CAU -HIGH SPEED TEST BENCH

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OVERVIEW

- dv/dt filter design
    - Design Approach
    - Inductor Optimization
    - Next steps
- Control Scheme for electric drive
    - Introduction
    - Fuzzy based ALADRC
    - Next steps

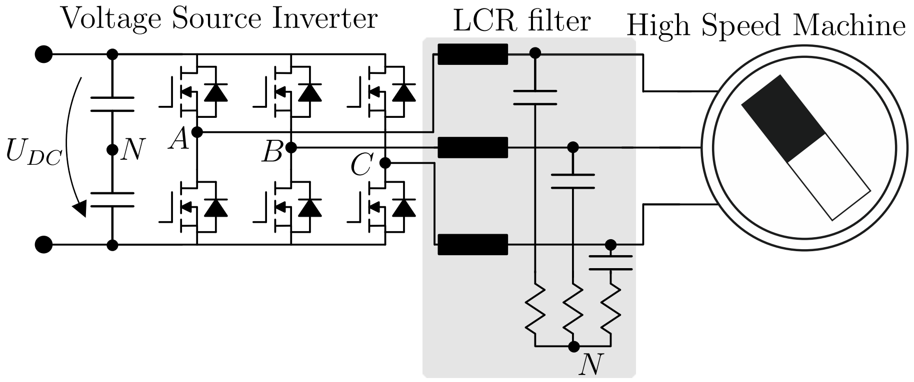
dv/dt filter design for high speed machine drives

HIGH SPEED MOTOR DRIVE

PE-Region Platform

- *High speed machines are characterized by low impedance and high fundamental frequency*
- *Wide Band Gap (WBG) technology suitable for high speed and high frequency inverters but come with challenges*
- *Studies show strong dependence of winding insulation lifetime on voltage slewrate (dv/dt) for stator windings of electric machines*
- *Multiple (dv/dt) mitigation strategies available, out of which passive LCR filter strategy is analyzed in this work*

System Architecture



dv/dt mitigation strategies

dv/dt-Limitation

Active Concepts	Passive Concepts	Hybrid Concepts
• Miller Feedback Cap.	• LCR-Filter	• Three-Step Transition
• Variable Gate Res.	• LC-Filter with DRC	• Multi-Step Transition
• Active Gate Drive	• Motor Terminal Filter	

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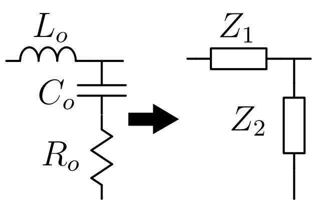
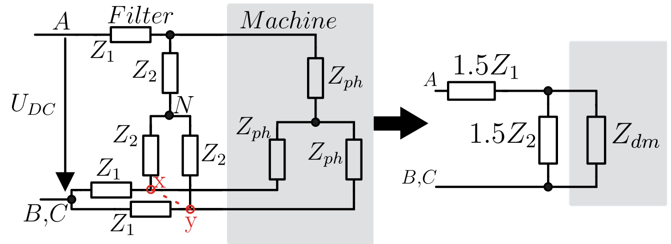
DESIGN APPROACH

- *P1: Standard second order filter approach ($Z_{dm} = \infty$) - unoptimized solution with high P_{diss} for given f_{sw}*
- *P2: Max Inductance ($\leq 2\%\ Z_{base}$) Approach – Reduced filter capacitor but higher than $0.1\%\ P_{diss}$*
- *P3: Machine Impedance Z_{dm} incorporated filter design*

LCR filter Impedance



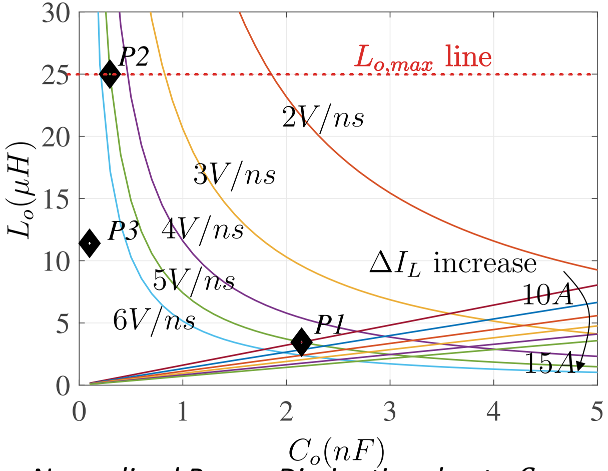
System Impedance in Differential Mode configuration



