

Thermal modelling of a high speed permanent magnet synchronous machine

A thesis submitted for the degree

Philosophiae Doctor

at the Potchefstroom campus of the North-West University by

Andries J. Grobler

12810932

Promoter: Prof. S. R. Holm

Co-promoter: Prof. G van Schoor

May 2011

“The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.”

Summary

Thermal modelling is of great importance in all electric machines but especially in permanent magnet synchronous machines (PMSMs). The thermally fragile permanent magnets (PMs) can more easily be demagnetized at high temperatures. When high speed machines are considered, heat extraction surfaces are small due to the higher energy density. This thesis focuses on the thermal modelling of a high speed slotless PMSM using analytical techniques. From literature it is clear that analytical distributed models have not reached its full potential in thermal modelling of electric machines. Thermal experiments on high speed electric machine, including rotor PM temperature measurements are not commonly found in literature.

The thermal behaviour of each component of the machine is influenced by the overall temperature distribution. The widely used lumped parameter (LP) cylindrical component model derived by Mellor *et al.* is used to derive a LP model of the entire machine. A two dimensional (2-D) analytical distributed model is derived for the rotor PM using the separation of variables method. Three of the boundaries are assumed to be of the convection type and the fourth of constant heat flow type. Different convection coefficients are assumed to exist in the radial and axial directions. The distributed model is verified using COMSOL[®] and good correlation is shown. The distributed model is used to determine the temperature distribution in the PM and the convection heat flow in the axial direction.

Loss calculation is an integral part of thermal modelling. Temperature changes in an electric machine is due to the interaction between the heat generation (losses) and heat removal. The losses found in a high speed slotless PMSM are investigated. A 2-D analytical magnetic model is used to determine the stator lamination loss as well as the stator winding eddy current loss. A simple LP model is derived for the rotor eddy current loss. Due to the relatively large resistivity of the shielding cylinder and PM material, the rotor eddy current loss is a significant part of the total machine loss. The tangential current width is determined empirically in this thesis but a 3-D distributed model which includes end space effects and skin depth could also be used.

A large part of thermal modelling is empirically based. The convection and interface resistances are determined through a set of experiments in this thesis. The measured and calculated convection coefficients correlated well for both forced and natural convection cooling. A large temperature increase found during the no-load test can be attributed to large bearing loss, possibly due to axial loading. The LP model is modified to include the phenomena found during the experiments.

The thermal model is used to predict the temperatures of a high speed PMSM at rated load

and speed. Although the PM is not heated above the Curie temperature, demagnetization is still possible. According to the model, the machine will not be able to operate at full load and speed for extensive periods due to mechanical stress limits being exceeded. The temperature distribution of the PM could not be verified since the temperatures in the air gap and end space could not be measured. It is expected that axial heat flow will be larger than what is currently predicted by the distributed model. A sensitivity analysis was used to investigate the influence of the thermal resistances and losses on the machine temperatures. Methods for reducing the rotor eddy current loss and interface resistances are also discussed.

The first contribution of this thesis is the 2-D analytical distributed model for the PM of a high speed PMSM. Hot spots and 2-D heat flow can be analysed using this model. Combining the LP and 2-D analytical distributed models is another contribution. This combines the simplicity and fast solution times of the LP model with the 2-D thermal distribution of the analytical distributed model. The systematic experimental investigation of the thermal behaviour of a high speed PMSM is a further contribution.

Keywords: Thermal modelling, permanent magnet synchronous machine, lumped parameter, analytical distributed.

Acknowledgments

The work presented in this thesis could not have been done without the contributions of various persons and institutions.

Our heavenly Father; You gave me this extraordinary opportunity and an abundance of grace throughout my PhD study. Soli Deo Gloria, Sola Gratia.

I am blessed with the best wife in the world. Leenta, you are my best friend, my comrade in this battle they call postgraduate study and my companion in the amazing life we have been given. Through all the ups and downs (I promised there would not be any but I was wrong) you were always the one that kept me going. There are not enough words in the world to convey my gratitude, love and appreciation for you.

