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Nonlinear modeling, identification and optimal feedforward torque control of induction machines using steady-state machine maps

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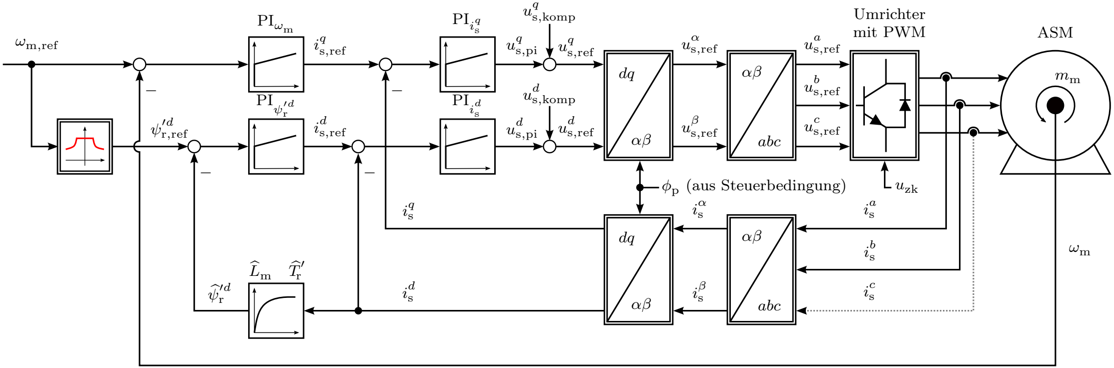
Outline

Outline

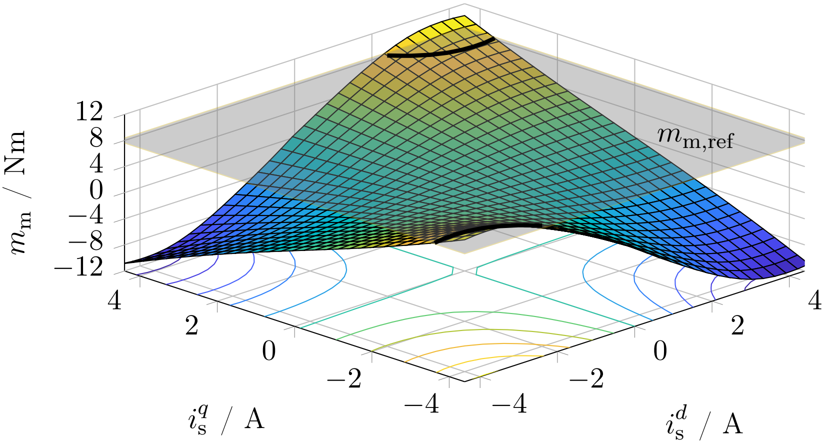
Motivation

Conventional field-oriented control (FOC) of induction machines (IMs)



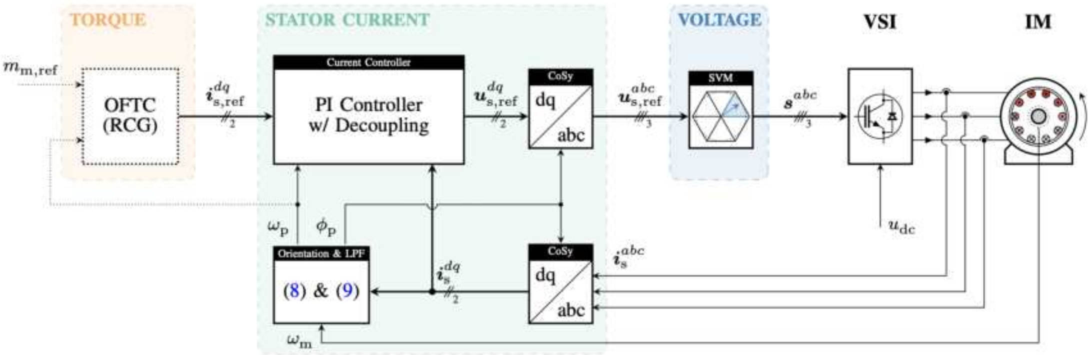
Motivation

Illustration of optimal feedforward torque control (OFTC) problem for IMs



Motivation

Proposed field-oriented control (FOC) with **OFTC** of IMs in **unique & reproducable reference frame**