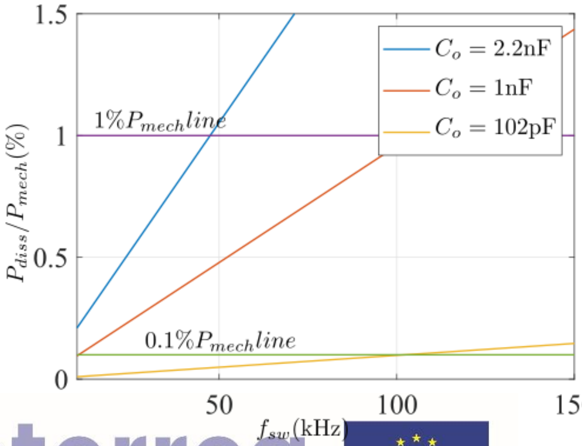
Design	$L_o(\mu H)$	$C_o(nF)$	$R_o(\Omega)$
Design Space Approach (P1)	3.5	2.1	20
Max Inductance Approach (P2)	25	0.21	174
Z_{dm} incorporated Approach (P3)	11.4	0.1	170

Around 54% reduction in filter inductor and less than 0.1% P_{diss} due to filter capacitor

Design Space



Normalized Power Dissipation due to C_o



INDUCTOR OPTIMIZATION

- *Fast analytical technique estimation of inductor parameters*
- *Two part optimization (1. Scaling factor σ , 2. Current density J_{rms}*

- *Power losses in Inductor : Winding(P_{wind}) , Core losses (P_{core})*

$$P_{wind} = R_{dc} {I_{dc}}^2 + c_0 R_{dc} {I_{ac}}^2 \qquad R_{dc} = \frac{N l_{avg}}{4 g A_{cond}}$$

$$P_{core} = V_e \cdot p_v \qquad p_v = \frac{k_i \left(\Delta B\right)^{\beta-\alpha}}{T} \sum_m \left| \frac{B_{m+1} - B_m}{t_{m+1} - t_m} \right|^{\alpha} (t_{m+1} - t_m)$$

- *Thermal losses in Inductor :*

$$P_{th} = \frac{T_{ind} - T_{amb}}{R_{th}}$$

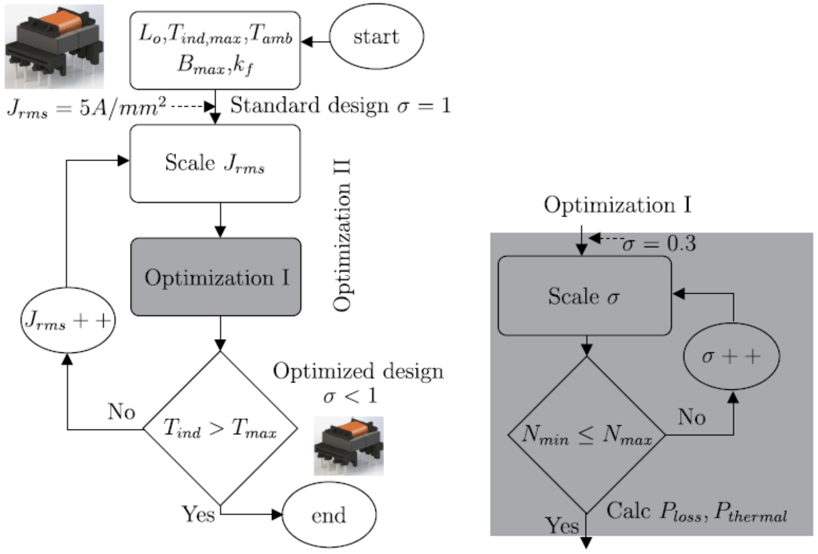
$$R_{th} = 53 \left(V_e \sigma^3\right)^{-0.54}$$

Comparison of different inductor design w.r.t Volume and Temperature

Design	V_e **(cm^3)**	T_{ind} **(°C)**	J_{rms} **A/mm^2**
D_1:Standard	7.63	52	5
D_2:Optimized I	6.33	60	5
D_3:Optimized II	4.21	100	8.6

