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Low harmonic and thermal stress control of power converters for electric drives

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1) Introduction to MPC
2) Application of MPC in high-speed electric drives
3) Application of MPC with Tj consideration
4) Summary & Conclusions

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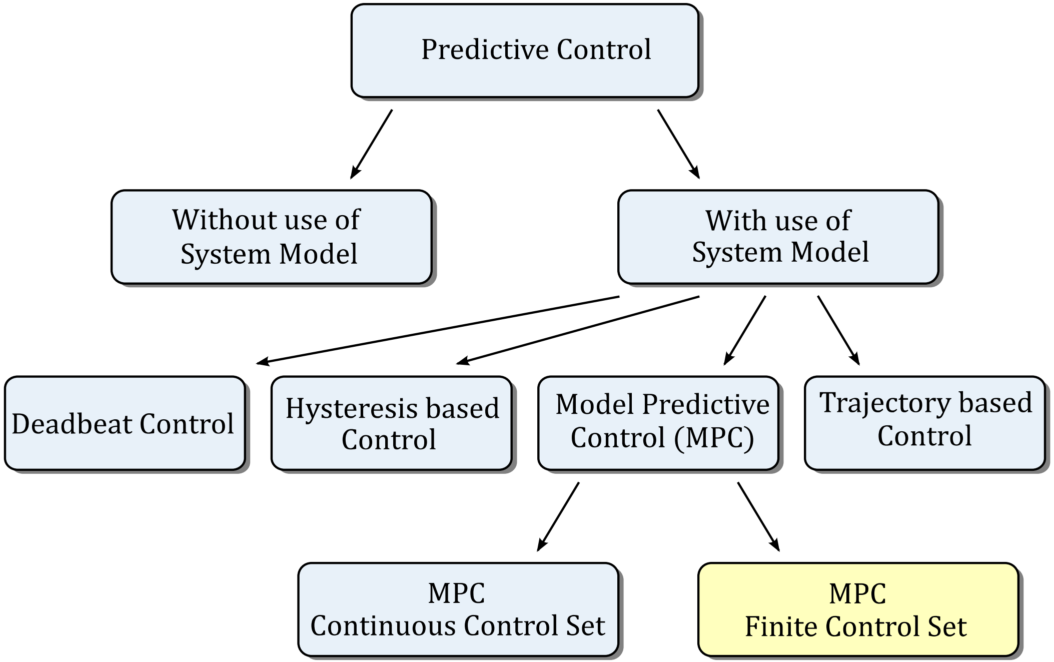
Introduction to MPC

Why should be use Model Predictive Control? And why should we select the states directly?

- Drives systems are non-linear and time variant
- MPC enables to optimize the trajectories during transients
- MPC enables to take constraints into account in the controller design
- MPC enables controller design in the time domain

Introduction to MPC

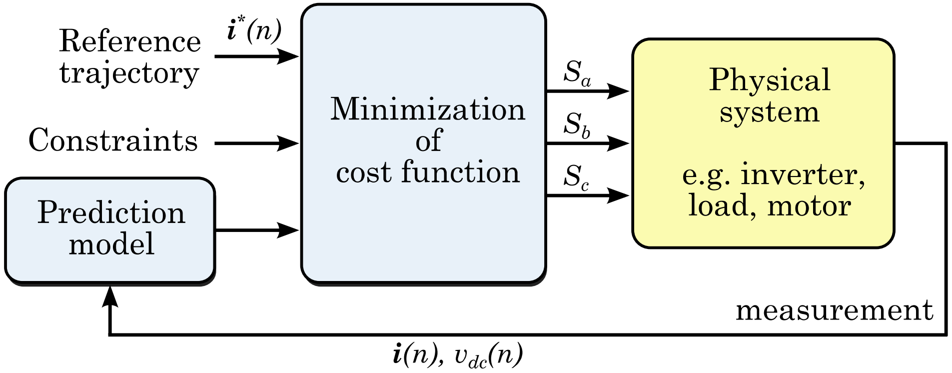
Classification of predictive control in power electronics



classification of MPC by the kind of output the control system is creating

Introduction to MPC

Control Structure of FCS-MPC



Additional constraints can be considered in the cost function

Cost Function of FCS-MPC (example):

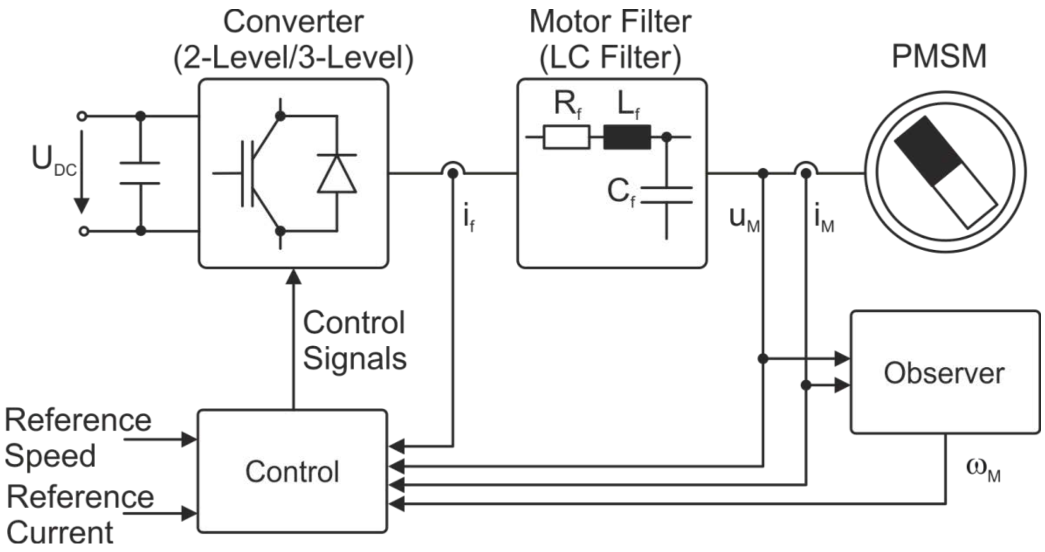
$$g_i(n,k) = \lambda_i \cdot \left(\left|i_d^* - i_{d,k}\right| + \left|i_q^* - i_{q,k}\right|\right)$$