unique & reproducible transformation angle:

$$\phi_p := \int \omega_p \, dt := \int \left(n_p \omega_m + \frac{1}{T_f} \frac{i_s^q}{\boldsymbol{i}^{dq}_{s,lpf}} \right) dt \qquad (8)$$

low-pass filtered stator currents:

$$\frac{d}{dt} \boldsymbol{i}^{dq}_{s,lpf} = \frac{1}{T_f} \left(\boldsymbol{i}^{dq}_{s} - \boldsymbol{i}^{dq}_{s,lpf} \right) \qquad (9)$$

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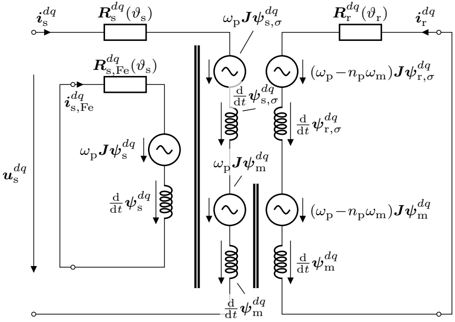
Nonlinear modelling

Equivalent electrical circuit diagram and governing equations



Dynamical system:

$$\left.\begin{aligned}
\boldsymbol{u}_{\mathrm{s}}^{dq} &= \boldsymbol{R}_{\mathrm{s}}^{dq}\boldsymbol{i}_{\mathrm{s}}^{dq} + \omega_{\mathrm{p}}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq}, \\
\boldsymbol{0}_2 &= \boldsymbol{R}_{\mathrm{s,Fe}}^{dq}\boldsymbol{i}_{\mathrm{s,Fe}}^{dq} + \omega_{\mathrm{p}}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq}, \\
\boldsymbol{u}_{\mathrm{r}}^{dq} &= \boldsymbol{R}_{\mathrm{r}}^{dq}\boldsymbol{i}_{\mathrm{r}}^{dq} + (\omega_{\mathrm{p}} - n_{\mathrm{p}}\omega_{\mathrm{m}})\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{r}}^{dq} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{r}}^{dq}, \\
\frac{\mathrm{d}}{\mathrm{d}t}\omega_{\mathrm{m}} &= \frac{1}{\Theta_{\mathrm{m}}}\big(m_{\mathrm{m}} - m_{\mathrm{l}}\big), \\
\frac{\mathrm{d}}{\mathrm{d}t}\phi_{\mathrm{m}} &= \omega_{\mathrm{m}}
\end{aligned}\right\}$$

Machine torque:

$$\begin{aligned}
m_{\mathrm{m}} &= -\frac{2n_{\mathrm{p}}}{3\kappa^2}\big(\boldsymbol{i}_{\mathrm{r}}^{dq}\big)^{\top}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{m}}^{dq} = \frac{2n_{\mathrm{p}}}{3\kappa^2}\big(\boldsymbol{i}_{\mathrm{s}}^{dq} + \boldsymbol{i}_{\mathrm{s,Fe}}^{dq}\big)^{\top}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq} \\
&= \frac{2n_{\mathrm{p}}}{3\kappa^2}\Big[\big(\boldsymbol{i}_{\mathrm{s}}^{dq}\big)^{\top}\Big(\boldsymbol{I}_2 + \boldsymbol{R}_{\mathrm{s,Fe}}^{dq}(\vartheta_{\mathrm{s}})^{-1}\boldsymbol{R}_{\mathrm{s}}^{dq}(\vartheta_{\mathrm{s}})\Big)^{\top}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq} \\
&\qquad - \big(\boldsymbol{R}_{\mathrm{s,Fe}}^{dq}(\vartheta_{\mathrm{s}})^{-1}\boldsymbol{u}_{\mathrm{s}}^{dq}\big)^{\top}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq}\Big]
\end{aligned}$$

