Hochschule
München
University of
Applied Sciences

Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

ISIE 2023: Nonlinear Three-Phase Reluctance Synchronous Machine Modeling With Extended Torque Equation

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Outline I

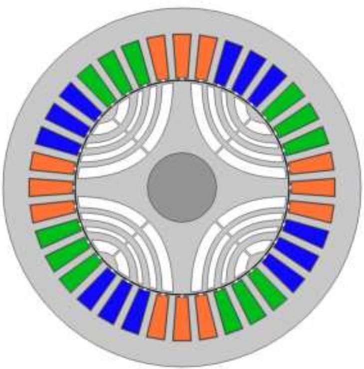
Outline I

Introduction

Reluctance synchronous machines

General issue and motivation

⇒ RSMs produce high torque ripple



Introduction

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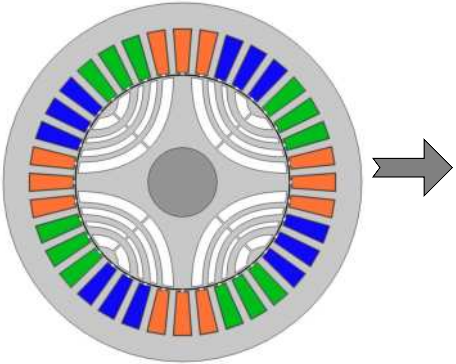

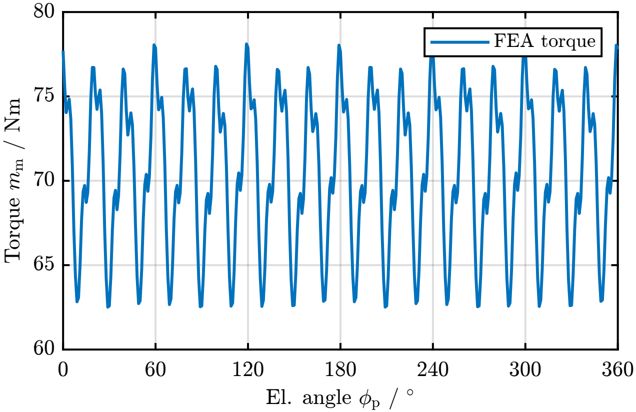

Introduction

Classic torque calculation

Classic torque equation in dq-reference frame:

- $m_{\mathrm{m}} = \frac{2n_{\mathrm{p}}}{3\kappa^2} \left(\boldsymbol{i}_{\mathrm{s}}^{dq}\right)^\top \boldsymbol{J} \boldsymbol{\psi}_{\mathrm{s}}^{dq}$
- No iron losses included
- No γ-component (or 0-component) included
- Nonlinearities are mostly neglected
- dq-torque corresponds to mean torque

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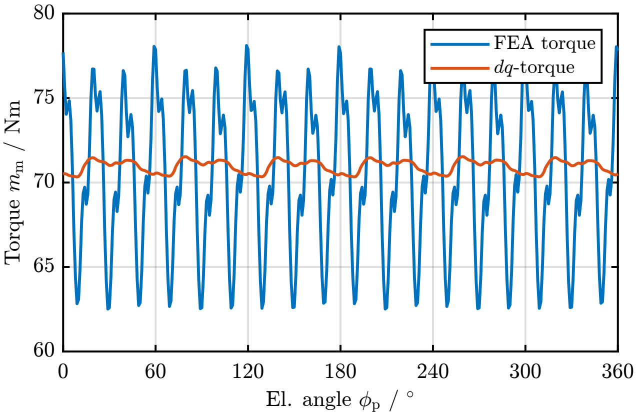

