Thermal modelling of a high speed permanent magnet synchronous machine

A thesis submitted for the degree

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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.

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“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]

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

s	Surface
t	Thermal
∞	Free stream conditions