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3 Machine identification

Machine identification

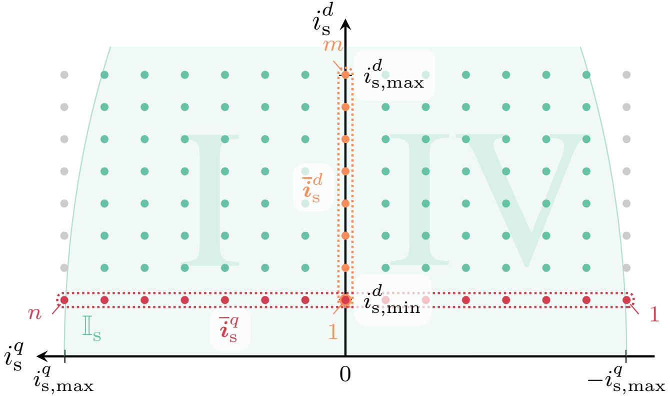
Identification goals

Goals:

- Stator flux linkage maps $\boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$
- Machine torque maps $m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$
- Iron resistance maps $\boldsymbol{R}_{\mathrm{s,Fe}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$
- Efficiency maps $\eta(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$
- OFTC look-up tables (LUTs) $\mathcal{L}^{\mathrm{M}}_{i^d_{\mathrm{s,ref}}}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$ and $\mathcal{L}^{\mathrm{M}}_{i^q_{\mathrm{s,ref}}}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$ (for e.g. M $\in$ {MTPC, MTPL, ...} to be able to compare the different strategies)

Machine identification

Identification procedure

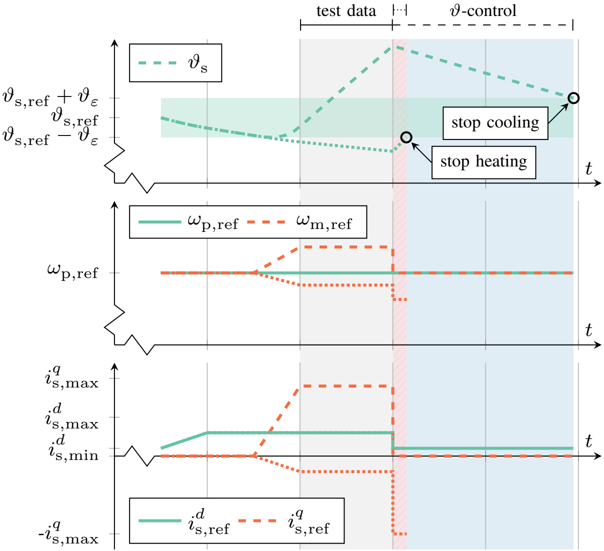


while guaranteeing with prime mover a **constant** asynchronous electrical frequency, i.e.

$$\omega_{\mathrm{m,ref}} = \frac{1}{n_\mathrm{p}}\left(\omega_{\mathrm{p,ref}} - \frac{1}{T_\mathrm{f}}\frac{i_{\mathrm{s,ref}}^q}{i_{\mathrm{s,ref}}^d}\right) \quad \Longrightarrow \quad \omega_\mathrm{p} = n_\mathrm{p}\omega_\mathrm{m} + \frac{1}{T_\mathrm{f}}\frac{i_\mathrm{s}^q}{\boldsymbol{i}_{\mathrm{s,lpf}}^{dq}} = const.$$

