COMPUTATIONALLY EFFICIENT, ELECTROTHERMALLY COUPLED MODEL FOR PERMANENT MAGNET MACHINES IN ELECTRIC VEHICLE TRACTION APPLICATIONS

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Outline

- Research Motivation
- Methodology (Equivalent d-axis current representing temperature effect)
- Electro-thermally Coupled Model
- FE Validation
- Simulation Results
- Experimental Validation
Electrical machine temperatures are subject to its copper loss, core loss, etc.

Machine copper loss and core loss are largely affected by machine temperatures

- Winding resistance increases by 39% for every 100°C temperature rise;
- Magnet remanence reduces by 12% for every 100°C temperature rise (for NdFeB);
- High nonlinearity in the machine flux linkage map due to core saturation

Diagram:
- Loss model
  - Copper loss
  - Rotor magnet temperature
- Thermal model
  - Core loss
  - Winding temperature
Electrical machine temperatures are subject to its copper loss, core loss, etc.

Machine copper loss and core loss are largely affected by machine temperatures

a) Winding resistance increases by 39% for every 100°C temperature rise;

b) Magnet remanence reduces by 12% for every 100°C temperature rise (for NdFeB);

c) High nonlinearity in the machine flux linkage map due to core saturation

Essential to accurately model the electro-thermally coupling effect in the electrical machine, in order to accurately simulate the waste heat recovery in the vehicle powertrain system.
Temperature Effects on Flux Linkages

\[ B_{r2}(T_2) = B_r(T_1) \times [1 + \alpha \times (T_2 - T_1)] \]

where \( \alpha \) is temperature coefficient, \( B_{r2} \) and \( B_{r1} \) represent the remanence at temperature of \( T_2 \) and \( T_1 \), respectively.

d-axis flux linkage increment over d-, q-axis current ranges when temperature decreases from 100°C to 20°C (normalized to the flux-linkage due to permanent magnets at 120°C)

The increment can be up to 18%; The increment is non-uniform in the range of d- and q- axis currents
Temperature Effects on Flux Linkages

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where \( \alpha \) is temperature coefficient, \( B_{r2} \) and \( B_{r1} \) represent the remanence at temperature of \( T_2 \) and \( T_1 \), respectively.

\( q \)-axis flux linkage increment over \( d \), \( q \)-axis current ranges when temperature decreases from 100°C to 20°C (normalized to the flux-linkage due to permanent magnets at 120°C)

Neglecting the temperature effect on the \( q \)-axis flux linkage does not incur large error

10kW 18-slot 8-pole IPM machine
\[ B_{r2}(T_2) = B_r(T_1) \times [1 + \alpha \times (T_2 - T_1)] \]

where \( \alpha \) is temperature coefficient, \( B_{r2} \) and \( B_{r1} \) represent the remanence at temperature of \( T_2 \) and \( T_1 \), respectively.

FE predicted open-circuit \( d \)-axis flux linkage \( \psi_d \) variation with magnet temperature.

Due to saturation effect, \( \psi_d \) varies not strictly linear with temperature.
Equivalent $d$-axis Current Representing Temperature Effects

Therefore the total equivalent excitation current in the $d$-axis seen by the stator windings is $i_d + i_m$

$i_m$ changes proportionally to the temperature variation
Therefore, when temperature changes,

\[
\psi_d(i_d, i_q, T_2) = \psi_D(i_d + i_{m1}, i_q)
\]
\[
\psi_d(i_d, i_q, T_2) = \psi_D(i_d + i_{m2}, i_q)
\]
\[
\psi_d(i_d, i_q, T_2) = \psi_D(i_d + i_{m1} + i_{m2} - i_{m1}, i_q)
\]
\[
= \psi_d(i_d + (i_{m2} - i_{m1}), i_q, T_1)
\]
\[
= \psi_d(i_d + i_{mc}, i_q, T_1)
\]

where \(i_{mc} = i_{m2} - i_{m1}\)