- *Around 45% reduction in volume with higher utilization of the inductor materials*

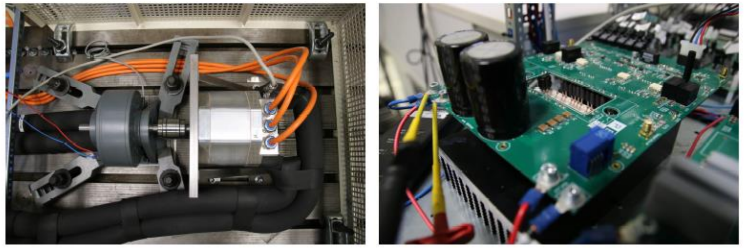
Inductor Optimization Algorithm for volume reduction



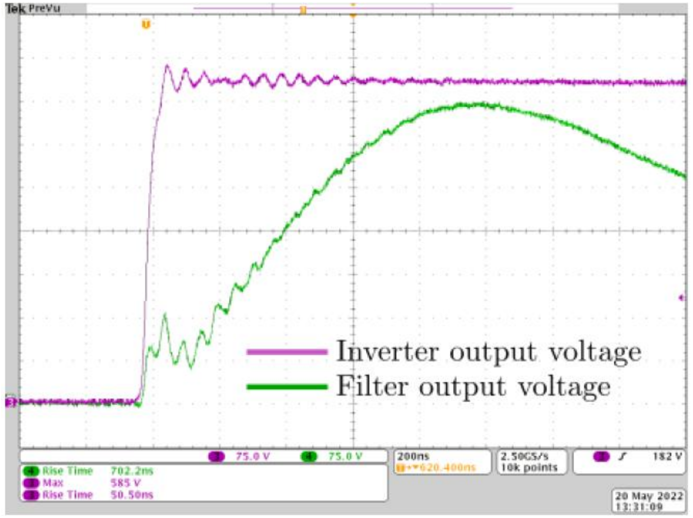
Parameter	**Description**	**Value**	**Unit**
L_o	Filter Inductance	11.4	μH
T_{ind}	Inductor temperature	100	°C
T_{amb}	Ambient temperature	25	°C
B_{max}	Maximum flux density	250	mT

EXPERIMENTAL VALIDATION

- *Initial experimental validation with existing inverter and components and connections in differential mode configuration*



Experimental validation with existing components with inverter voltage slewrate 9V/ns and $L_o = 36\mu H, C_o = 67pF, R_o = 225\Omega$



Outcomes

- *Accounting for machine impedance into LCR filter design can reduce the filter size (approx. 50%) and lead to high efficiency designs*
- *With inductor optimization around 45% reduction of inductor volume*

Next Steps

- *Implementation of inverter with Danfoss three-phase 2-level power module in progress*
- *Improve inductor design with suitable core material for application at high frequency*

Fuzzy based ALADRC

CURRENT LADRC (CLADRC)

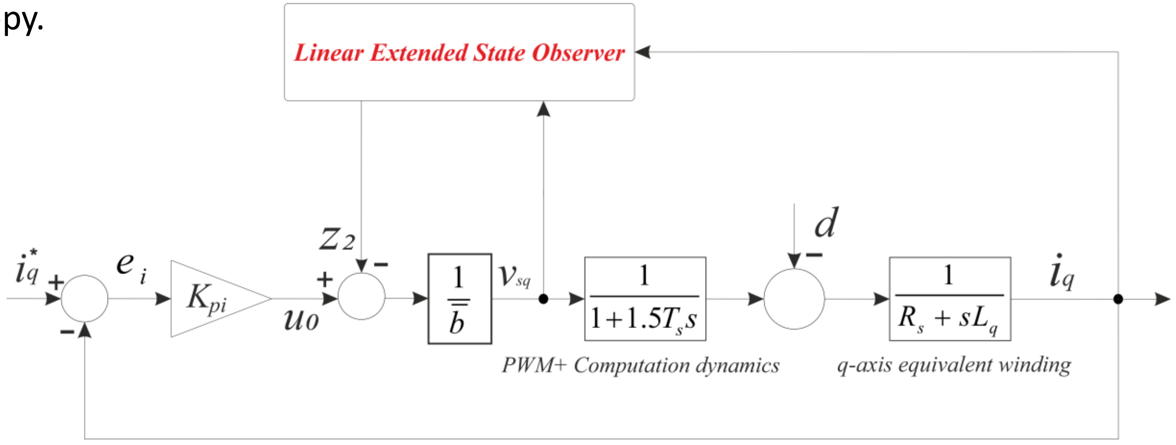
- In the PMSM dq frame model all the quantities are usually considered to be constant.
- the back electromotive force (bemf) term is $d = \omega\, \psi_{pm}(t)$ where if the linkage flux is assumed to be time-variant because of the distortion due to motor rotor anisotropy.
- The latter effect might lead to motor phase currents harmonic distorsion.
- To cope with this problem a Current Linear Active Rejection Control (CLADRC) has been used to perform a better rejection action on motor currents.
- $\frac{di_q}{dt} = \frac{1}{\bar{L}_q} v_{sq} - \left(\frac{1}{\bar{L}_q} - \frac{1}{L_q}\right) v_{sq} - \omega\, i_d - \frac{R_s}{L_q} i_q - \frac{\psi_{pm}}{L_q} \omega$, setting as

