Review of PWM Filters for AC Voltage Source Converters

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AGENDA

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1. Applications/Challenges of Passive Filters
2. Characterization of Passive Filters
3. Damping Methods and Loss Optimization
4. Characterization of Inductive Components
5. Design Examples
6. Conclusions
7. Questions

1. Applications/Challenges of Passive Filters

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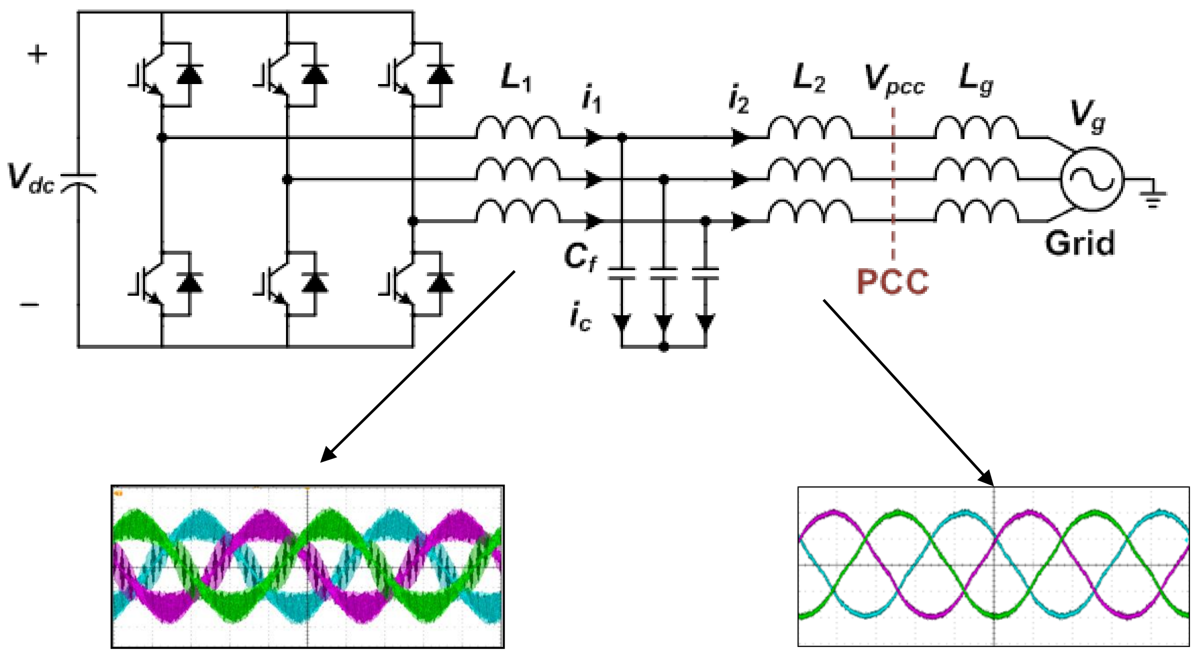
A Voltage-Source converter (VSC) is the enabling technology of efficient power-electronics [1] in:

- Drives
- UPS and power conditioning
- Battery storage
- EV stations
- Air craft & marine power systems
- Railway electrification
- HVDC power system

[1] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power Electronics as Efficient Interface in Dispersed Power Generation Systems," IEEE Trans. Power Electron., vol. 19, no. 5, pp. 1184–1194, Sep. 2004.

1. Applications/Challenges of Passive Filters

- High-order passive filtering is needed on the AC-side of the filter for size/cost considerations
- The LCL filter is widely adopted by industry [2]



