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Nonlinear MPC for Winding Loss Optimized Torque Control of Anisotropic PMSM

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Aim

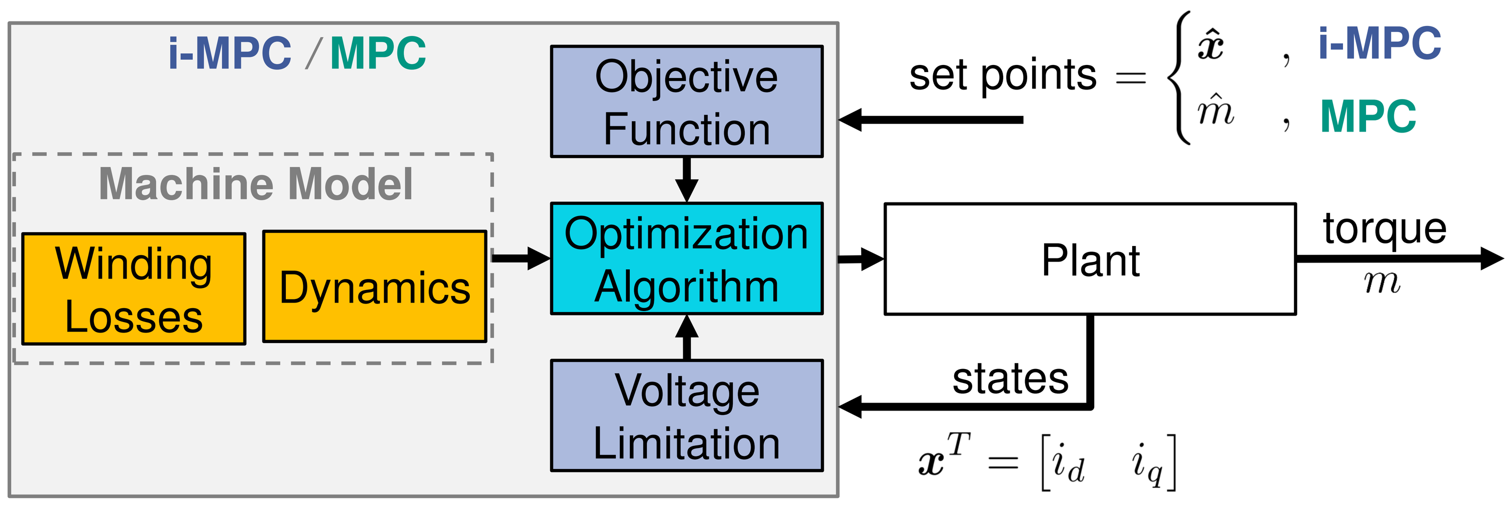
Subject

- Torque tracking of permanent magnet synchronous machines (PMSM)
- Nonlinear anisotropic PMSM for automotive applications
- Continuous Control Set Model Predictive Control (CCS MPC) in dq-frame

Goals

- High dynamic response
- Winding loss optimization
- Straight forward controller synthesis
- Less simplifications in MPC-model

System Overview



Methods

Machine Modelling for MPC

Starting Point

- 2D LUTs (look-up-tables) mapping currents to Fluxes
- Per unit system
- Standard torque equation
- Standard voltage equation

→ total differential → coupled differential equation →

- 1st order Taylor linearization
- 3rd order Picard discretization

→ time discrete state space system → stacking

$$x_s(k)^T = \begin{bmatrix} [i_d \quad i_q]^T(k) \\ \dots \\ [i_d \quad i_q]^T(k+N) \end{bmatrix}$$

Prediction Model

- Affine, operating point dependent

$$x_s(k+1) = A_s x(k) + B_s u_s(k) + G_s$$
$$m_s(k) = C_s x_s(k) + F_s$$

Loss Model for MPC

- Winding loss model

$$P(x_s(k)) = x_s(k)^T R x_s(k)$$

Objective Function (OF)