-> minimize error in current

Application of MPC in high-speed electric drives

Energy efficient, reliable, and compact high speed drive

- PMSM Control Strategies
- Converter topologies
- Capacitor technologies for the DC-Link
- Influence of LC filter



Application of MPC in high-speed electric drives

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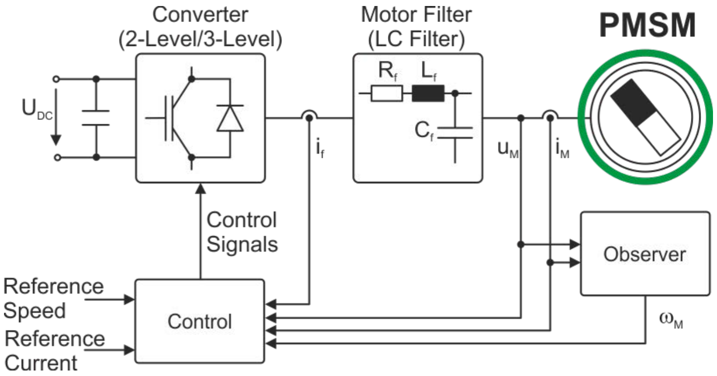
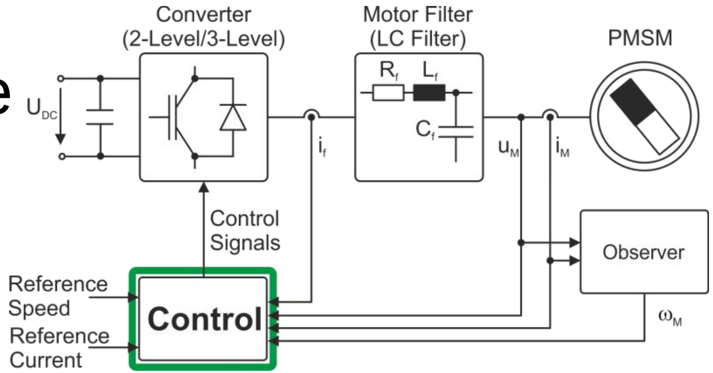


Advantages of a high-speed PMSM

- No gear system is needed,
  Direct coupling to the PM machine
- High efficiency over wide speed
  range (10 – 25 % better efficiency compared to traditional technology)
- Use of Air or Magnetic bearings– no maintenance
- Compact system

Application of MPC in high-speed electric drives



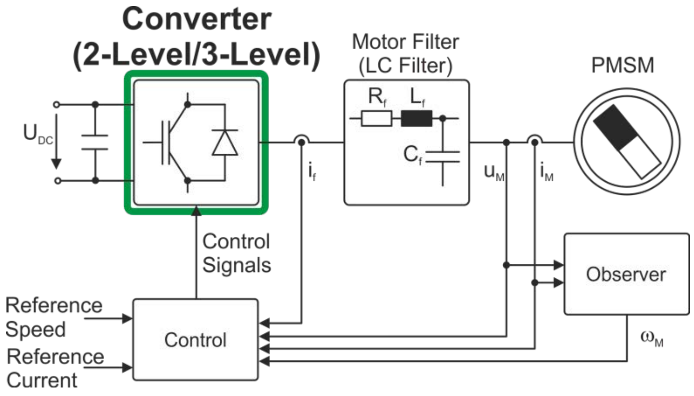
Develop state-of-the-art control scheme for high-speed PMSM

- Cascaded PI Control
- Predictive Control
  - Deadbeat control
  - Model predictive control
- Trajectory-based, hysteresis-based, ...

Application of MPC in high-speed electric drives

Effects of inverter topologies on high-speed electrical machines

- 2-Level converter
- 3-Level converter (NPC, T-Type, ...)