$y(t) = i_q(t)\,,\quad u(t) = v_{sq}(t)$ and then :

$$\frac{di_q}{dt} = \bar{b}\, v_{sq} + f$$

where $\bar{b} = \frac{1}{\bar{L}_q}$, $b = \frac{1}{L_q}$ and $f = -\left(\frac{1}{\bar{L}_q} - \frac{1}{L_q}\right) v_{sq} - \omega\, i_d - \frac{R_s}{L_q} i_q - \frac{\psi_{pm}}{L_q} \omega$

- The decoupling terms are supposed to be feed forwarded such that the LADRC will only have to compensate for non linearities and uncertainties.



- CLADRC block diagram .

CURRENT LADRC (CLADRC)

- $u_0 = K_p\left(i_q^* - i_q\right)$, $v_{sq} = \frac{u_0 - z_2}{\bar{b}}$ and $\dot{i_q} = \bar{b}\, v_{sq} + f = u_0 - z_2 + f$ and if the LESO is able to estimate the disturbance perfectly then:

$$\frac{u_0}{s} \approx i_q(t)$$

and the closed loop transfer function can be approximated to a first order:

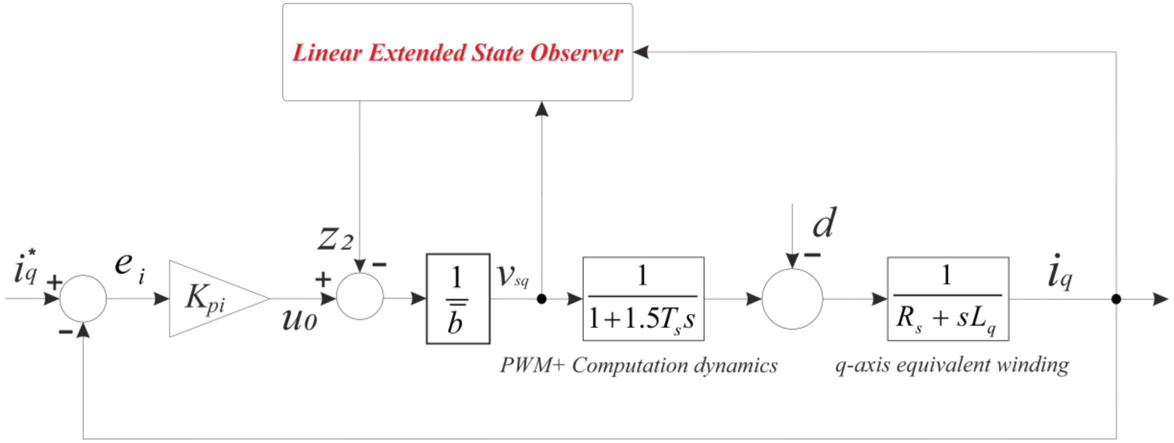
$$\frac{i_q}{i_q^*} = \frac{k_p}{s + k_p}$$

- In this case, Kp has been tuned in order to match the CLADRC and Technical Optimum (TO) dynamics.
- By considering the equivalent TO first order transfer function then:

$$\frac{k_p}{s + k_p} = \frac{1}{1 + 3Ts}$$

i.e.

$$\boxed{k_p = \frac{1}{3Ts}}$$



- CLADRC block diagram .

