Design of Permanent Magnet Machines for Field-Weakening Operation

Chun Tang

A thesis presented for the degree of Doctor of Philosophy

2015
Dedicated to my parents
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Abstract

This research focuses on the electromagnetic design of permanent magnet (PM) machines in terms of the iron loss, torque pulsations and field-weakening performance. It covers the investigation of the effect of stator-slot and rotor-pole number combinations for surface-mounted PM (SPM) machines, and the stator-slot and rotor-effective-slot number combinations for interior permanent magnet (IPM) machines.

The effect of changing the number of slots and poles on the performance of a particular SPM machine design is studied in detail using finite element analysis. This includes examining the back-EMF, the open-circuit/full-load power losses, the cogging/ripple torque, and the field-weakening performance. The simulation results are compared with the expected relationships to provide electric machine designers useful insights on the effect of the number of slots and poles on the performance of SPM machines.

Operation at high speed in traction drives corresponds to deep field-weakening conditions. Due to the high electrical frequencies, the iron loss of IPM machines at high speeds can significantly affect the overall efficiency. This thesis investigates the rotor-
cavity positioning and the combination of stator-slot and rotor-effective-slot number on the eddy-current loss for IPM/reluctance machines operating under deep field-weakening conditions. A new closed-form expression for the stator and rotor eddy-current loss is developed. The optimal barrier-positioning for the minimum total loss and the effect on the eddy-current loss of varying the stator-slot and rotor-effective-slot number are investigated for 1-, 2-, 3- and full-layered rotors.

FEM optimisation and experimental verification of an example IPM machine design are presented. An optimized 30 slot, 4 pole (slot/pole/phase = 2.5) three-layered IPM machine with a significantly reduced iron loss under field-weakening operation is proposed and compared to the baseline 36-slot 4-pole (slot/pole/phase = 3) three-layered IPM machine. The detailed comparison of the optimized and baseline designs using a combination of the analytical, FEM and experimental tests are presented.
Statement of Originality

This work contains no material which has been accepted for any other degree or
diploma in any university or tertiary institution, and to the best of my knowledge and
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Signed: ______________________________________________________

Date: __________________June-29-2015________________________
List of Publications


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Nomenclature

\begin{align*}
\theta & \quad \text{Stator circumferential coordinates} \quad \text{elec. deg} \\
\omega_s & \quad \text{Synchronous angular frequency} \quad \text{rad/s} \\
\mu_0 & \quad \text{Magnetic permeability of vacuum} \quad \text{H/m} \\
\alpha_j & \quad \text{rotor cavity angular position} \quad \text{elec. deg} \\
\Delta_s & \quad \text{Stator tooth pitch angle} \quad \text{elec. deg} \\
\Delta_r & \quad \text{Rotor channel pitch angle} \quad \text{elec. deg} \\
\xi_j & \quad \text{Rotor channel circumferential position} \quad \text{elec. deg} \\
\delta & \quad \text{Angle between the cavity and } d\text{-axis} \quad \text{mech. deg} \\
\Psi_m & \quad \text{Magnet flux linkage} \quad \text{Wb} \\
\Psi_d & \quad \text{Stator } d\text{-axis flux linkage} \quad \text{Wb} \\
\Psi_q & \quad \text{Stator } q\text{-axis flux linkage} \quad \text{Wb} \\
\Phi_{\text{rem}} & \quad \text{Magnet remanent flux} \quad \text{Wb} \\
\Phi_{\text{rk}} & \quad \text{Rotor-rib leakage flux} \quad \text{Wb} \\
B_e & \quad \text{Radial airgap flux density} \quad \text{T} \\
B_{gm} & \quad \text{Magnet created airgap flux density} \quad \text{T} \\
B_{gr} & \quad \text{Rotor-MMF contributed airgap flux density} \quad \text{T} \\
B_r & \quad \text{Magnet remanent flux density} \quad \text{T}
\end{align*}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tr>
<td>$B_t$</td>
<td>Stator-teeth flux density</td>
<td>T</td>
</tr>
<tr>
<td>$B_y$</td>
<td>Stator-yoke flux density</td>
<td>T</td>
</tr>
<tr>
<td>$B_{chl}$</td>
<td>Rotor-channel tunnelling flux density</td>
<td>T</td>
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<td>Phase back-EMF voltage</td>
<td>$V_{rms}$</td>
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<td>$n_s$</td>
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<tr>
<td>(n_r)</td>
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<tr>
<td>(N_t)</td>
<td>Number of series turns per phase</td>
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<tr>
<td>(p)</td>
<td>Number of pole-pairs</td>
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<tr>
<td>(P)</td>
<td>Number of poles</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>(R_s)</td>
<td>Stator phase resistance (\text{ohms})</td>
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</tr>
<tr>
<td>(R_b)</td>
<td>Rotor barrier magnetic reluctance (\text{H}^1)</td>
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<td>(R_g)</td>
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<td>(R_{\text{yoke}})</td>
<td>Stator-yoke average radius (\text{m})</td>
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<td>(R_{\text{teeth}})</td>
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<td>(R_{\text{rot}})</td>
<td>Rotor outer radius (\text{m})</td>
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<td>(T_{\text{ave}})</td>
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<tr>
<td>(V_{\text{yoke}})</td>
<td>Stator-yoke volume (\text{m}^3)</td>
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<td>(V_{\text{teeth}})</td>
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