My family; Andries, Maria, Miemie, Martin, Magda, Jana, Marne, Grandmother Bessie, Grandmother Leenta, Grandmother Kleintjie, Grandfather Koos and Grandfather Louis. You gave me the most valuable gift one can give, knowledge. Not only did you ensure that I get all the support I needed to complete my studies, but through your examples I could learn about life, love, faith and hard work. I want to specially thank Grandfather Louis; your living example of what a man of the Lord looks like will stay with me always. Even though I miss you, I can also say "I have so much to be thankful for" through the grace of our God.

Prof. Robert Holm is one of the smartest people that I know and I am truly lucky to have you as a promoter. Thank you very much for your excellent guidance into the amazing world of electric machines. Your humility and support means incredibly much to me. Now, and always, "I want to try and understand electrical machines a bit better this year".

In the six years Prof. George van Schoor have been part of my life he has done so much for me and given so much to me I don't know were to begin. Thank you for being the father of McTronX. To me, this is the most precious part of my postgraduate experience. I know that the Father will one day greet you with the words "Well done, good and faithful servant! ...". Thank you for the incredible way you care for and guide each of your students.

My colleague Gert Kruger, the (other) parent of the TWINS. I hope to one day have just a fraction of you knowledge, determination and skills. We learned a great deal through this piece of hardware and I was truly lucky to have had you working with me. Through endless hours of winding and noise minimization, you always just kept going. Even though I broke your baby a few times, and handled her carelessly at other times, you always found a way to make

it work again. Thank you very much.

The McTronX team; Jan, Stefan, Rikus, Gerhard, Angelique, Albert, Chris, Pieter, Christian, Jaco, Roelof, Corrie, Marais, Pieter, Kenny as well as those I mentioned in my M.Eng dissertation. I regard you all as dear friends. Thank you for the great times we had drinking coffee and the inputs you gave me. My only regret about completing my studies is not “working” with you each day.

My friends; Melvin, Joubert, Leandi, Valerie. Time spent with you are always invigorating. Thank you for the shared suppers and conversation. I know that your PhDs will be brilliant.

“Whatever you do, work at it with all your heart, as working for the Lord, not for men, since you know that you will receive an inheritance from the Lord as a reward. It is the Lord Christ you are serving. ” Colossians 3:23 - 24 [NIV]

Contents

Foreword	iii
List of figures	xiv
List of tables	xvi
List of abbreviations	xvii
List of symbols	xvii
1 Introduction	1
1.1 Global trends	1
1.1.1 Thermal modelling	1
1.1.2 Thermal modelling solution methods	2
1.1.3 Permanent magnet synchronous machines	3
1.2 Test platform	4
1.2.1 Thermal issues of the test platform	7
1.3 Research problem	8
1.4 Issues to be addressed and methodology	8
1.5 Contributions	9
1.6 Thesis overview	10
2 Background	11

2.1	Permanent magnet machines	11
2.2	High speed electric machines	12
2.3	Conduction	13
2.4	Convection	14
2.4.1	Natural convection	15
2.4.2	Forced convection in the air gap	16
2.4.3	Forced convection from the housing	17
2.5	Thermal interface resistance	18
2.6	Solution techniques	19
2.6.1	Distributed analytical methods	19
2.6.2	Lumped parameters	20
2.6.3	Numerical methods	22
2.7	Losses in electric machines	23
2.7.1	Losses due to current flow	24
2.7.2	Losses due to magnetic domain changes	25
2.7.3	Mechanical losses	26
2.7.4	Loss mechanisms in high speed slotless PMSMs	27
2.8	Conclusion	28
2.8.1	Research direction	28
2.8.2	Towards a contribution	29
3	Lumped parameter thermal modelling	31
3.1	Modelling approach	31
3.1.1	Combination of the LP and distributed models	32
3.2	Background	33
3.3	Derivation of the general cylindrical component	34
3.3.1	Zero internal generation	35
3.3.2	Zero surface temperature, internal generation	36