Therefore the flux linkages at a new temperature \(T_2\) can be predicted using the model at the reference temperature \(T_1\) with its d-axis current displaced by a constant \(i_{mc}\), which is equal to the magnet equivalent current difference between the two temperatures.
Considering the flux linkage variation due to different rotor position:

\[
\psi_d(i_d, i_q, \theta, T_2) = \psi_d(i_d + i_{mc}, i_q, \theta, T_1)
\]

\[
\psi_q(i_d, i_q, \theta, T_2) = \psi_q(i_d + i_{mc}, i_q, \theta, T_1)
\]

Neglecting the saturation effect in the rotor bridge region:

\[
i_{mc} = i_{m2} - i_{m1} = i_{m1} \times \alpha \times (T_2 - T_1)
\]

\(i_{m1}\) can be calculated using the short-circuit condition:

\[
\psi_D(i_{d-sc1} + i_{m1}, 0) = \psi_d(i_{d-sc1}, 0, T_1) = 0
\]

Once \(i_{m1}\) has been determined from the FE simulation of the short-circuit condition at the reference temperature \(T_1\), the \(i_{mc}\) at any given temperature \(T_2\) can be obtained.

Then, use the modified \(d\)-axis current \(i_d + i_{mc}\) to calculate the flux linkages and torque at any temperature.
Inverse Flux Linkage Model with Temperature Effects

Conventional flux linkage model:

Inverse flux linkage model:

\[ i_d(\psi_d, \psi_q, \theta, T) = i_{d1}(\psi_d, \psi_q, \theta, T_1) - k(T - T_1) \]

\[ i_q(\psi_d, \psi_q, \theta, T) = i_{q1}(\psi_d, \psi_q, \theta, T_1) \]
**d-axis flux linkage error**

![d-axis flux linkage error graph]

**q-axis flux linkage error**

![q-axis flux linkage error graph]

RMS error over $i_d$ and $i_q$ ranges:

<table>
<thead>
<tr>
<th>Variables</th>
<th>% change (from 100°C to 20°C)</th>
<th>Relative error of proposed model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi_d$</td>
<td>10.82%</td>
<td>1.41%</td>
</tr>
<tr>
<td>$\psi_q$</td>
<td>1.45%</td>
<td>1.51%</td>
</tr>
<tr>
<td>$\psi_m$</td>
<td>8.98%</td>
<td>1.28%</td>
</tr>
<tr>
<td>$T_q$</td>
<td>4.66%</td>
<td>0.98%</td>
</tr>
</tbody>
</table>
Rated torque and base speed (35Nm and 1350r/min)

Good agreement achieved
Field weakening operation (20Nm and 4500r/min)

Good agreement achieved
With the temperature effect considered, the winding and magnet temperatures are \(\sim 5^\circ C\) higher than the results calculated using the conventional method when the machine gets into thermal steady state.

Rated torque and base speed operation

‘w/o temperature effect’ refers to assuming the machine temperature is fixed at 100\(^\circ\)C

With the temperature effect considered, the winding and magnet temperatures are \(\sim 5^\circ\)C higher than the results calculated using the conventional method when the machine gets into thermal steady state.
With the temperature effect considered, the winding and magnet temperatures are ~20°C higher than the results calculated using the conventional method and ~10°C higher than the results considering only the temperature effects on winding resistance.
A prototype machine of the 36-slot 6-pole IPM is driven by a dynamometer in the generator mode with a resistive load at different temperatures.
With the calibrated remanence, the predicted open-circuit back EMFs at 20°C have good agreements with the measure ones.
Current Measurements

6% reduction in fundamental current when temperature rises from 20°C to 70°C
Comparison

20°C

70°C

Good agreement achieved
Experimental validation

Measured torque

Mean torque error: 0.58%
This paper proposed a high fidelity, computationally efficient method for representing the temperature effect of magnets on the machine behaviors.

It employs an equivalent d-axis current proportional to the temperature variations in the machine flux linkage maps characterized at a reference temperature and expressed as functions of d- and q-axis currents and rotor position.

The method can greatly reduce simulation time for performance evaluation under driving cycles various driving conditions.

The effectiveness of the method has been validated by finite element analysis and tests on a prototype machine.
Thank you for your attention!