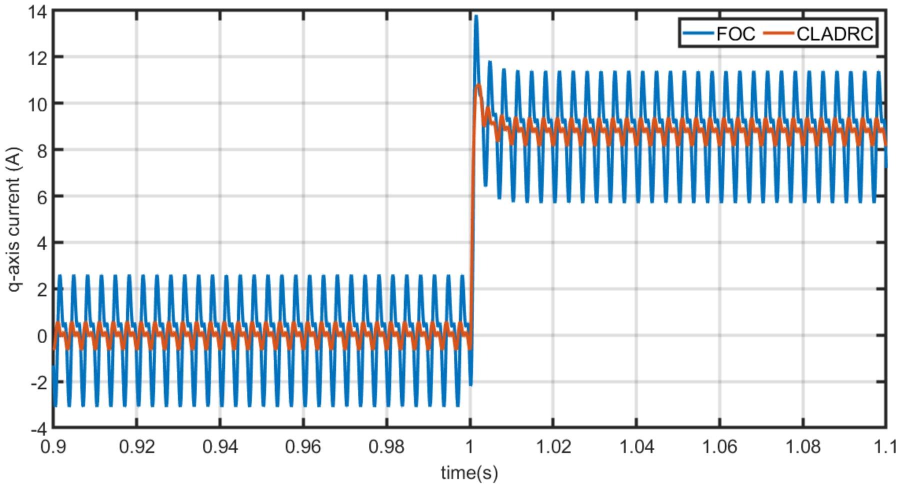
RESULTS: CLADRC

- As can be shown from the fig. below the q-axis currents are characterized by the same dy However CLADRC achieves less overshoot as well as reduced current oscillation.
- At t=1 s a 2 Nm torque applies.
- The k_p and $\omega_{0\ CLADRC}$ values to achieve for the desired dynamic performances are the following:

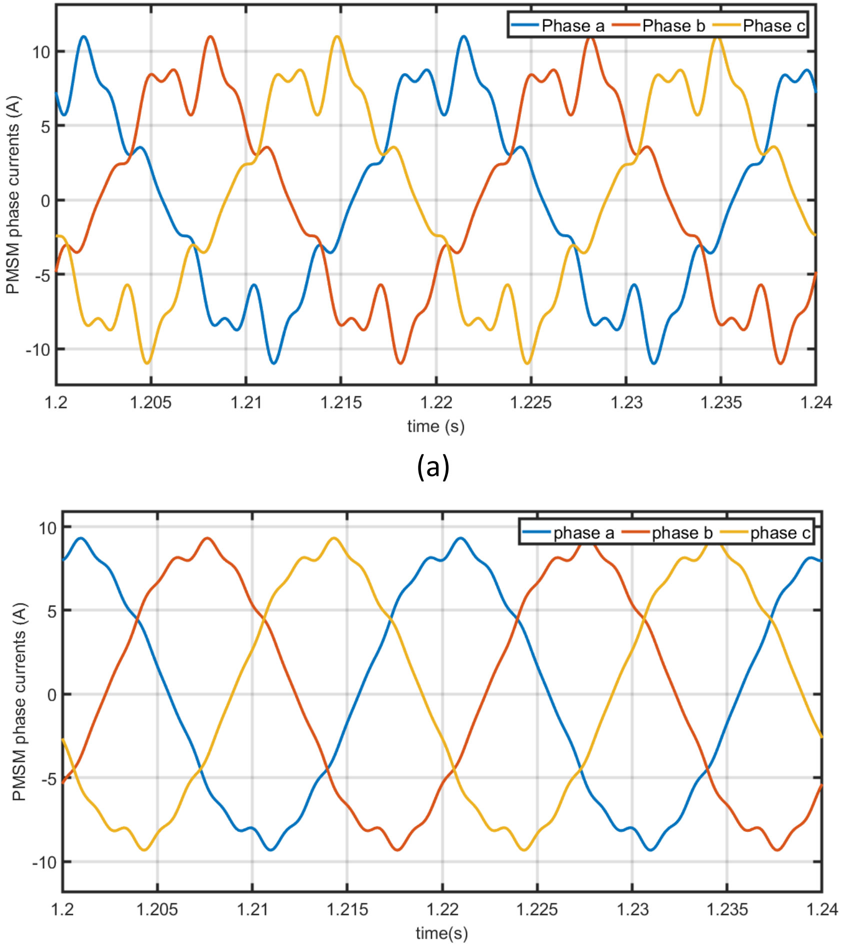
$$k_p = \frac{1}{3T_s}$$

$$\omega_{0\ CLADRC} = 20\ 10^3\ rad/s$$

- where T_s is the switching period of 20kHz.