- i-MPC: torque set → LUT → current set → OF: $J_1(k) = \|\Delta x_s(k)\|_2^2$
- MPC: torque set → OF: $J_2(k) = \|\Delta m_s(k)\|_2^2 + \lambda P(x_s(k))$

Voltage Limitation

- Rotating hexagon in dq-frame

Optimization Algorithm

- Projected Fast Gradient Method (PFGM)
- Modified first order gradient search

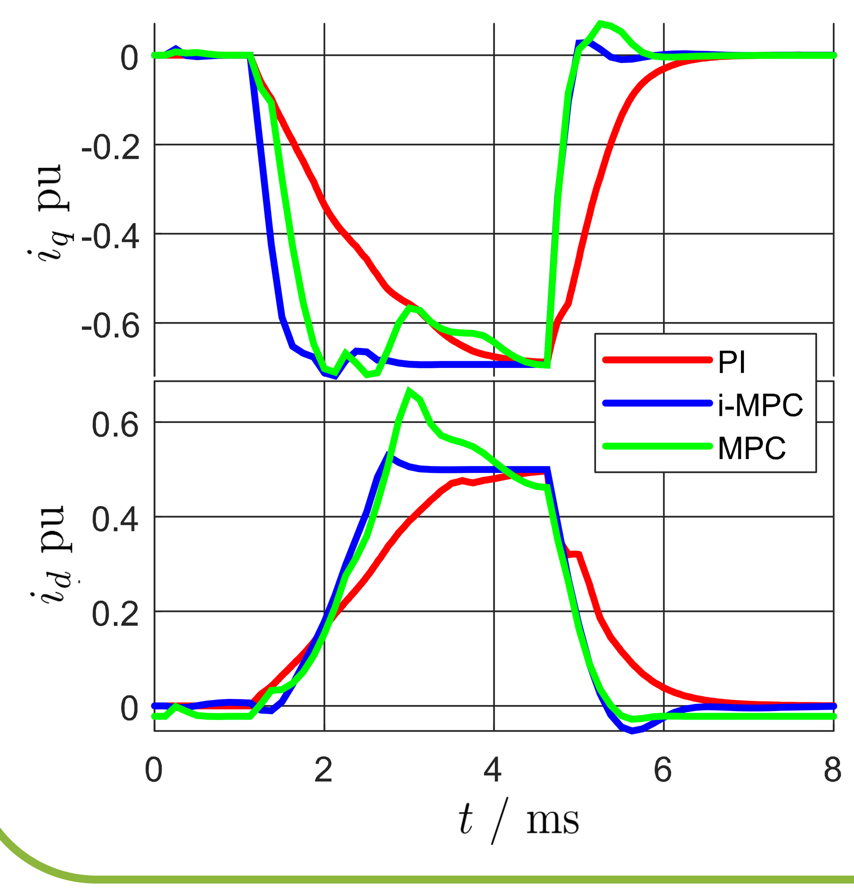
Results

Simulation Study

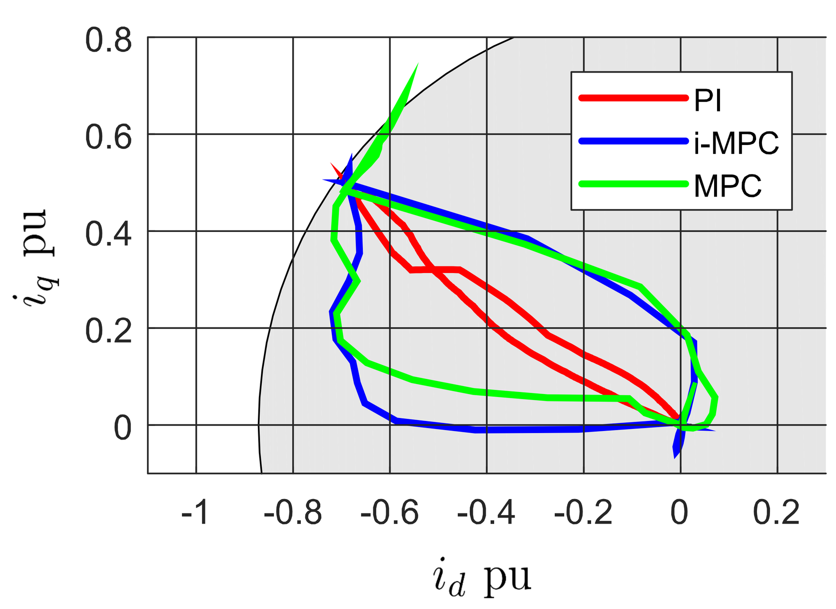
- MPC: Loss weighting factor λ ↑
  → slows down dynamics
  → minimizes current oscillations along torque hyperbola

P_n	90.32 kW		p	3
Ω_n	5000 1/min		R_s	0.0284 Ω