Influence of DC-Link Capacitor technology

- Electrolytic capacitor
- Film capacitor

Application of MPC in high-speed electric drives

PI Current Control for electric drives:

$$G_{PI}(s) = K_P + \frac{K_I}{s}$$

Using Tustin Transformation for discretization:

$$G_{PI}(z) = G_{PI}(s)\Big|_{s=\frac{2}{T_S}\frac{z-1}{z+1}} = K_P + \frac{K_I T_S}{2}\frac{z+1}{z-1}$$

Carrier ratio: Ratio of swiching frequency to electrical frequency (f_{sw}/f_{el})

- Discretizing PI Control → Instable
- Direct design of PI Control in discrete time domain: Pole-Zero Cancellation (Used for comparison)
- Problem occurs for **high-speed** machines, **high power** machines, or other **slow switching converter**

→ Deadbeat Control: Using motor equations (predictive) + pole zero cancellation to increase bandwidth and dynamic performance

- Use of PWM
- Motor parameters have to be known

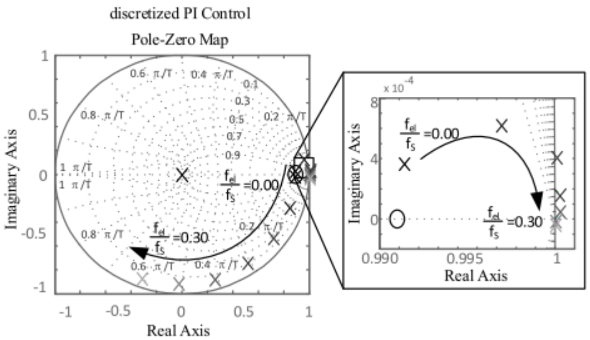


Fig: Pole-Zero map of Discretized PI Control for fel/fS = [0.00, 0.05, … , 0.30].

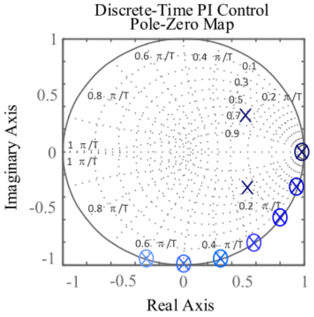


Fig: Pole-Zero map of Discrete-Time PI Control for fel/fS = [0.00, 0.05, … , 0.30].

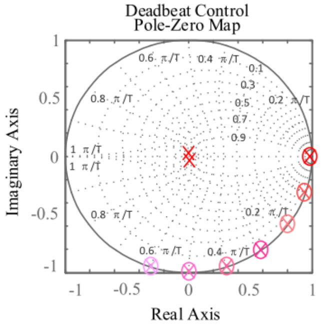


Fig: Pole-Zero map of Deadbeat Control for fel/fS = [0.00, 0.05, … , 0.30].

Application of MPC in high-speed electric drives

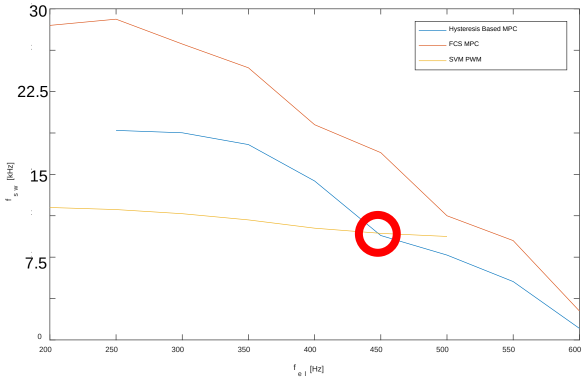
MPC without Modulator: FCS vs. hyst. based MPC in case of low carrier ratios

- Basic simulation results for high-speed PMSM

- **High Speed PMSM**
  n_{rated} = 30000 rpm
  f_{rated} = 500 Hz
  $I_{max,rms}$ = 280 A
  $L_{s,dq}$ = 110.3 uH
  R_S = 0.01 Ohm

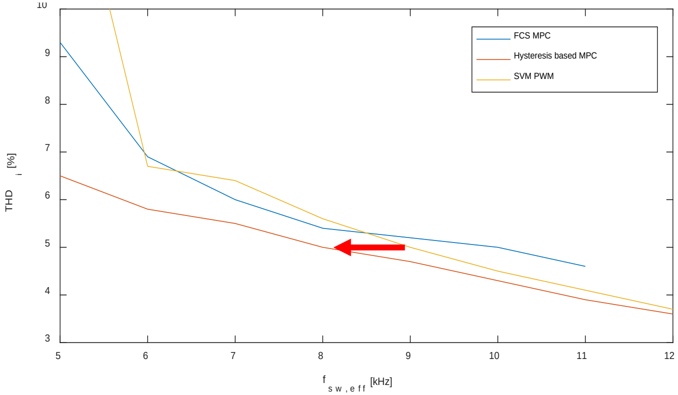
- **2-Level VSI**
  $f_{control}$ = 100 kHz
  U_{DC} = 565 V

THDi = const (5%)



→ Break-even at ~440Hz
→ MPC advantageous at low carrier ratios

f_{el} = const (500Hz)



→ Reduction of eff. Switching frequency

Hys. based MPC

Hysteresis based MPC / MPC with Bounds / Direct Current Control

- Maximize time inside hysteresis bounds

Problem: Low number of switching instances per fundamental (el.) period

→ Increase number of predictions

Main features:

- Short switching horizon but long prediction horizon
- Bound width proportional to THD

1-step hys. based MPC:

- Prediction based on motor equations
- Trajectory estimation, e.g. done by Bologniani:

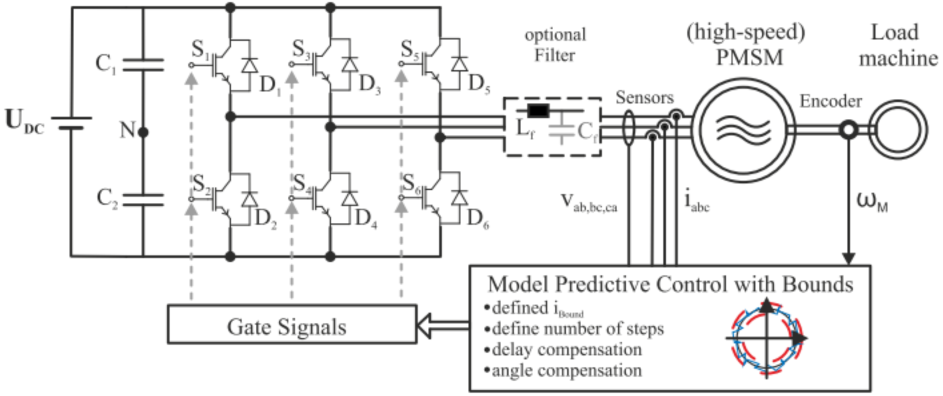
$$T_x^i = 2 \cdot i_{\text{Bound}} \cdot \frac{\cos\left(\pi + \arctan\frac{i_q(k+1) - i_q^i(k+2)}{i_d(k+1) - i_d^i(k+2)} - \arctan\frac{i_q^*(k) - i_q(k+1)}{i_d^*(k) - i_d(k+1)}\right)}{\text{abs}\left(i_{dq}(k+1) - i_{dq}^i(k+2)\right)}$$

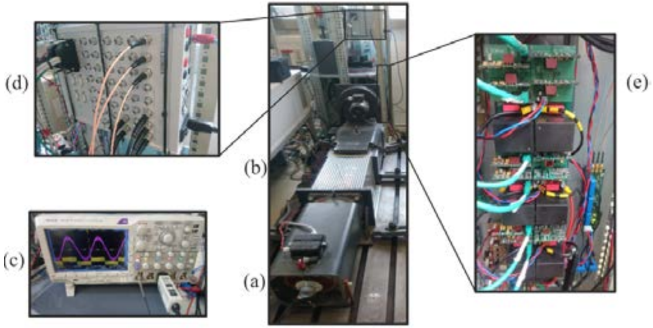
- Correction term (same result)

$$c_i = \frac{\sum \| i_{dq}^* - i_{dq}^i(k+T_n) \|}{i_{\text{Bound}} \cdot n_p^i}$$

Cost function:

$$ind = \max_{i=[1\ldots7]} \left(\frac{\text{floor}(T_x^i / T_S)}{n_{\text{com}}} \right)$$





Experimental results

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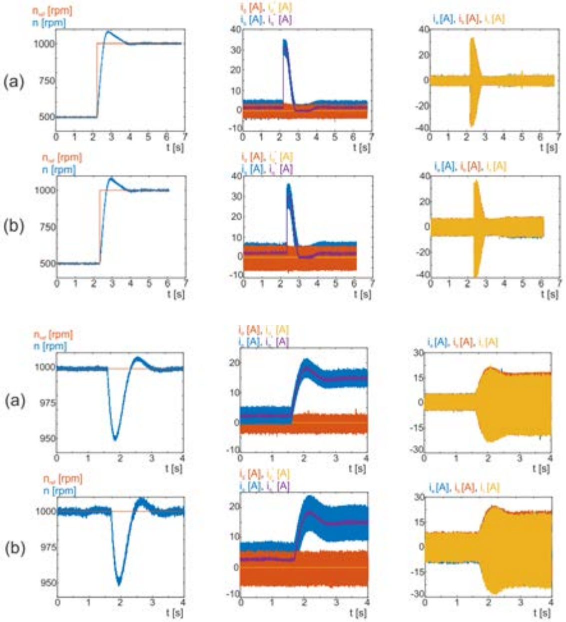
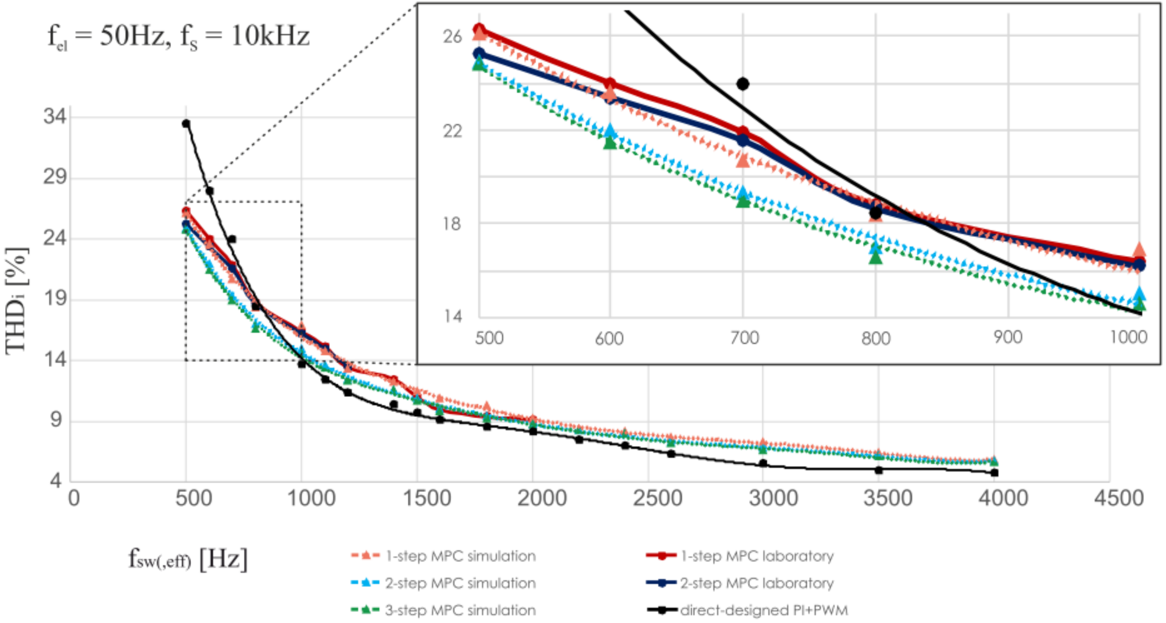
Emulation of high speed with PMSM:

→ Same carrier ratio (f_S/f_{el} ratio)





MPC with Tj consideration

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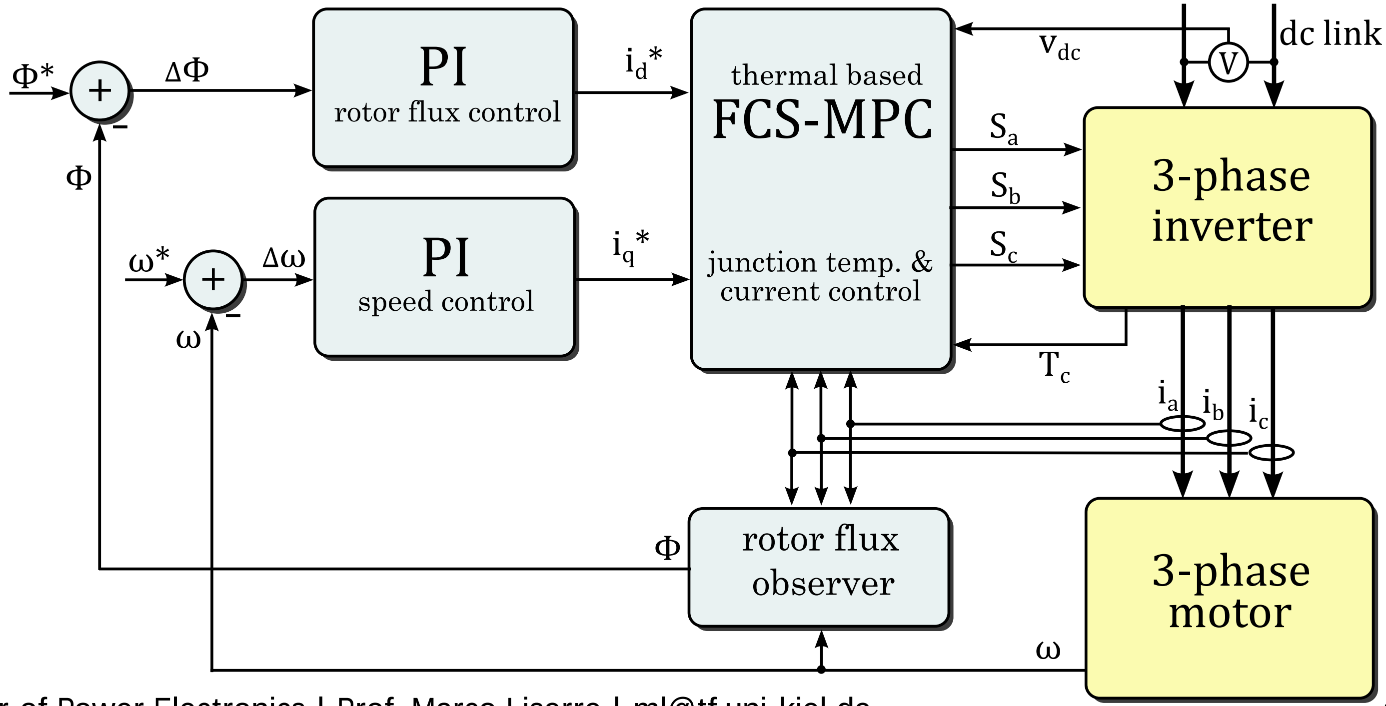
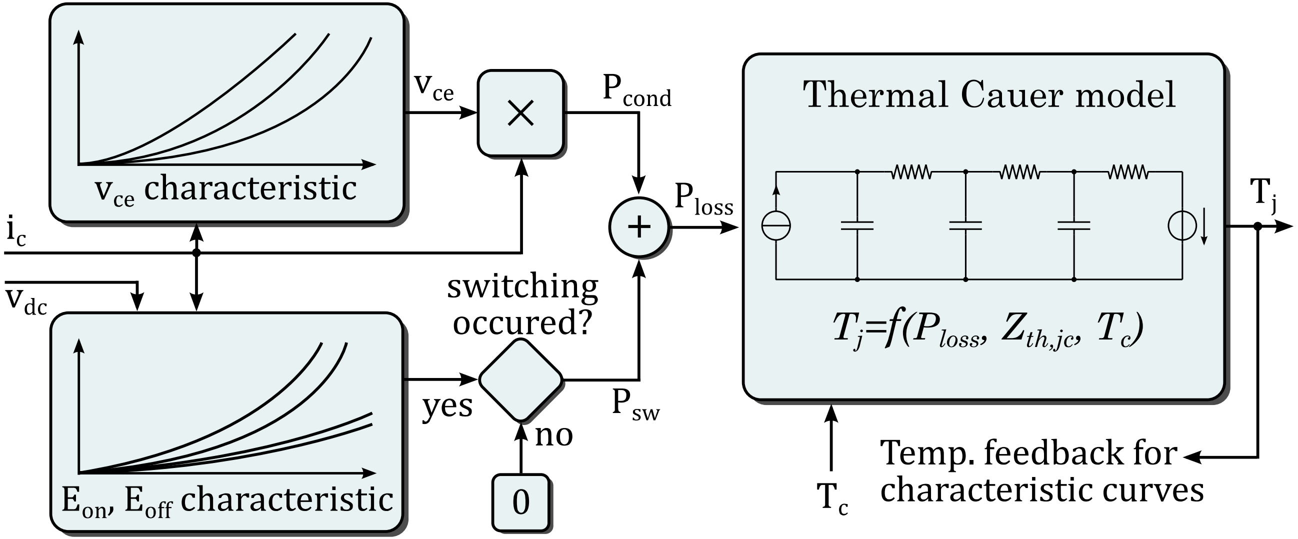
Schematic of the proposed thermal-based FCS-MPC procedure