- Fig. q-axis current dynamics.



- Fig. (a) SPMSM phase currents with distorted flux linkage and classic PI control .
  (b) SPMSM phase currents with distorted flux linkage and CLADRC .

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OUTLOOK ON FUTURE STEPS

- ✓ Effectiveness evaluation by means of experimental results.
- ✓ Further improvement of ALADRC by robust control strategy integration.
- ✓ Further improvement of CLADRC by resonant control integration.

Thank you for your attention!

Back up slides - dv/dt filter design for high speed machine drives

DESIGN APPROACH

- *Standard design approach is second order filter design formulae for dv/dt reduction*

$$\omega_o = \frac{1}{\sqrt{L_o C_o}} \qquad Q = \frac{1}{R_o}\sqrt{\frac{L_o}{C_o}}$$

- $f_o = {}^{\omega_o}/_{(2\pi)}$ *is chosen a decade higher than* f_{sw} *while maintaining* $Q = 0.5$ *and respecting the NEMA standard*

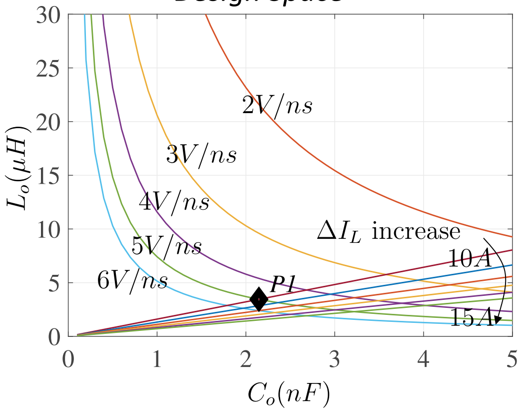
$$\omega_o = \Omega\frac{1}{t_r} \qquad Z_o = \gamma \cdot Z_{eff}$$

- *The above formulae can be linked to system requirements of dv/dt and the ripple current in the inductor leading to the parameters* C_o, L_o, R_o

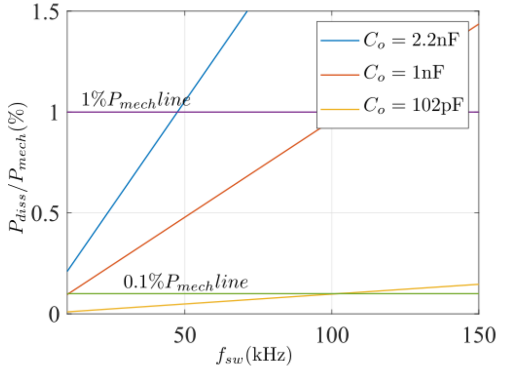
$$C_o = \frac{1}{Z_o \omega_o} \quad , \qquad L_o = \frac{Z_o}{\omega_o} \quad , \qquad R_o = Q \cdot Z_o$$

- *For a dv/dt of 5V/ns and current ripple of 10A leads to* $L_o = 3.5\mu H, C_o = 2.2nF, R_o = 20\Omega$ *(point P1) leading to high losses due to* C_o *for high switching frequency* f_{sw}

Design Space



Normalized Power Dissipation due to C_o



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DESIGN APPROACH

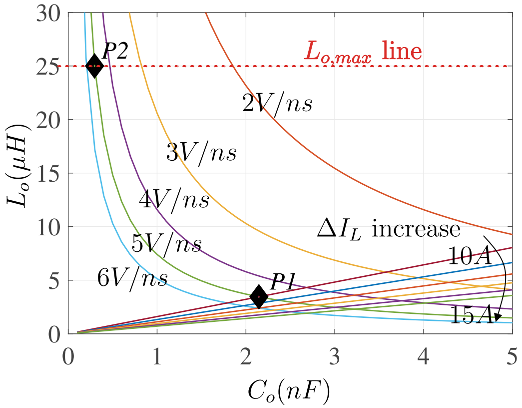
- *Max Inductance design technique can reduce the losses due to filter capacitor for a given dv/dt.*
- *Max filter inductance < 2% of* Z_{base}

$$Z_o = \omega L_o \le 2\%\ Z_{base} = (2\%) \cdot \left(\frac{U_{base}^2}{S_{base}}\right)$$