$M_{max,N}$	170 Nm		Ψ_{PM}	0.1019 Wb
U_{DClink}	400 V			

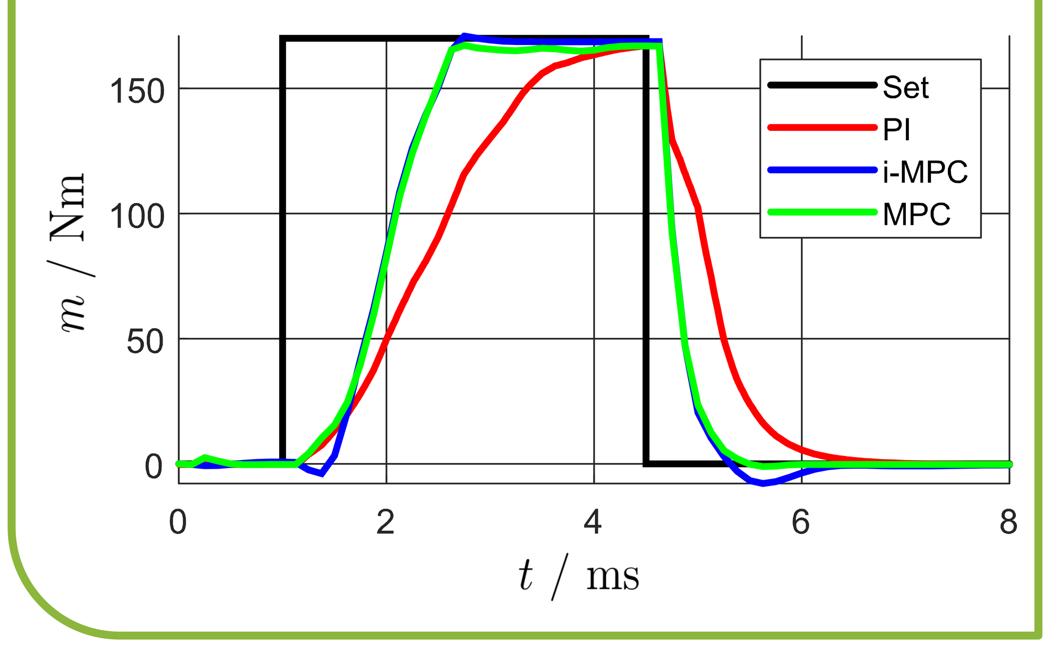
- MPC: currents oscillate, after torque has settled and subside slowly



- MPC: moves along torque hyperbola
- (i-)MPC: shows different trajectory than PI



- i-MPC / MPC: torque settles simultaneously
- MPC: stationary offset due to loss weighing



Conclusion

- Model based approach → inherent consideration of exact voltage limitation, saturation of magnetic flux and cross coupling between q- and d-flux
  → LUTs for current references not necessary for MPC

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