3.3.3	Thermal capacitance	38
3.3.4	LP assumptions	38
3.4	Natural convection resistance	38
3.5	Implementation on the TWINS machine	39
3.6	Conclusion	40
4	Distributed thermal modelling	43
4.1	Background	43
4.1.1	Bessel functions	43
4.1.2	Separation of variables	44
4.1.3	Series expansions for thermal models	46
4.1.4	Boundary conditions	47
4.2	Permanent magnet model	47
4.2.1	Boundary conditions of the PM	48
4.2.2	Solving the constants C_{1-4}	49
4.2.3	Permanent magnet model verification using FEM	52
4.3	Stator winding model	54
4.3.1	Derivation of a 1-D solution for the TWINS stator winding	55
4.3.2	Verification of 1-D stator winding model	55
4.4	Conclusion	55
5	Loss modelling	57
5.1	Introduction	57
5.2	Magnetic field model	57
5.3	Stator iron losses	59
5.4	Stator winding eddy current loss	61
5.4.1	Analytical model	61
5.4.2	FEM model	61

5.5	Shielding cylinder eddy current loss	61
5.5.1	Background	61
5.5.2	Resistive model	63
5.5.3	Rotor eddy current loss in the TWINS	65
5.6	Mechanical losses	68
5.6.1	Bearing loss	69
5.6.2	Windage loss	70
5.7	Summary of calculated losses	70
5.8	Conclusion	71
6	Experimental model refinement	73
6.1	Overview	73
6.1.1	Rotational velocity used in experiments	75
6.2	Test platform details	76
6.2.1	Phase resistance measurement	76
6.2.2	Temperature measurement locations and combination	76
6.3	DC test	79
6.3.1	Thermal results	79
6.3.2	Convection coefficients	80
6.3.3	Interface resistances	82
6.4	No-load test	84
6.4.1	Measured results	84
6.4.2	Loss modelling at 10000 r/min	85
6.4.3	Including the no-load losses into the model	87
6.5	Generator test with resistive load	90
6.6	Generator test with rectifier and resistive load	92
6.6.1	Eddy current loss calculation	92
6.7	Switched test	93

6.7.1	Measured results	93
6.7.2	Rotor eddy current loss	94
6.8	Final model	96
6.9	Conclusion	98
7	Model evaluation	99
7.1	Model temperatures at 30000 r/min	99
7.1.1	PM temperature distribution	101
7.2	Sensitivity analysis	104
7.3	Interface resistance reduction	106
7.3.1	Factors influencing interface resistance	107
7.3.2	Influence of interface resistances on the TWINS	107
7.3.3	Stator housing and stator lamination interface	108
7.3.4	Coil former and stator winding interface	108
7.3.5	Rotor interfaces	109
7.4	Rotor eddy current reduction	109
7.4.1	Reduction of the harmonic stator currents	110
7.4.2	Reduction of the eddy current loss in the tangential direction	110
7.4.3	Reduction of eddy current loss in the axial direction	111
7.4.4	Predicted machine temperature when using a copper shielding cylinder	111
7.5	Bearing loss reduction	111
7.6	Conclusion	112
8	Conclusions and recommendations	115
8.1	Conclusions	115
8.2	Unique contributions	116
8.3	Recommendations for future work	117
8.3.1	Thermal modelling	117

8.3.2	Measuring	117
8.3.3	Manufacturing	118
8.4	Closure	118
Bibliography		119
A TWINS LP calculations		131
A.1	Dimensions	131
A.2	Material properties	131
A.3	Thermal resistor values	131
B Mechanical drawings		135
C System photos		143

List of Figures

1.1	Temperature dependence of VACODYM 655	4
1.2	Radial cross section of TWINS	5
1.3	Axial cross section of TWINS	6
1.4	Block diagram of the TWINS	6
1.5	Forced cooling of TWINS: (a) side view; and (b) section view.	7
2.1	Electric machine classification	12
2.2	Convection coefficient vs. surface temperature	17
2.3	Interface resistance between laminations and solid component	18
2.4	Screen shot of MotorCAD® LP model	21
2.5	Brake disk temperature calculated using COMSOL®	23
2.6	Current density in copper wires	24
2.7	Eddy currents in a solid cylinder due to alternating current flowing in a wire	25
2.8	Loss types and their location in a high speed slotless PMSM like the TWINS	27
3.1	PM thermal energy system in (a) 2-D and (b) 1-D	32
3.2	LP model and distributed model combination	33
3.3	Erroneous LP model. (a) Cylinder with internal heat generation, (b) erroneous LP model.	33
3.4	Temperatures of a cylinder with internal heat generation	34
3.5	Generalised cylindrical component	35
3.6	Variable natural convection resistor implementation	39