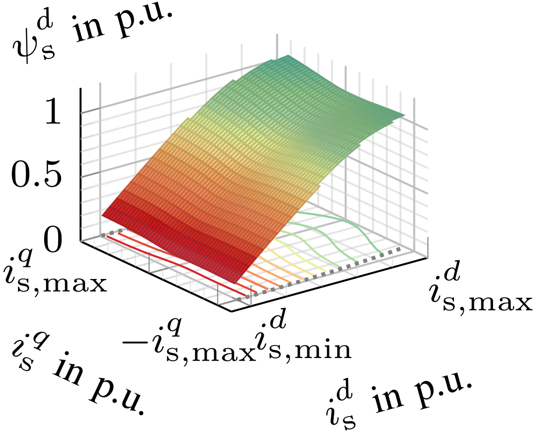
Machine identification

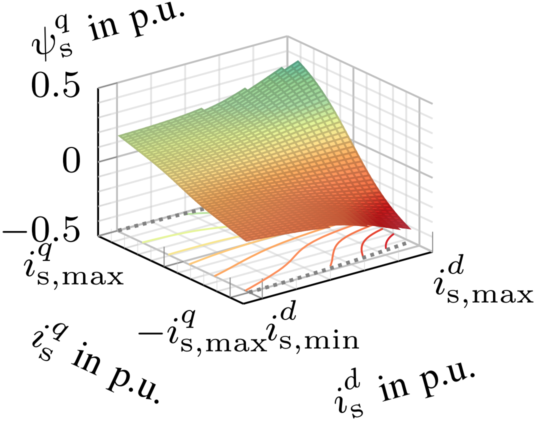
Temperature control guaranteeing an almost constant $\vartheta_s \implies R_s(\vartheta_s) = R_{s,0}\left[1 + \alpha(\vartheta_s - \vartheta_{s,0})\right] = const.$



Machine identification

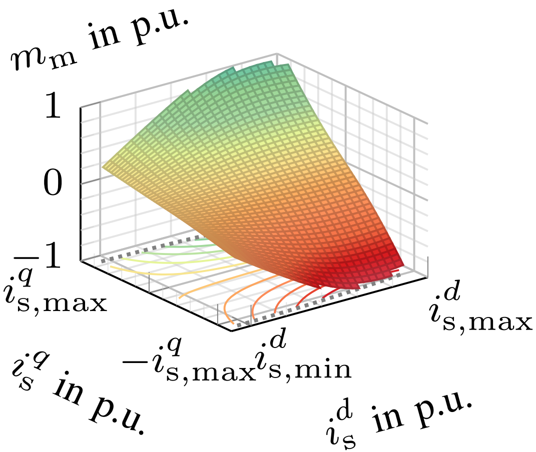
Flux linkage maps at $\omega_{\mathrm{p}} = 0.5\omega_{\mathrm{p,R}}$

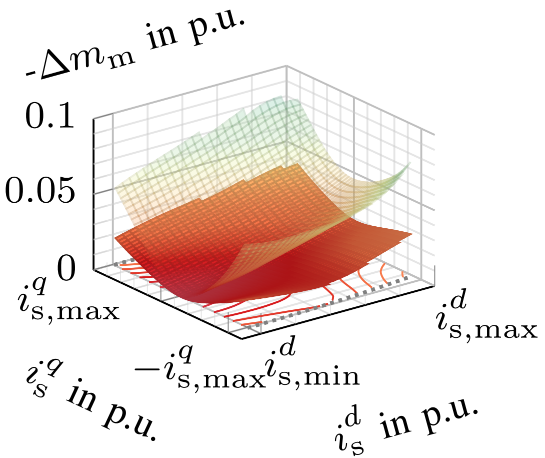




Machine identification

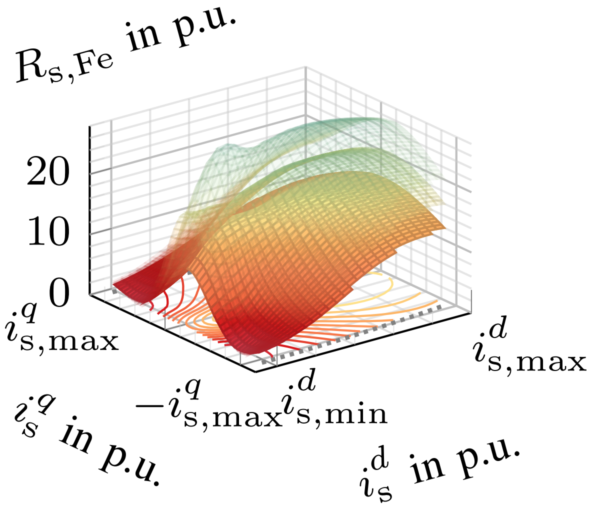
Torque maps at $\omega_{\mathrm{p}} = 0.5\omega_{\mathrm{p,R}}$ using $\widehat{m}_{\mathrm{m}}^{(1)} = \frac{2n_{\mathrm{p}}}{3\kappa^2}(\boldsymbol{i}_{\mathrm{s}}^{dq})^\top \boldsymbol{J}\overline{\boldsymbol{\psi}_{\mathrm{s}}^{dq}}$ (avg.) and $\widehat{m}_{\mathrm{m}}^{(2)} = \frac{2n_{\mathrm{p}}}{3\kappa^2}(\boldsymbol{i}_{\mathrm{s}}^{dq})^\top \boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq}$ (w/o iron current)