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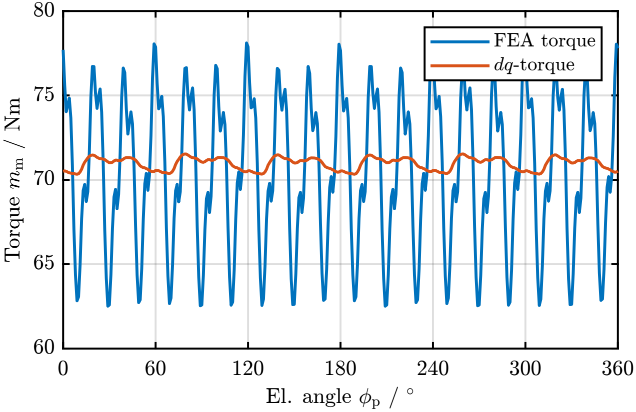
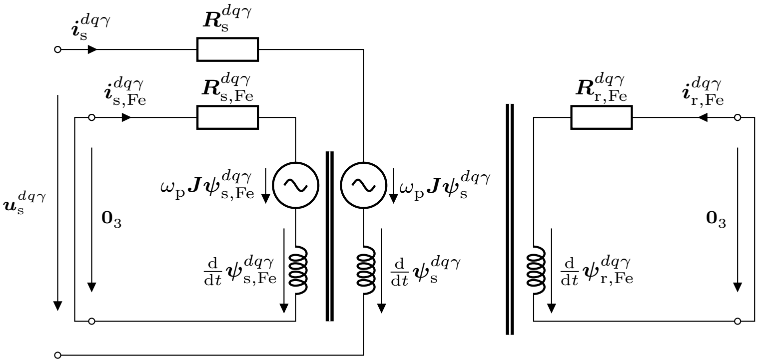


$\Rightarrow$ Nonlinear model required, which covers real torque and also losses and γ-component

Outline I

Machine Modeling

Extended transformer-like electrical model

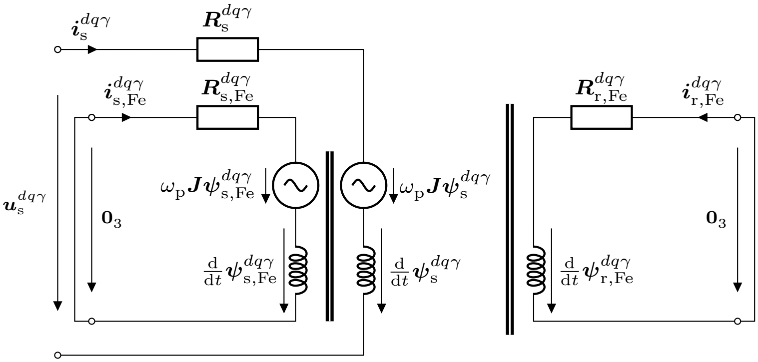


Machine Modeling

Extended transformer-like electrical model

Equivalent circuit of a RSM:

- Synchronous operation
- Iron losses in separate stator and rotor circuit
- Circuits are coupled inductively
- Resistances and fluxes depend on several inputs



Machine Modeling

Extended transformer-like electrical model

Electric equations

$$\boldsymbol{u}_{\mathrm{s}}^{dq\gamma} = \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} + \omega_{\mathrm{p}}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}$$

$$\boldsymbol{0}_3 = \boldsymbol{R}_{\mathrm{s,Fe}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma} + \omega_{\mathrm{p}}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}$$

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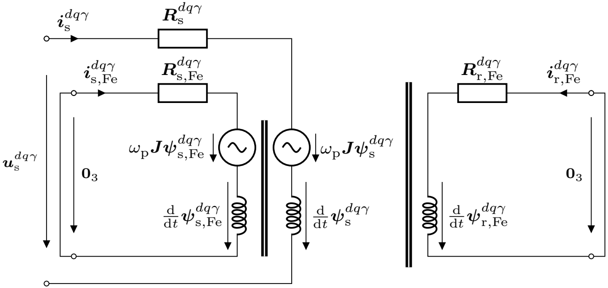

Machine Modeling

Extended transformer-like electrical model

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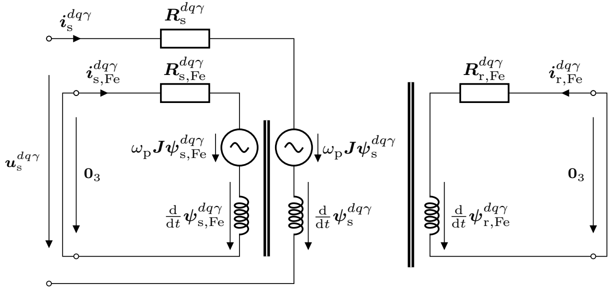
$$\boldsymbol{0}_3 = \boldsymbol{R}_\mathrm{r,Fe}^{dq\gamma}\boldsymbol{i}_\mathrm{r,Fe}^{dq\gamma} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_\mathrm{s}^{dq\gamma}$$