3.7	LP thermal model implementation on TWINS machine	40
4.1	Bessel and modified Bessel functions of the first and second kind	44
4.2	Boundary conditions of the PM	48
4.3	Values of λ_n ; $l = 0.06$	51
4.4	Implementation of PM 2-D analytical model in MATLAB®	53
4.5	Percentage difference, FEM and analytical method	53
4.6	Percentage difference for m upper range	54
4.7	Winding temperature (a) temperature; and (b) difference between LP and distributed models	56
5.1	Machine simplification for magnetic field calculation	58
5.2	Contour plot of the magnetic vector potential of the TWINS	59
5.3	Magnetic flux density in the TWINS	60
5.4	Current density in a strand of the stator winding at 30000 r/min.	62
5.5	Eddy current loss inside the winding	62
5.6	Eddy current patterns in rotor of two pole, three phase PMSM: (a) $r\phi$ - plane; and (b) linear $z\phi$ - plane	63
5.7	Penetration depth of the TWINS' PM and shielding cylinder	64
5.8	Equivalent circuit for rotor eddy currents	65
5.9	VSI harmonic spectrum with $m_a = 1$	66
5.10	Frequency dependent stator resistance (per phase)	67
5.11	Frequency dependent stator inductance(per phase)	68
5.12	Calculated rotor eddy current loss vs. tangential current width (w_t).	69
5.13	Calculated $P_{s,Fe}$, $P_{s,Cu,e}$, $P_{bearing}$, P_{wind} and sum of these losses vs. rotational speed	71
6.1	Test setup diagrams	75
6.2	Temperature measure locations in TWINS A machine	77
6.3	RTD values for 12 A DC test, natural convection and forced convection. RTD names according to Figure 6.2	78

6.4	DC test temperatures. Natural convection: 12 ADC, forced convection: 14, 16, 12 ADC.	79
6.5	Forced convection flow area: (a) side view; and (b) sectional view.	81
6.6	Difference in temperatures when interface resistances are included.	83
6.7	Difference in temperatures when interface resistances are ignored.	84
6.8	No-load test temperatures	85
6.9	Difference between modelled and measured temperatures for no-load test	88
6.10	Generator test: Resistive load	90
6.11	Generator test voltage (a); and (b) current waveforms for resistive load.	91
6.12	Differences between temperatures for resistor generator test.	91
6.13	Phase current plots for generator test with rectifier and resistive load	92
6.14	Measured temperatures for generator test with rectifier and resistive loads. . . .	93
6.15	Change in temperature during the switched test	94
6.16	Stator winding current in motor when driving a generator.	95
6.17	Calculated rotor eddy current loss vs. w_t	95
6.18	Difference between measured and modelled temperatures for the motor.	96
6.19	Modified LP model for the TWINS	97
7.1	Predicted TWINS temperatures at 30000 r/min, 4 kW output.	100
7.2	Predicted PM temperature distribution of the TWINS at 30000 r/min.	103
7.3	Predicted PM temperature distribution of the TWINS with smaller h	104
7.4	Modelled influence of the interface resistances on the TWINS at 30000 r/min. . .	108
7.5	Predicted temperatures when a copper shielding cylinder is used	112
B.1	TWINS stator housing	136
B.2	TWINS stator flange	137
B.3	TWINS pillar block	138
B.4	TWINS top cover	139
B.5	TWINS coil former	140

B.6	TWINS rotor assembly	141
B.7	TWINS machine assembly	142
C.1	Glue between rotor laminations and PM	143
C.2	TWINS rotor	144
C.3	TWINS mounted on the vertical base plate	144
C.4	TWINS top view	145
C.5	TWINS side view	145