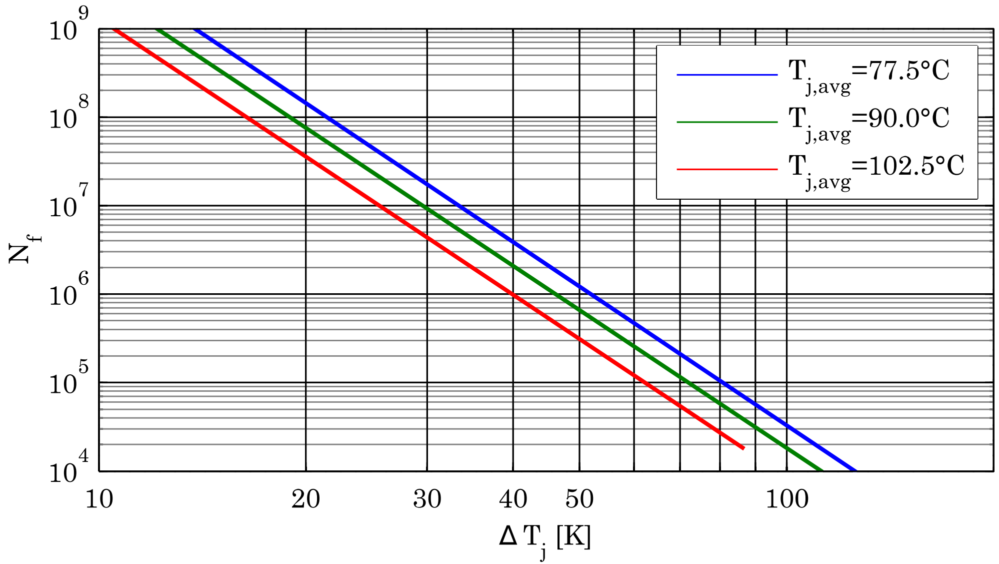
MPC with Tj consideration

Online junction temperature estimation model for FCS-MPC



MPC with Tj consideration

Bayerer lifetime model



$$N_f = A \cdot \Delta T_j^{\beta_1} \cdot exp\left(\frac{\beta_2}{T_{j,min}}\right) \cdot t_{on}^{\beta_3} \cdot i_B^{\beta_4} \cdot V_C^{\beta_5} \cdot d_b^{\beta_6}$$