General maps:

- Stator flux linkage
  $\boldsymbol{\psi}_\mathrm{s}^{dq\gamma} = \boldsymbol{\psi}_\mathrm{s}^{dq\gamma}(\boldsymbol{i}_\mathrm{s}^{dq\gamma}, \omega_\mathrm{p}, \phi_\mathrm{p})$
- Stator winding resistances
  $\boldsymbol{R}_\mathrm{s}^{dq\gamma} = \boldsymbol{R}_\mathrm{s}^{dq\gamma}(\boldsymbol{i}_\mathrm{s}^{dq\gamma}, \omega_\mathrm{p}, \vartheta_\mathrm{s}, \phi_\mathrm{p})$
- Stator iron resistances
  $\boldsymbol{R}_\mathrm{s,Fe}^{dq\gamma} = \boldsymbol{R}_\mathrm{s,Fe}^{dq\gamma}(\boldsymbol{i}_\mathrm{s}^{dq\gamma}, \omega_\mathrm{p}, \vartheta_\mathrm{s,Fe}, \phi_\mathrm{p})$
- Rotor iron resistances
  $\boldsymbol{R}_\mathrm{r,Fe}^{dq\gamma} = \boldsymbol{R}_\mathrm{r,Fe}^{dq\gamma}(\boldsymbol{i}_\mathrm{s}^{dq\gamma}, \omega_\mathrm{p}, \vartheta_\mathrm{r,Fe}, \phi_\mathrm{p})$

Assumption: flux leakage is neglected

$$\Rightarrow \boldsymbol{\psi}_\mathrm{s}^{dq\gamma} = \boldsymbol{\psi}_\mathrm{s,Fe}^{dq\gamma} = \boldsymbol{\psi}_\mathrm{r,Fe}^{dq\gamma}$$



Machine Modeling

Extended mechanical model

Derivation of the extended mechanical model:

Conservation of power:

$$p_{\mathrm{el}} = p_{\mathrm{m}} + \underbrace{p_{\mathrm{s,Cu}} + p_{\mathrm{s,Fe}} + p_{\mathrm{r,Fe}}}_{=:p_{\mathrm{loss}}} + p_{\mathrm{mag}}$$

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with

- $p_{\mathrm{el}} = \frac{2}{3\kappa^2}\left(\boldsymbol{u}_{\mathrm{s}}^{dq\gamma}\right)^\top \boldsymbol{i}_{\mathrm{s}}^{dq\gamma}$
- $p_{\mathrm{m}} = m_{\mathrm{m}}\omega_{\mathrm{m}}$
- $p_{\mathrm{s,Cu}} = \frac{2}{3\kappa^2}\left(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}\right)^\top \boldsymbol{R}_{\mathrm{s}}^{dq\gamma} \boldsymbol{i}_{\mathrm{s}}^{dq\gamma}$
- $p_{\mathrm{s,Fe}} = \frac{2}{3\kappa^2}\left(\boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma}\right)^\top \boldsymbol{R}_{\mathrm{s,Fe}}^{dq\gamma} \boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma}$
- $p_{\mathrm{r,Fe}} = \frac{2}{3\kappa^2}\left(\boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma}\right)^\top \boldsymbol{R}_{\mathrm{r,Fe}}^{dq\gamma} \boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma}$
- $p_{\mathrm{mag}} = \frac{\mathrm{d}W_{\mathrm{mag}}}{\mathrm{d}t}$

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- $p_{\mathrm{r,Fe}} = \frac{2}{3\kappa^2}\left(\boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma}\right)^\top \boldsymbol{R}_{\mathrm{r,Fe}}^{dq\gamma}\boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma}$
- $p_{\mathrm{mag}} = \frac{\mathrm{d}W_{\mathrm{mag}}}{\mathrm{d}t}$