List of Tables

2.1	Temperature sensitivity of h	16
5.1	Iron loss at 30000 r/min	60
6.1	Test summary: Location and types of losses	74
6.2	Phase resistance	76
6.3	Air properties at 293 K	81
6.4	Natural convection resistance from DC test data	81
6.5	Interface resistance width: DC test	83
6.6	Calculated iron loss at 10000 r/min	86
6.7	No-load loss summary	88
6.8	Interface resistance width: No-load test	89
6.9	Harmonic currents of 22 Ω resistor and rectifier load	93
6.10	Final interface and convection resistances	97
7.1	Expected losses in the TWINS at 30000 r/min in motor mode.	100
7.2	Sensitivity analysis: Temperature variation due to thermal interface resistance variation	105
7.3	Sensitivity analysis: Temperature variation due to loss variation	106
7.4	Shielding cylinder materials	110
A.1	TWINS dimensional parameters	132
A.2	Material properties	133

A.3	Radial resistances	133
A.4	Axial resistances	133

LIST OF ABBREVIATIONS

1-D, 2-D, 3-D	One, two or three dimensional
PMBLDM	Permanent magnet brushless direct current machine
CFD	Computational fluid dynamics
FEM	Finite element method
ID	Inner diameter
LP	Lumped parameter
OD	Outer diameter
ODE	Ordinary differential equation
PDE	Partial differential equation
PM	Permanent magnet
PMSM	Permanent magnet synchronous machine
PWM	Pulse width modulation
RMS	Root mean square
RTD	Resistive temperature detector
SOV	Separation of variables
VSI	Voltage source inverter

LIST OF SYMBOLS

Latin letters

A	Cross sectional area	$[m^2]$
C	Thermal capacitance	$[J/K]$
c	Specific heat	$[J/(kg.K)]$
d	Diameter	$[m]$
Ga	Grashoff number	
g	Gravitational acceleration	$[m/s^2]$
h	Convection coefficient	$[W/(m^2.K)]$

I	Electrical current	[A]
k	Thermal conductivity coefficient	[W/(m.K)]
k	Roughness coefficient	
L	Characteristic length	[m]
Nu	Nusselt number	
P	Power	[W]
Pr	Prandtl number	
q	Heat transfer rate	[W]
$\dot{q}$	Rate of energy generation per unit volume	[W/m ³]
q'	Heat transfer rate per unit length	[W/m]
q''	Heat flux	[W/m ²]
r	radius	[m]
Ra	Rayleigh number	
Re	Reynolds number	
R	Thermal resistance	[K/W]
T	Temperature	[K]
v	Average fluid velocity	[m/s]

Greek letters

α	Thermal diffusivity	[m ² /s]
α_0	Temperature coefficient	[1/K]
β	Volume expansivity	[K ⁻¹]
δ	Skin depth	[m]
δ	Air gap length	[m]
μ	Dynamic viscosity	[kg/(s.m) or (N.s)/m ²]
μ	Permeability	[H/m]
ν	Kinematic viscosity	[m ² /s]
ρ	Mass density	[kg/m ³]

ρ	Resistivity	[Ωm]
σ	Conductivity	[S/m]
ω	Angular frequency	[rad/s]

Latin subscripts

0	Free space
<i>A</i>	Air gap
<i>a</i>	Air
<i>B</i>	Bearing
C1	Coil former 1
C1	Coil former 2
<i>E</i>	End winding
<i>e</i>	Electrical
<i>fr</i>	Friction
<i>I</i>	Interface gap
<i>i</i>	Inside
<i>o</i>	Outside
<i>Rl</i>	Rotor laminations
<i>Rs</i>	Rotor shaft
<i>P</i>	Permanent magnet
<i>Sc</i>	Shielding cylinder
<i>Sl</i>	Stator laminations
<i>Sh</i>	Stator housing
<i>W</i>	Winding
<i>cond</i>	Conduction
<i>conv</i>	Convection
<i>for</i>	Forced
<i>nat</i>	Natural

s	Surface
t	Thermal
∞	Free stream conditions