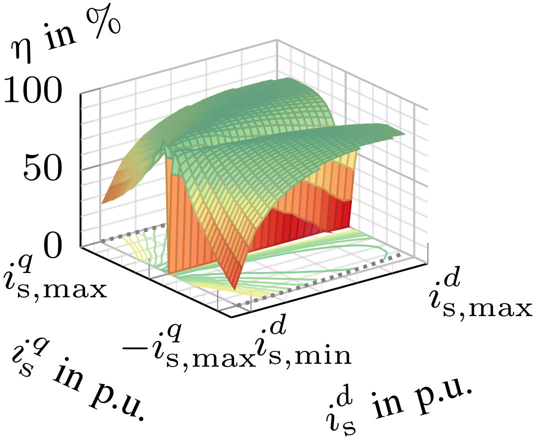
Machine identification

Iron resistance maps at $\omega_{\mathrm{p}} \in \{0.5,\ 0.6,\ 0.7\} \cdot \omega_{\mathrm{p,R}}$

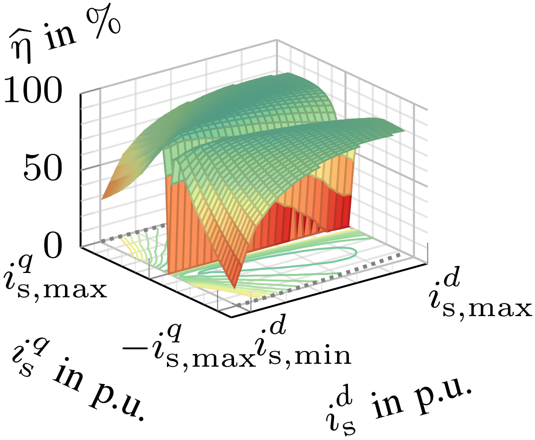


Machine identification

Efficiency maps $\eta = \frac{p_\mathrm{m}}{p_\mathrm{s}} = \frac{m_\mathrm{m}\omega_\mathrm{m}}{(\boldsymbol{u}_\mathrm{s}^{dq})^\top \boldsymbol{i}_\mathrm{s}^{dq}}$ at $\omega_\mathrm{p} = 0.5\omega_{\mathrm{p,R}}$



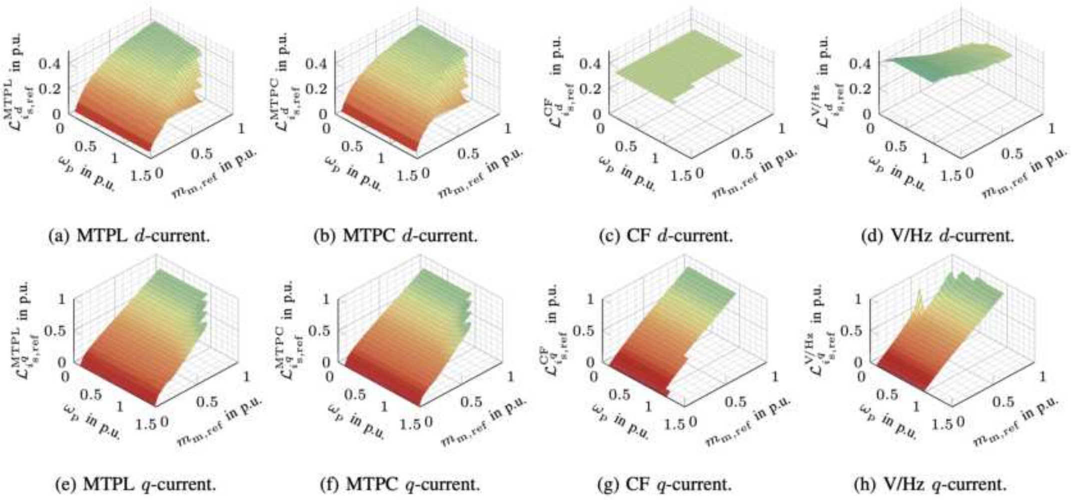
(using measured m_m)