$$\Rightarrow$$

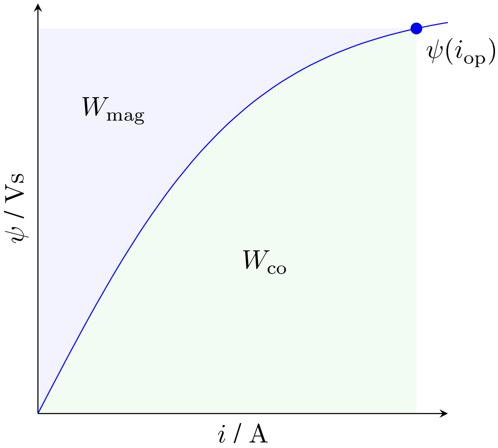
$$\begin{aligned} m_{\mathrm{m}} = &\frac{2n_{\mathrm{p}}}{3\kappa^2}\left(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} + \boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma}\right)^\top \boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} \\ &+ \frac{2}{3\kappa^2}\left(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} + \boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma} + \boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma}\right)^\top \frac{\mathrm{d}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\mathrm{d}\phi_{\mathrm{m}}} \\ &- \frac{\mathrm{d}W_{\mathrm{mag}}}{\mathrm{d}\phi_{\mathrm{m}}} \end{aligned}$$

Machine Modeling

Extended mechanical model

Torque depends on magnetic energy

- $$W_{\mathrm{mag}}\left(\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}\right) := \frac{2}{3\kappa^2} \int_{\mathbf{0}_3}^{\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}} \boldsymbol{i}_{\mathrm{s}}^{dq\gamma}\left(\widetilde{\boldsymbol{\psi}}_{\mathrm{s}}^{dq\gamma}\right)^{\top} \mathrm{d}\widetilde{\boldsymbol{\psi}}_{\mathrm{s}}^{dq\gamma}$$



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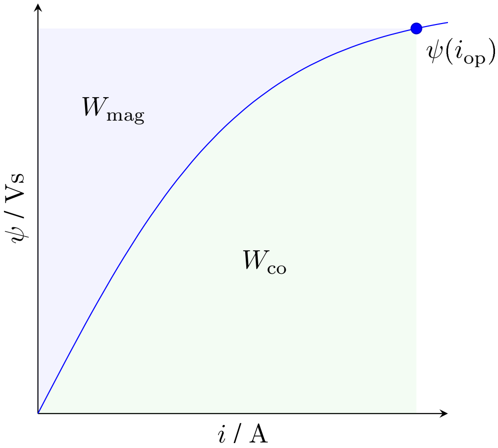
More practicable: magnetic co-energy

- $W_{\mathrm{co}}\left(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}\right) := \frac{2}{3\kappa^2} \int\limits_{\mathbf{0}_3}^{\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}} \boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}\left(\tilde{\boldsymbol{i}}_{\mathrm{s}}^{dq\gamma}\right)^\top \mathrm{d}\tilde{\boldsymbol{i}}_{\mathrm{s}}^{dq\gamma}$



Machine Modeling

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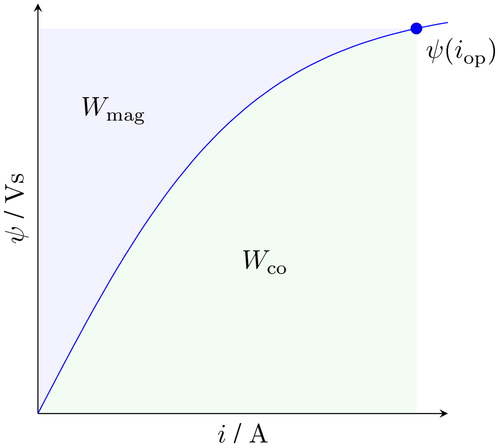
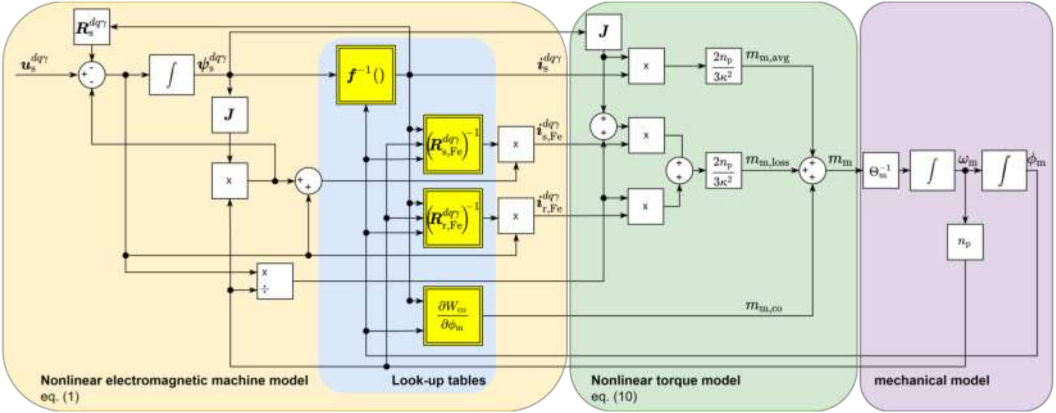