- *Reduce the filter capacitor* $C_o = 300pF$
- $R_o = 174\Omega$ *and* $L_o = 25\mu H$ *seen as P2*

- *The power dissipation due to filter capacitor are reduced but still not highly efficient solution. If the filter capacitor can be reduced below* $102pF$*, these losses are less than 0.1% and allow to push the WBG inverter frequency higher.*

Design Space



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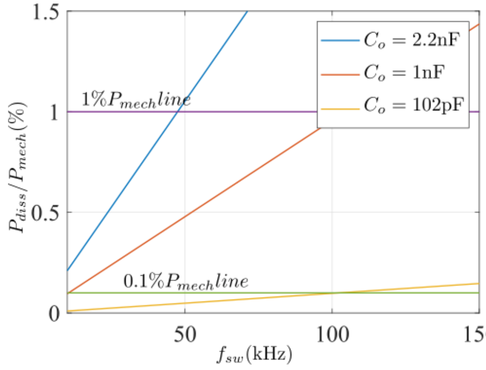
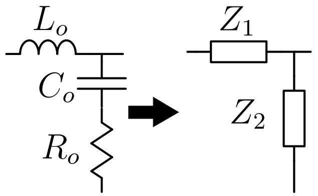


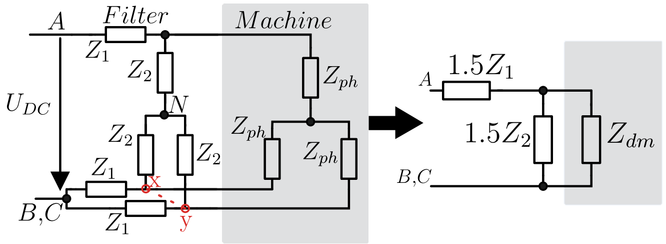
DESIGN APPROACH

- *Machine Impedance Z_{dm} incorporated filter design*

LCR filter Impedance



System Impedance in Differential Mode configuration



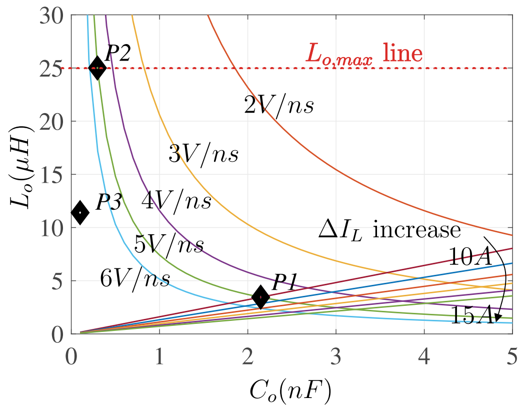
- *High frequency model of the machine required for the integrated design to reduce filter size*
- *FFT based evaluation of the design space and leads to polynomial fit for requirements as*

$$L_o = (-5.39 \cdot 10^{-8} \cdot {C_o}^3 + 6.39 \cdot 10^{-5} \cdot {C_o}^2 - 0.0363 \cdot C_o + 14.48)$$

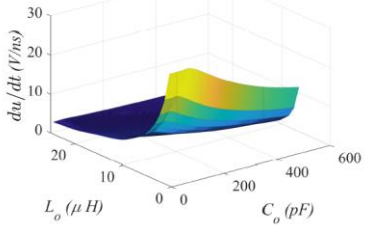
$$(L_o \ in \ \mu H, \ C_o \in [0, 600] \ \ in \ pF)$$

- *Reduced filter parameters $L_o = 11.4\mu H$, $C_o = 100pF$, $R_o = 174\Omega$*
- *Capacitor dissipation losses less than 0.1%*
- *Around 54% reduction in filter inductor*

Design Space



dv/dt-filter design space



overshoot-filter design space