Deriving a Fast and Accurate PMSM Motor Model from Finite Element Analysis

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Motivation

• Traditionally, workflow of the machine design team and the control team have proceeded separately.

• DoE on a dyno setup requires an understanding of the machine characteristics and simulation can help determine a minimum number of points to test.

• Accurate torque ripple profile of a high fidelity machine model facilitates the development of torque ripple mitigation algorithms.
Content

MathWorks

• Objective and Workflow Overview
• Three Levels of PMSM Model Fidelity
• How to Obtain Saturation + Spatial Harmonics Data
• Saturation + Spatial Harmonics PMSM Model Structure

ANSYS

• Introduction of Maxwell Equivalent Circuit Extraction (ECE) Model
• Importing Raw Data from Maxwell Finite Element Result to Simulink
• Comparison between PMSM model in Simulink and Maxwell (FEA)
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Objective and Workflow Overview

ANSYS Maxwell

Simulink

<Current>

<Flux_Linkage>

<Torque>
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Three Levels of PMSM Model Fidelity

Lumped Parameter

Saturation

Saturation + Spatial Harmonics
Lumped-Parameter Model
Electrical Model

\[
v_d = R_i d - L_q p \omega_r i_q + L_d \frac{d}{dt} i_d
\]

\[
v_q = R_i q + p \omega_r (L_d i_d + \lambda) + L_q \frac{d}{dt} i_q
\]

\[
\omega_e = p \omega_r
\]

\[
T_e = 1.5p [\lambda i_q + (L_d - L_q) i_d i_q]
\]

\[
T_e = K_t i_q \text{ (assumes round rotor, } L_d = L_q \text{)}
\]

Mechanical Model

\[
\frac{d}{dt} \omega_r = \frac{1}{J} (T_e - \text{sgn}(\omega_r) J_0 - b \omega_r - T_{load})
\]
## Motor Tests

<table>
<thead>
<tr>
<th>Motor Tests</th>
<th>Parameters Identified</th>
<th>Identification method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back EMF Test</td>
<td>Number of Pole Pairs (p)</td>
<td>Calculation</td>
</tr>
<tr>
<td></td>
<td>Flux Linkage Constant (λ)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Torque Constant (K_t)</td>
<td></td>
</tr>
<tr>
<td>Friction Test</td>
<td>Viscous Damping Coefficient (b)</td>
<td>Curve fitting</td>
</tr>
<tr>
<td></td>
<td>Coulomb Friction (J_0)</td>
<td></td>
</tr>
<tr>
<td>Coast Down Test</td>
<td>Rotor Inertia (J)</td>
<td>Curve fitting</td>
</tr>
<tr>
<td>DC Voltage Step Test</td>
<td>Resistance (R)</td>
<td>Parameter estimation</td>
</tr>
<tr>
<td></td>
<td>Inductance (L)</td>
<td></td>
</tr>
</tbody>
</table>

How to Get Those Parameters?

Saturation Model

Torque vs. Current

Calculate Flux

Calculate Speed

Calculate Torque

Diagram showing the calculation flow for torque, flux, and speed in a saturation model.
Two Ways to Obtain Saturation Data

Dyno testing

FEA
Nonlinear Flux and Current Tables
Saturation PMSM Model in Simscape

Mechanical Eqn.
Saturation + Spatial Harmonics Model
Animation: flux variation at different rotor position
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How to Obtain Saturation + Spatial Harmonics Data?

Current → Flux Linkage
Rotor Position → Torque

Sweep in FEA Tool
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What does ANSYS Maxwell do?

• ANSYS Maxwell is a premier low-frequency electromagnetic field simulation solution which uses the highly accurate finite element method to solve static, frequency-domain, and time-varying electromagnetic and electric fields. Typical application of Maxwell includes electric machines, transformer, actuator, sensor, etc.
Objective and Workflow Overview

1. ANSYS Maxwell generates Model_RawData.txt file
2. Process raw data into proper format through MATLAB scripting
3. Bring processed data into Simulink saturation + harmonics motor model structure
How to obtain raw data for PMSM model by ANSYS Maxwell?

Steps to Generate ECE Model for PMSM

1. Create Regular FEA Model
2. Specify Model Resolution
3. Run FEA Model to Generate Lookup Table

**ECE3 Model**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DeviceName</td>
<td>ECE3_Model1</td>
<td></td>
</tr>
<tr>
<td>Windings</td>
<td>PhaseA, PhaseB, PhaseC</td>
<td></td>
</tr>
<tr>
<td>CurrentSwe...</td>
<td>(30A, 10)</td>
<td></td>
</tr>
<tr>
<td>PhAngleInt...</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Status</td>
<td>Active</td>
<td></td>
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</tbody>
</table>

**ECER Model**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DeviceName</td>
<td>ECER_Model1</td>
<td></td>
</tr>
<tr>
<td>RotAngMax</td>
<td>15</td>
<td>deg</td>
</tr>
<tr>
<td>InElecDeg</td>
<td></td>
<td>deg</td>
</tr>
<tr>
<td>RotAngInt...</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>SkewAng</td>
<td>0</td>
<td>deg</td>
</tr>
<tr>
<td>Poles</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Status</td>
<td>Active</td>
<td></td>
</tr>
</tbody>
</table>

Current & Position

Flux & Torque

Model_RawData.txt
What is Equivalent Circuit Extraction (ECE) Model in ANSYS Maxwell

- ECE Model - A circuit model based on a lookup table from precomputed Finite Element Analysis result. It is also known as Reduced Order Model (ROM).
ECE Models Needed for PMSM – ECE3 and ECER
Equivalent Circuit Extraction (ECE)

