3071.htm>
- [121] Anon. (2007). *AK Steel Product Data Sheet 316/316L Stainless Steel*. Available: http://www.aksteel.com/pdf/markets_products/stainless/austenitic/316_316L_Data_Sheet.pdf
- [122] C. Pollock and W. Chi-Yao, "Acoustic noise cancellation techniques for switched reluctance drives," *IEEE Transactions on Industry Applications*, vol. 33, pp. 477-484, 1997.
- [123] J. Y. Chai, *et al.*, "Comparative study of switching controls in vibration and acoustic noise reductions for switched reluctance motor," *IEE Proceedings Electric Power Applications*, vol. 153, pp. 348-360, 2006.
- [124] E. H. V. T. Interational. (2012, July 2012) Future e-powertrain designs. *Electric & Hybrid Vehicle Technology Interational*.
- [125] J. D. Widmer, B. C. Mecrow *et al.*, "Use of a 3 phase full bridge converter to drive a 6 phase switched reluctance machine," in *IET Int. Conf. Power Electronics, Machines and Drives, PEMD*, 2012, pp. 1-6.
- [126] J. D. Widmer, R. Martin, *et al.*, "Winding configurations for a six phase switched reluctance machine," in *XXth Int. Conf. on Electrical Machines, ICEM*, 2012, pp. 532-538.
- [127] D. Staton, *et al.*, "Solving the More Difficult Aspects of Electric Motor Thermal Analysis in Small and Medium Size Industrial Induction Motors," *IEEE Transactions on Energy Conversion*, vol. 20, pp. 620-628, 2005.