Variable Flux Machine for Electric Vehicles

From 2016-04-01 To 2019-03-31

Division of Electric Power Engineering
Chalmers University of Technology

Project budget: 4.25 MSEK
(Chalmers: 3.75 MSEK; Lund: 0.5 MSEK)
# Why Variable Flux Machine

<table>
<thead>
<tr>
<th></th>
<th>IM</th>
<th>PMSM</th>
<th>VFM</th>
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<tbody>
<tr>
<td>Cross-Section</td>
<td><img src="cross_section.png" alt="Diagram" /></td>
<td><img src="cross_section.png" alt="Diagram" /></td>
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<tr>
<td>Power-Speed Curve</td>
<td><img src="power_speed.png" alt="Diagram" /></td>
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<tr>
<td>Construction</td>
<td>Easy</td>
<td>Complicated</td>
<td>Complicated</td>
</tr>
<tr>
<td>Magnets</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Current Control</td>
<td>$I_{sd} &amp; I_{sq}$</td>
<td>$I_{sd} &amp; I_{sq}$</td>
<td>$I_{sd} &amp; I_{sq} &amp; I_f$</td>
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Why Variable Flux Machine

• By 2030, electric vehicle stock will exceed **110 million** by *Paris Declaration*. And this 110 million is only **10%** of the vehicle volume all over the world today.

• Today, Permanent Magnet Synchronous Machines (PMSM) are widely used.
  • However, if 1 kg rare earth material / vehicle, we need **110,000 tons of NdFeB magnets**, whereas only 7,500 tons are produced in 2015, i.e. it needs to be increased by over 14 times.
  • In addition, the production of *permanent magnets* gives *pollution* and are *difficult to recycle*.

• Therefore, it is not possible to continue with *Rare Earth Permanent Magnet* for ever.
Variable Flux Machine Performance

Variable Flux Machine is *Environmentally Friendly*, but how about *Performance*?

- **Safer Operation** – since field can be cut off at any time
  \[ \psi_m = L_m I_f \]

- **Higher Peak Torque** – higher acceleration
  \[ T_{em} = \frac{3n_p}{2} [L_m I_f + (L_d - L_q)I_d]I_q \]

- **Wider Speed Range** – able to run faster
  \[ |U_s| = \omega_r \sqrt{(L_q I_q)^2 + (L_d I_d + L_m I_f)^2} \]

- **Higher Power Factor** – smaller converter
  \[ Q_{stator} = \frac{3}{2} (U_q I_d - U_d I_q) = \frac{3}{2} \left( L_d I_d^2 + L_q I_q^2 + L_m I_f I_d \right) = 0 \quad \Rightarrow \quad I_f = -\frac{L_d I_d^2 + L_q I_q^2}{L_m I_d} \]
Variable Flux Machine Challenges

Variable Flux Machine is *Environmentally Friendly*, and gives *High Performance*. However, there are some *Challenges* before it prevails.

- **Machine Design**
  There are various kinds of requirement due to various kinds of Electric Vehicles. How to categorize the requirement and how to achieve them?

- **Optimized Control Strategy**
  Variable Flux Machine provides us with one more dimension of control freedom than PMSM, but how to make fully use of the freedom to maximize the performance?

- **Field Winding Excitation**
  How to transfer power to the rotor? Brushes and slip rings introduces mechanical losses. Can we transfer the power through air?

- **Cooling Design**
  Stator is easy to cool down by a cooling jacket, but how to cool down the rotor winding?
Machine Design

There are various kinds of requirement due to various kinds of Electric Vehicles, but we can generally categorize them into two: high power density machine and high efficiency machine.

- **High Power Density Machine**
  - High kW / kg;
  - For start-up and energy recovery, i.e. hybrid vehicle.

- **High Efficiency Machine**
  - Minimized Losses;
  - For continuous operation, i.e. all-electric vehicle.
Machine Design

Field Distribution @ Peak Torque. Design for 48 V Hybrid Vehicle.

- 8-pole VFM, 120 mm diameter.
- FEM simulation: 3025 elements.
- Thick tooth to guarantee the core is unsaturated.
- Power density in FEM: 4 kW / kg.

<table>
<thead>
<tr>
<th>$T_e \cdot \text{avg}$</th>
<th>47.6</th>
<th>[N·m]</th>
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</thead>
<tbody>
<tr>
<td>$T_e \cdot \text{max} - T_e \cdot \text{min}$</td>
<td>6.47</td>
<td>[N·m]</td>
</tr>
<tr>
<td>$\frac{T_e \cdot \text{max} - T_e \cdot \text{min}}{T_e \cdot \text{avg}} \times 100%$</td>
<td>13.6</td>
<td>[%]</td>
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Control Strategy

• The efficiency is calculated as

\[
\eta = \frac{P_{em} - P_{mech\cdot loss} - P_{stray\cdot loss}}{P_{em} + P_{Cu} + P_{Fe}} \times 100\%
\]

• Variable Flux Machine: High Efficiency at High Speed Region.
  Permanent Magnet Machine: High Efficiency at Medium Speed Region

• More Control Freedom available for Variable Flux Machine:
  We can adjust the workload of stator and rotor due to the situation.

Copper Loss Minimization

Field Current Minimization
Control Strategy

Copper Loss Minimization

Field Current Minimization
Field Winding Excitation

\[ i_1 \quad i_2 \]

\[ N_1 \quad N_2 \]

\[ L_{1a} \quad L_{2a} \]

\[ L_M \]

\[ TA^+ \quad TB^+ \quad TA^- \quad TB^- \]

\[ DA^+ \quad DB^+ \quad DA^- \quad DB^- \]

\[ R_\sigma \]

\[ L_r \]

H-Bridge Inverter

Rotating Transformer

Rectifier

Rotor

Rotary Part

Stationary Part

Rectifier

Rotor

Shaft
Field Winding Excitation

Test of Field Winding Excitation
Field Winding Excitation

DC-Link Current and Field Current at 120 °C

Rise Time = 18.2 [ms]
- Fast Enough to Start-Up the Car.

DC-Link Current / Field Current at different temperature

DC-Link Current / Field Current = 1.73
- Good Linearity, Easy to Control Field Current.
Cooling Design: Rotating Transformer

- Cut-Outs on the heat sink
  - To maximize heating dissipation area
  - To introduce turbulence during rotating

Test at Standing Still
- Rotating Transformer is much colder than field winding
Cooling Design: Field Winding

Working Package: Lund University

Solution 1: Turbulence
Solution 2: Forced Ventilation
Solution 3: Heat Pipe
20 kW Variable Flux Machine Prototype

- Side View
- Stator
- Converter
- CAD
- Rotor
- Test is going on
Conclusions & Future Work

Conclusions

• Rare Earth Material is not sustainable. We must search for other solutions. And Variable Flux Machine is a potential alternative.

• Variable Flux Machine is categorized into High Power Density and High Efficiency Machines, according to the requirement of electric vehicles.

• Control Strategies of Copper Loss Minimization and Field Current Minimization are developed.

• Rotating Transformer for Field Winding Excitation is developed and works well in the test.

• Ideas for the cooling of field winding of Variable Flux Machine are brought up and will be studied.

On-Going and Future Work

• Test of the 20 kW Variable Flux Machine.

• Investigation on the cooling of field winding of Variable Flux Machine.

• Prototype of 70 kW Variable Flux Machine for All-Electric-Car.

• Compact Design of Integrated Electric Drive for Variable Flux Machine.
Thank You!