$$\Rightarrow m_{\mathrm{m}} = \underbrace{\frac{2n_{\mathrm{p}}}{3\kappa^2}\left(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}\right)^{\top}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}_{=:m_{\mathrm{m,avg}}} + \underbrace{\frac{2}{3\kappa^2}\left(n_{\mathrm{p}}\left(\boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma}\right)^{\top}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} + \left(\boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma} + \boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma}\right)^{\top}\frac{\mathrm{d}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\mathrm{d}\phi_{\mathrm{m}}}\right)}_{=:m_{\mathrm{m,loss}}} + \underbrace{\frac{\partial W_{\mathrm{co}}}{\partial \phi_{\mathrm{m}}}}_{=:m_{\mathrm{m,co}}}$$

Machine Modeling

Complete model



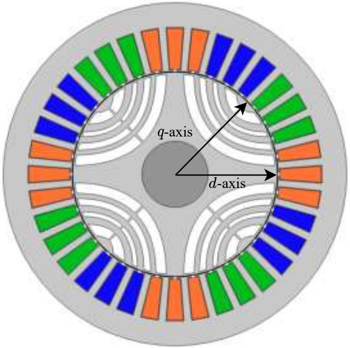
Outline I

3 Validation

Validation

Investigated motor

Parameter	Symbol	Value
Slots	Q_s	36
Pole pairs	n_p	2
Flux barriers	n_fb	4
Least common multiple (lcm)		36
Rated mechanical power	$p_{\mathrm{m,R}}$	30 kW
Rated mechanical speed	$n_{\mathrm{m,R}}$	3 600 rpm
Rated mechanical torque	$m_{\mathrm{m,R}}$	80 Nm
Maximum current	$\widehat{i}_{\mathrm{max}}$	50 A
Stator winding resistance	$\boldsymbol{R}_\mathrm{s}^{dq\gamma}$	$0.12\,\boldsymbol{I}_3\,\Omega$
Nonlinear flux linkages	$\boldsymbol{\psi}_\mathrm{s}^{dq\gamma}$	Maps
Nonlinear stator iron losses	$p_{\mathrm{s,Fe}}$, $R_{\mathrm{s,Fe}}$	Maps
Nonlinear rotor iron losses	$p_{\mathrm{r,Fe}}$, $R_{\mathrm{r,Fe}}$	Maps
Nonlinear co-energy	W_{co}	Maps



Validation

Map generation

Map generation with FEA:

- Simulation with COMSOL Multiphysics
- Loss maps are not angle dependent
- Impact of eddy currents on magn. energy neglected

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Maps:

- $\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} = \boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q}, i_{\mathrm{s}}^{\gamma}, \phi_{\mathrm{p}})$
- $p_{\mathrm{s,Fe}} = p_{\mathrm{s,Fe}}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q}, i_{\mathrm{s}}^{\gamma}, \omega_{\mathrm{p}})$
- $p_{\mathrm{r,Fe}} = p_{\mathrm{r,Fe}}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q}, i_{\mathrm{s}}^{\gamma}, \omega_{\mathrm{p}})$
- $W_{\mathrm{co}} = W_{\mathrm{co}}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q}, i_{\mathrm{s}}^{\gamma}, \phi_{\mathrm{p}})$

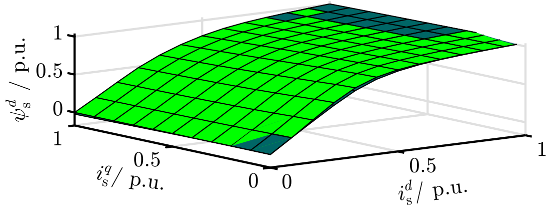
with:

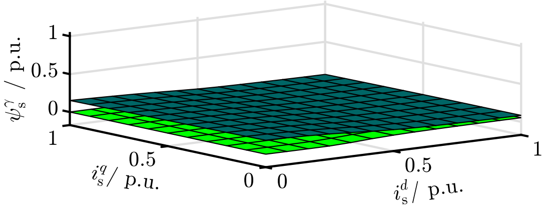
- $\phi_{\mathrm{p}} \in \{x \in \mathbb{N}_0^+ \mid 0^\circ \text{ el.} \leqslant x \leqslant 360^\circ \text{ el.}\}$
- $i_{\mathrm{s}}^{d} \in \{x \in \mathbb{R}_0^+ \mid 0 \text{ p.u.} \leqslant x \leqslant 1 \text{ p.u.}\}$
- $i_{\mathrm{s}}^{q} \in \{x \in \mathbb{R}_0^+ \mid 0 \text{ p.u.} \leqslant x \leqslant 1 \text{ p.u.}\}$
- $i_{\mathrm{s}}^{\gamma} \in \{x \in \mathbb{R} \mid -0.6 \text{ p.u.} \leqslant x \leqslant 0.6 \text{ p.u.}\}$

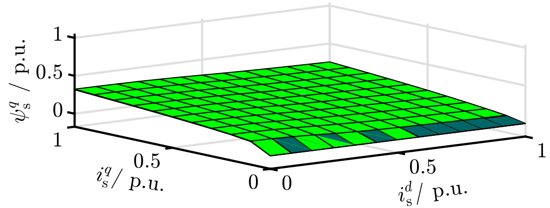
- $\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}$-mesh: 13×11×9

Validation

Flux linkage maps







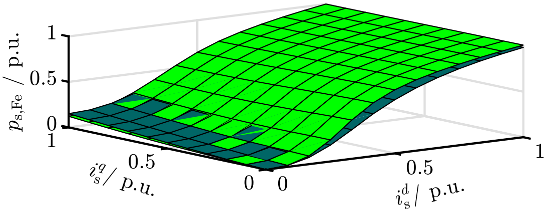
$i_s^\gamma = 0\,\mathrm{p.u.}$ [ ] $i_s^\gamma = 0.6\,\mathrm{p.u.}$ [ ] at $\phi_p = 0°$

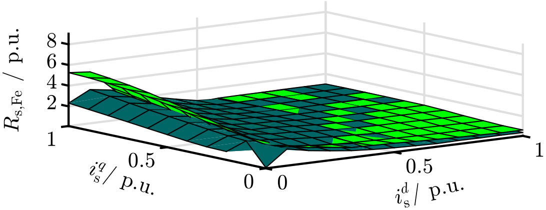
at rated speed

Validation

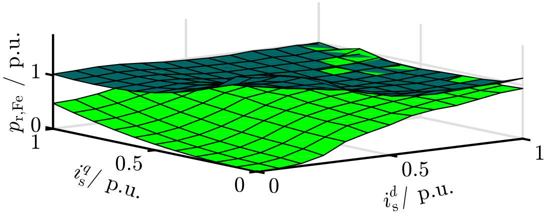
Iron loss maps

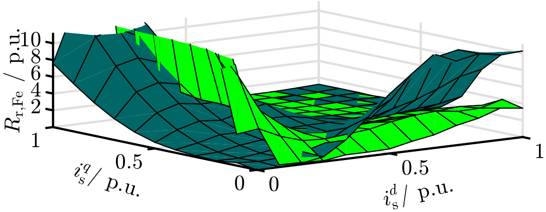
Stator loss maps:





Rotor loss maps:





$i_s^q = 0\,\mathrm{p.u.}$ [light green] $i_s^q = 0.6\,\mathrm{p.u.}$ [dark green] at $\phi_p = 0°$ at rated speed

Validation

Co-energy map

Co-energy map:

- Co-energy can be obtained directly by FEA

Validation

Co-energy map

Co-energy map:

- Co-energy can be obtained directly by FEA
- Analytic calculation is also possible

$$
\begin{aligned}
W_{\mathrm{co},\int}\left(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}\right) = \frac{2}{3\kappa^2} \Bigg(& \int\limits_{i_{\mathrm{s}}^{d}=0}^{\hat{i}_{\mathrm{s}}^{d}} \psi_{\mathrm{s}}^{d}\left(\tilde{i}_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q\gamma} = 0_2\right) \mathrm{d}\tilde{i}_{\mathrm{s}}^{d} \\
& + \int\limits_{i_{\mathrm{s}}^{q}=0}^{\hat{i}_{\mathrm{s}}^{q}} \psi_{\mathrm{s}}^{q}\left(\hat{i}_{\mathrm{s}}^{d}, \tilde{i}_{\mathrm{s}}^{q}, i_{\mathrm{s}}^{\gamma} = 0\right) \mathrm{d}\tilde{i}_{\mathrm{s}}^{q} \\
& + \int\limits_{i_{\mathrm{s}}^{\gamma}=0}^{\hat{i}_{\mathrm{s}}^{\gamma}} \psi_{\mathrm{s}}^{\gamma}\left(\hat{i}_{\mathrm{s}}^{dq}, \tilde{i}_{\mathrm{s}}^{\gamma}\right) \mathrm{d}\tilde{i}_{\mathrm{s}}^{\gamma} \Bigg)
\end{aligned}
$$

Validation

Co-energy map

Co-energy map:

- Co-energy can be obtained directly by FEA
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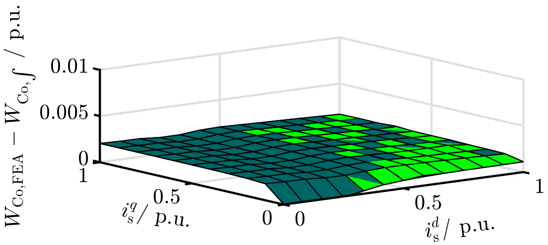
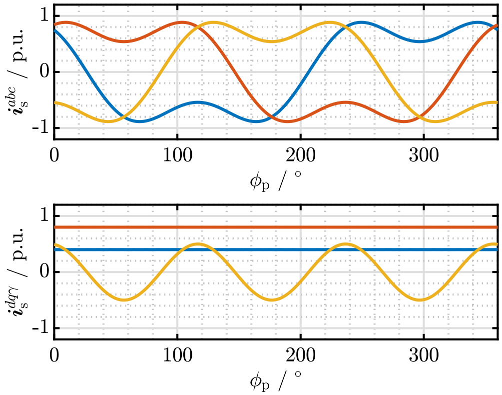
$$W_{\mathrm{co},\int}\left(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}\right) = \frac{2}{3\kappa^2}\left(\int_{i_{\mathrm{s}}^{d}=0}^{\hat{i}_{\mathrm{s}}^{d}} \psi_{\mathrm{s}}^{d}\left(\tilde{i}_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q\gamma}=0_2\right) \mathrm{d}\tilde{i}_{\mathrm{s}}^{d} + \int_{i_{\mathrm{s}}^{q}=0}^{\hat{i}_{\mathrm{s}}^{q}} \psi_{\mathrm{s}}^{q}\left(\hat{i}_{\mathrm{s}}^{d}, \tilde{i}_{\mathrm{s}}^{q}, i_{\mathrm{s}}^{\gamma}=0\right) \mathrm{d}\tilde{i}_{\mathrm{s}}^{q} + \int_{i_{\mathrm{s}}^{\gamma}=0}^{\hat{i}_{\mathrm{s}}^{\gamma}} \psi_{\mathrm{s}}^{\gamma}\left(\hat{i}_{\mathrm{s}}^{dq}, \tilde{i}_{\mathrm{s}}^{\gamma}\right) \mathrm{d}\tilde{i}_{\mathrm{s}}^{\gamma} \right)$$



$i_{\mathrm{s}}^{\gamma} = 0\,\mathrm{p.u.}$ [ ] $i_{\mathrm{s}}^{\gamma} = 0.6\,\mathrm{p.u.}$ [ ] at $\phi_{\mathrm{p}} = 0°$