(using estimated $\widehat{m}_\mathrm{m}$)

Machine identification

OFTC LUTs $\mathcal{L}^{\mathrm{M}}_{i^d_{\mathrm{s,ref}}}$ and $\mathcal{L}^{\mathrm{M}}_{i^q_{\mathrm{s,ref}}}$ for M $\in$ {MTPL, MTPC, CF, V/Hz}, $\omega_{\mathrm{p}} \in [0.1, 1.5] \cdot \omega_{\mathrm{p,R}}$ and $m_{\mathrm{m,ref}} \in [0, 1] \cdot m_{\mathrm{m,R}}$



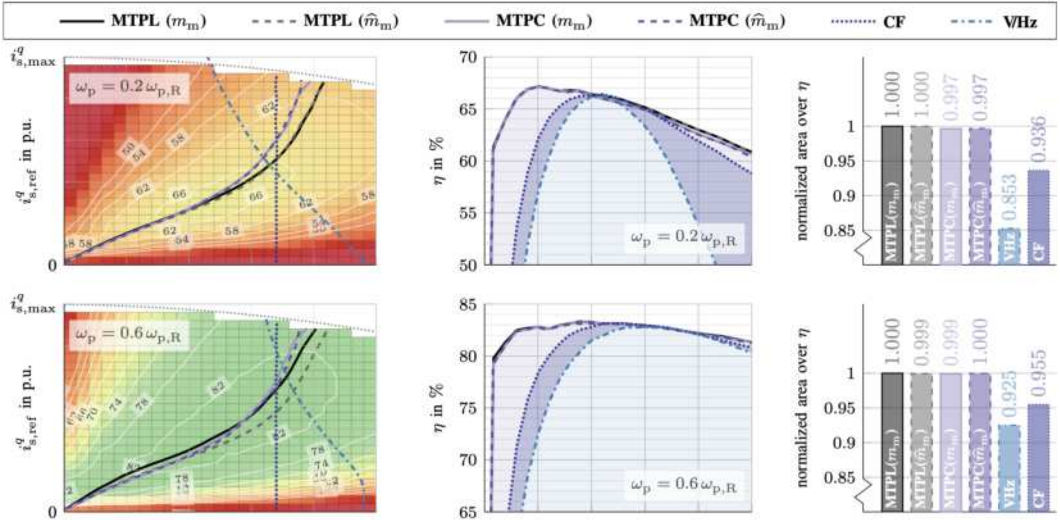
(a) MTPL d-current. (b) MTPC d-current. (c) CF d-current. (d) V/Hz d-current.

(e) MTPL q-current. (f) MTPC q-current. (g) CF q-current. (h) V/Hz q-current.