MPC with Tj consideration

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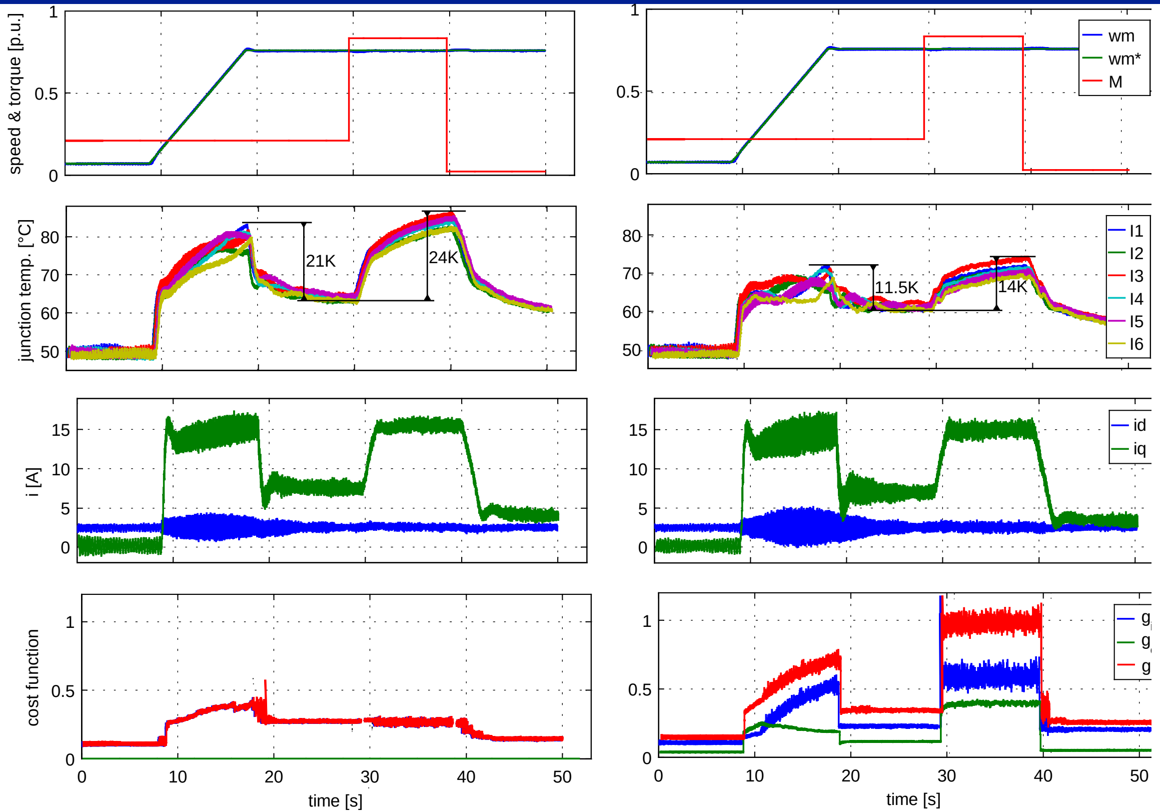
Experiment 1:
Thermal cycling reduction

term in cost function:

$$g_c(n,k,l) = \lambda_{c,l} \cdot N_{f,n,k,l}^{-1}$$

-> minimize damage
caused by cycles



left: conventional
right: active thermal control

MPC with Tj consideration

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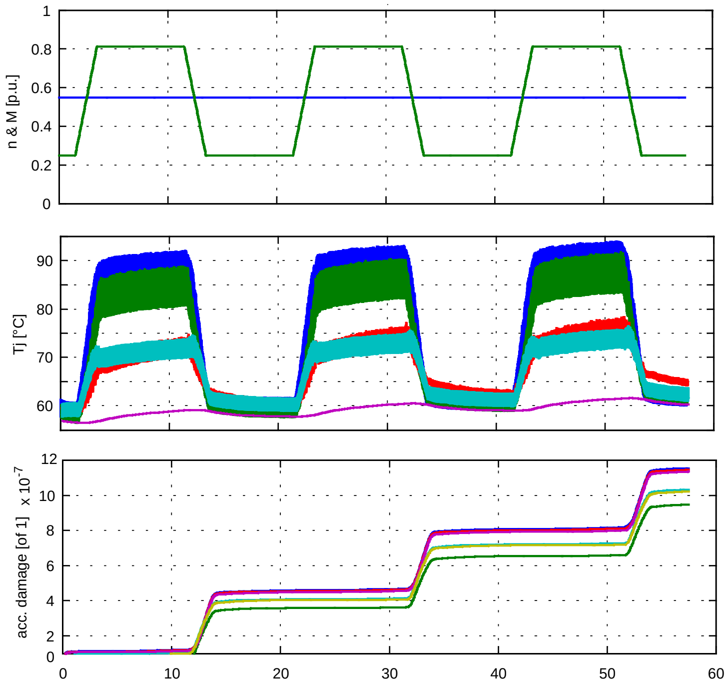
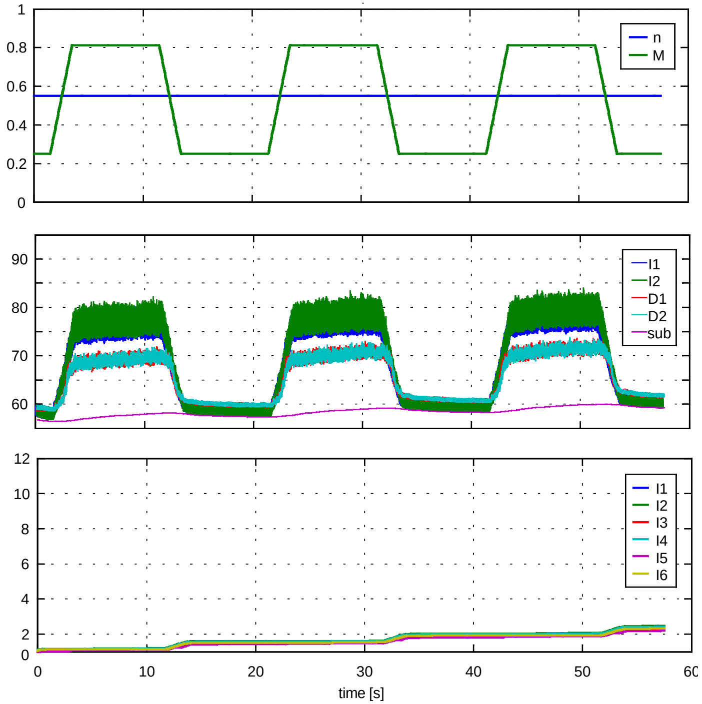
Simulation: Accumulated damage