Validation

Simulation scenario



Validation

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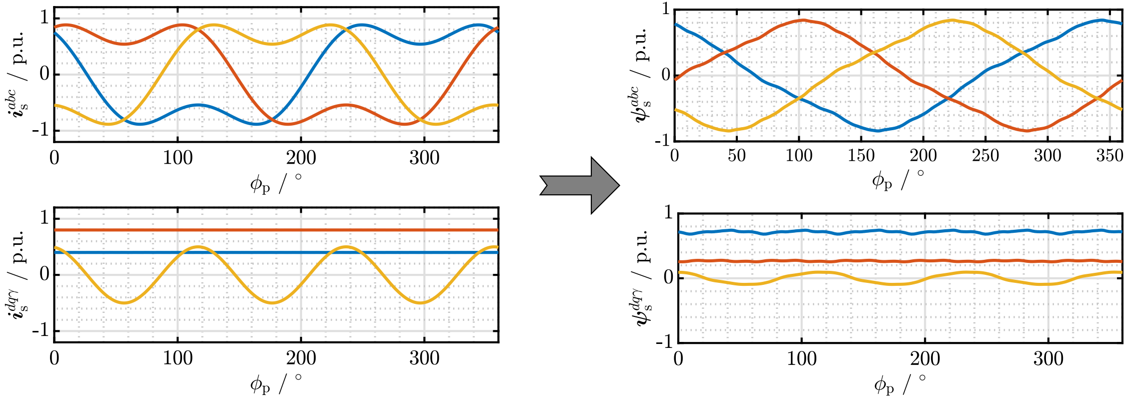
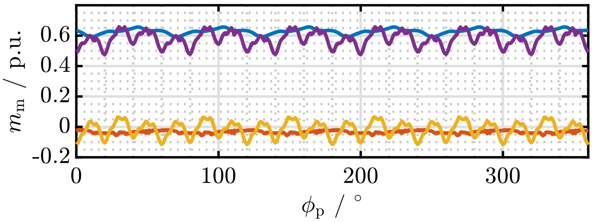
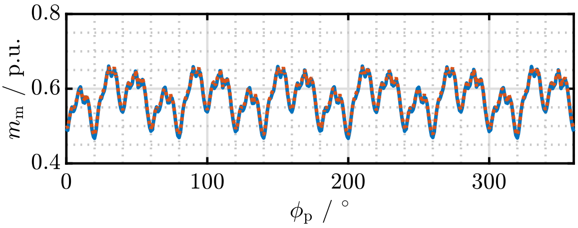


Validation

Torque comparison and conclusion



$m_{m,avg}$ [—], $m_{m,loss}$ [—], $m_{m,co}$ [—], m_m [—]

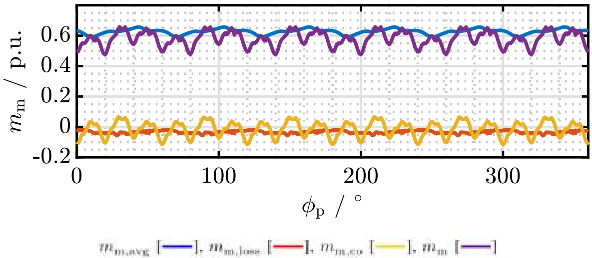


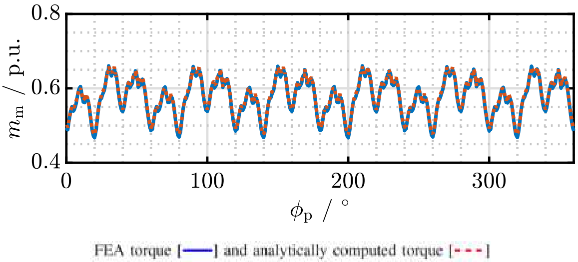
FEA torque [—] and analytically computed torque [- - -]

Validation

Torque comparison and conclusion

- Analytic torque comprises three parts:
  - Mean torque
  - Loss torque
  - Co-energy torque
- Analytic torque equals FEA torque
- Maximum error < 0.01 p.u.





Outline I

Conclusion

Summary and Outlook

To take home:

- ✓ Unified electromagnetic and torque model
- ✓ Saturation and cross-coupling included
- ✓ New model covers iron losses and γ-component
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Next steps:

- Consideration of eddy currents on magnetic energy
- Consideration of leakage flux linkages
- Measurement of angle dependent flux maps on testbench