- Maxwell Circuit Components for Sweep Setup
  - ECEW_Model: ECE one winding model
  - ECE3_Model: ECE three-phase model
  - ECER_Model: ECE rotation model
  - ECEL_Model: ECE linear motion model
  - ECET_Model: ECE transformer model

- ECE Model Formats
  - ECE Simplorer model in file .sml
  - ECE Look-up table for third parties (Saber, ETAS, NI)
  - ECE VHDL model (Future)
  - ECE Simulink Model (.txt)

Models Needed for PMSM

EC3_Model - Setup the sweeping of currents in three-phase windings

ECER_Model - Setup the sweeping of rotor position
ECE3 Model - Setup Sweeping of Current in Three-Phase Winding

- CurrentSweep: Specify Current Range and Resolution
- PhAngIntervals: Choose Current Sweep Coordinate System
ECE3 Model - Current Sweep Coordinate System Options

1) **DQ Coordinate System**:
   - 0: positive d & q.
   - 1: positive q, all d.
   - 2: all d & q (default)

2) **αβ Coordinate System**

3) **Polar DQ Coordinate System**

- e.g. PhAngIntervals=16
ECER Model - Setup Sweeping of Rotor Position

• RotAngMax: Maximum rotating angle for sweep for each ld-lq variation. In balanced cases, a 60 elec. degree sweep is sufficient.

• Auto d-axis alignment (no need to manually adjust initial rotor position)

• Slots: enable a separate lookup table for cogging torque.
Fast Model Generation Technique - Partial Model Sweeping for Symmetric Structure

• 60 Degree Phase Symmetry - Duplicate Data from 60 degree segments:
  PhaseA Reconstruction: A, -B, C, -A, B, -C
  PhaseB Reconstruction: B, -C, A, -B, C, -A
  PhaseC Reconstruction: C, -A, B, -C, A, -B

One 60 elec. Degree Sweep

360 elec. degree Reconstructed

auto d-axis alignment
Example – Setups- Takes 3 h 30 min single core

- Current Sweeps: \((10\times2+1)^2 = 441\) \(I_d-I_q\) variations
  \[I_d = -300A, -270A, \ldots, -30A, 0, 30A, \ldots, 270\ A, 300A\]
  \[I_q = -300A, -270A, \ldots, -30A, 0, 30A, \ldots, 270\ A, 300A\]
- Rotor Position Sweep: 0 deg (d-axis), 1 deg, 2 deg, 3 deg, \ldots, 14deg. 15 rotor positions.
- For each \(I_d-I_q\) variation, 15 rotor positions will be swept to reconstruct a 360 elec. degree sweep.
- Total number of time steps calculated = \(441 \times 15 = 6615\). (About 2 second/step)
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Four Steps in Maxwell_to_MATLAB Script.m

1. Import Original Raw Data from Maxwell ECE Model.
2. Create (Id, Iq, Angle) to (Flux D, Flux Q, Torque) Lookup Table (3D Lookup Table) based on the raw data.
3. Create inverse lookup table to get current from flux input. (Flux D, Flux Q, Angle) to (Id, Iq, Torque) Lookup.
n-D Lookup Table in Simulink

• There are three Tabs in the n-D Lookup Table block: 1) Table and Breakpoints; 2) Algorithm and 3) Data Types.

• As an example, the screen shots below show a Table and Breakpoints setup for d-axis flux 3D lookup table. Iq_index, Id_index, Angle_index and Flux_d_ofIdIqTheta are defined in Workspace already.

![3D Data Table Diagram](image-url)

3D Data Table

\[
\text{Flux}_d(\text{Iq,Id,Theta})
\]

Input indexes for data lookup

Output
Set up n-D Lookup Table in Simulink

- Model Structure.

Current to Flux Lookup - Maxwell Direct Result
Current Excitation, Frequency = 2 Hz, 30 rpm
No Mechanical Dynamic
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Comparison between Simulink model and Maxwell FEA model:
Four cases to compare **current, flux, and torque** waveform.

1. Open circuit
2. Sinusoidal winding current input
3. Voltage input under constant rotor speed
4. Voltage input with mechanical dynamic (Starting of PMSM)
Example – Prius IPM motor – Open circuit – Cogging torque & Back EMF

Flux to Current Lookup - Inversed Maxwell Result
Cogging Torque Waveform Display,
Voltage = 0, Frequency = 0.4 Hz. (6 rpm),
Phase Resistance = 3.45 Ohm. NO Mechanical Dynamic

• Simulink result is compared with Maxwell result. The results are very close.
• Inverse lookup is successful.
Sinusoidal winding current input
Torque ripple

Current to Flux Lookup - Maxwell Direct Result
Current Excitation, Frequency = 2 Hz, 30 rpm
No Mechanical Dynamic

• Simulink result is compared with Maxwell result. The results are identical.
• Data transfer is successful.
Voltage input under constant rotor speed

Electrical Transient

- Simulink result is compared with Maxwell result. The results are very close.
- Motor phase resistance is considered.
Voltage input with mechanical dynamic
Mechanical & Electrical Transient

- Simulink result is compared with Maxwell result. The results are very close.
- Mechanical dynamic is considered.
Key Takeaways:

• ANSYS Maxwell can perform sweeping and generate raw machine data.

• Raw machine data can be processed and brought into Simulink for high fidelity machine modeling.

• High fidelity machine model is an accurate representation of the actual machine and it runs really fast in Simulink.