Outline

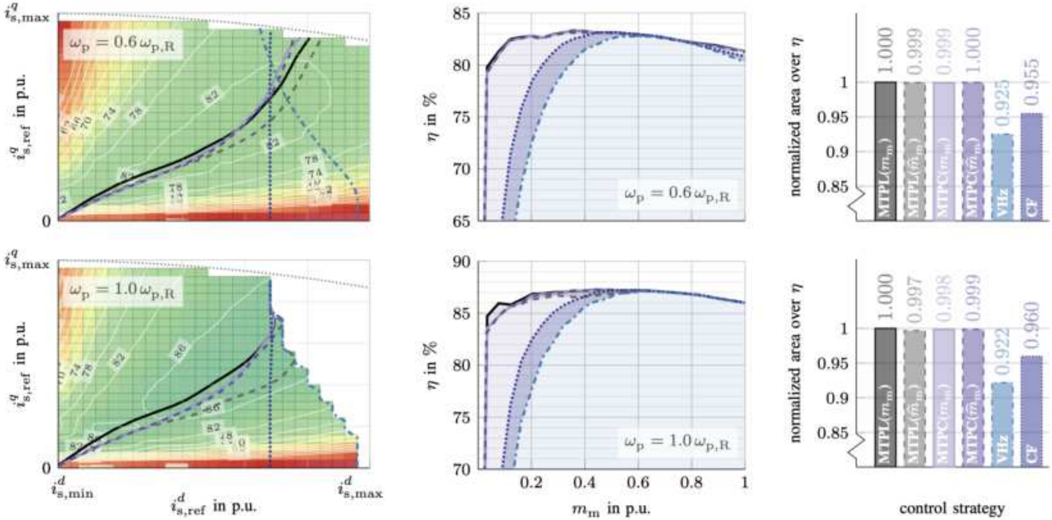
Implementation results

Comparison of different OFTC strategies



Implementation results

Comparison of different OFTC strategies



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5 Conclusion

Conclusion

Summary and future work

To take home

- Nonlinear transformer-like IM model
  - in unique & reproducible reference (no parameter uncertainties),
  - iron losses (in stator) considered,
  - current, temperature, angle and speed dependencies in flux, resistance(s), etc. admissible
- Generic machine identification
  - Stator flux linkage maps $\boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$
  - Machine torque maps $m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$
  - Iron resistance maps $\boldsymbol{R}_{\mathrm{s,Fe}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$
  - Efficiency maps $\eta(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{s}}, \omega_{\mathrm{p}}, (\phi_{\mathrm{p}}))$
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    (for e.g. M $\in$ {MTPC, MTPL, CF, V/Hz} to be able to compare the different strategies)

Future work

- dynamic machine identification (e.g. also rotor flux linkages)
- consideration of *rotor* iron losses
- combination with minimization of *conduction and switching losses*

References

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Nonlinear modeling, identification and optimal feedforward torque control of induction machines using steady-state machine maps

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***Abstract*—A novel but simple machine map based modeling, identification and optimal feedforward torque control (OFTC) approach for induction machines (IMs) is presented. It is based on (i) a generic, nonlinear transformer-like machine model considering nonlinear flux linkages (with magnetic saturation and cross-coupling) and iron losses in the stator laminations in a novel, arbitrarily rotating but unique, robust & reproducible (d,q)-reference frame; (ii) a holistic machine identification procedure which evaluates steady-state measurements over a grid of (d,q) stator currents and produces temperature and frequency dependent machine maps for e.g. flux linkages, torque, iron resistance and efficiency; and (iii) a numerical offline optimization and extraction of different OFTC look-up tables (LUTs) for *optimal* current reference generation depending on reference torque and electrical frequency (and temperature). During the identification, stator winding temperature and electrical stator frequency of the IM are kept constant by an intelligent temperature and speed**

ϕ_p & $\omega_\mathrm{p} = \frac{\mathrm{d}}{\mathrm{d}t}\phi_\mathrm{p}$: Park transformation angle and angular velocity; $\boldsymbol{J} := \left[\begin{smallmatrix}0 & -1\\ 1 & 0\end{smallmatrix}\right]$: rotation matrix (by $\frac{\pi}{2}$).

I. Motivation and Contributions

Maximum efficiency operation (or *loss minimizing control*) of induction machines has been subject to extensive research in the past. In contrast to LUT-based direct torque control (see e.g. [1]), for vector control, two main approaches are typically distinguished: (i) Offline calculation of optimal references (e.g. [2–4]) or (ii) search-based online techniques (e.g. [5–8]).

The objective is to compute *optimal* reference currents (set points) for a given reference torque while complying with physical constraints (e.g. current & voltage limits) and