conventional



active thermal control

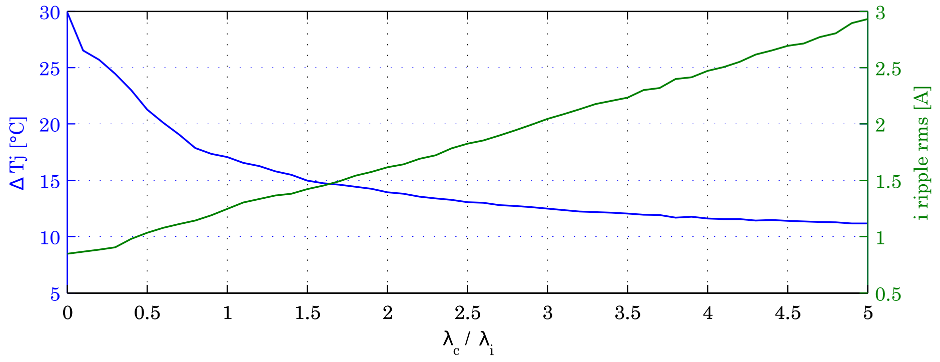


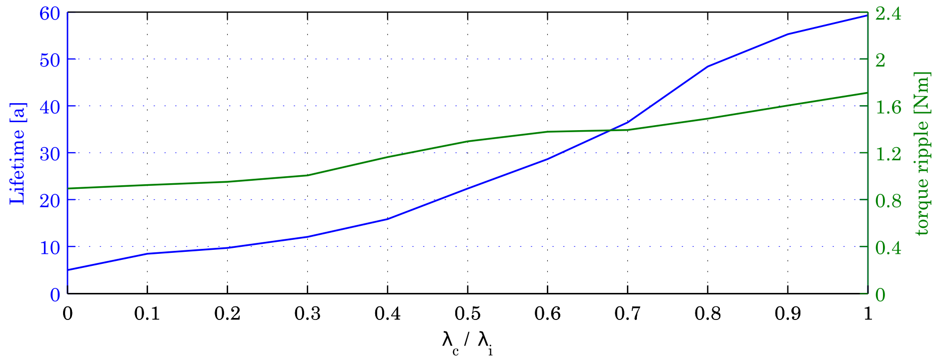
MPC with Tj consideration

Simulation:
lifetime vs. ripple current

$$i_{s,ripple} = \sqrt{\frac{1}{n} \cdot \sum_{k=1}^{n} \left(i_s - i_{s,avg}\right)^2}$$

$$T_e = \frac{2}{3} \cdot p \cdot L_m \left(i_{s,q} \cdot i'_{r,d} - i_{s,d} \cdot i'_{r,q}\right)$$





MPC with Tj consideration

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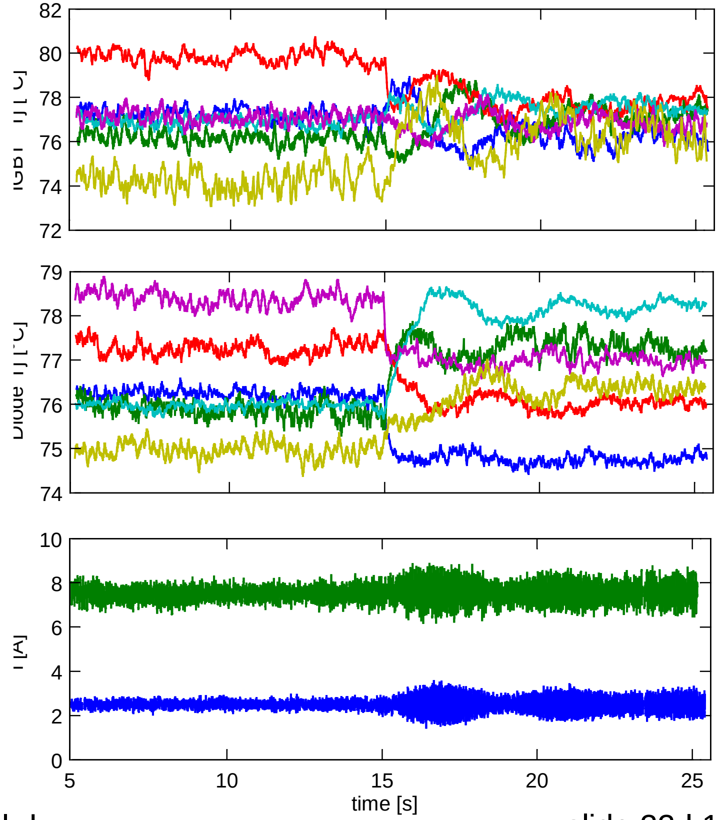
Experiment 2:
Equalizing thermal stress in the module

At t=15s an additional term in the cost function is activated:

$$g_{sp}(n,k) = \lambda_{sp} \cdot \mathrm{Var}\left(T_{j,l}(n+1,k)\right)$$

-> minimize variance of all Tj in the module



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Summary & conclusions

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- MPC enables to optimize converter control with addition (non-linear boundaries)

- MPC was shown to be superior to PWM-based methods for high electrical output frequencies and low switching frequencies

- Different MPC-methods were implemented and compared (THD_I vs. switching frequency)

- MPC was used to manipulate the junction temperature for reducing the accumulated damage of electric drives and thereby increase the lifetime of the drive

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Thank you for your attention