Converter current

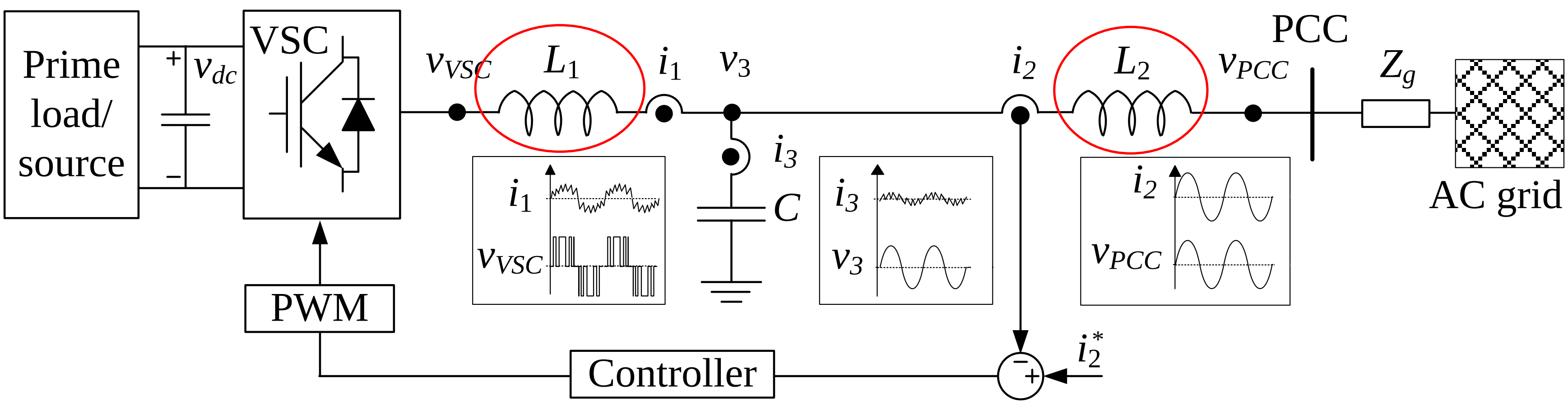
Grid current

[2] M. Liserre, F. Blaabjerg, and S. Hansen, "Design and Control of an LCLFilter-Based Three-Phase Active Rectifier," IEEE Trans. Ind. Appl., vol. 41, no. 5, pp. 1281–1291, Sep. 2005.

1. Applications/Challenges of Passive Filters

Main challenges for passive filter design:

- Design of inductive components [3]
- Minimize resonance interaction between filter, control and grid



[3] R. Beres, H. Matsumori, T. Shimizu, X. Wang, F. Blaabjerg and C. L. Bak, "Evaluation of Core Loss in Magnetic Materials Employed in Utility Grid AC Filters," in Proc. of the 31st Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2016, pp. 3051-3057.

2. Characterization of Passive Filters

Filter admittance characterization:

- Filter input admittance (20 dB/dec):

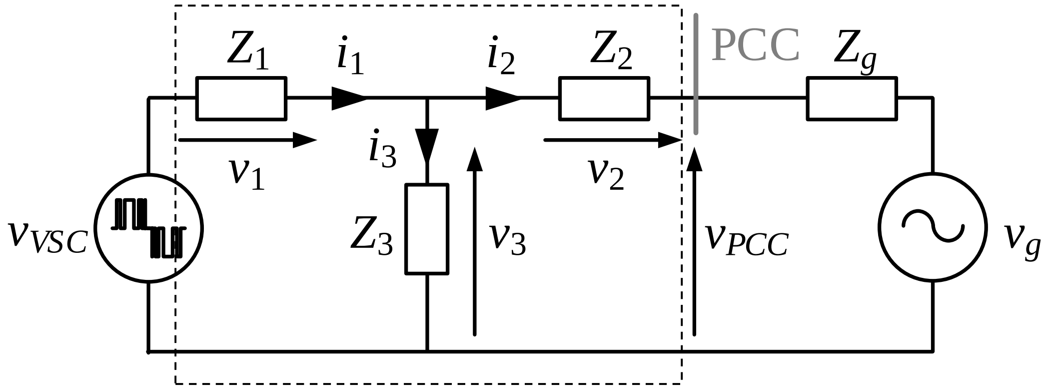
$$Y_{11}(s) = \left.\frac{i_1}{V_1}\right|_{V_2=0}$$

Filter output admittance (20 dB/dec):

$$Y_{22}(s) = \left.\frac{-i_2}{V_2}\right|_{V_1=0}$$

- Filter transfer admittance (20 dB/dec at LF and 40~60 dB/dec at HF):

$$Y_{21}(s) = \left.\frac{i_2}{V_1}\right|_{V_2=0}$$



High-order Passive Filter

2. Characterization of Passive Filters

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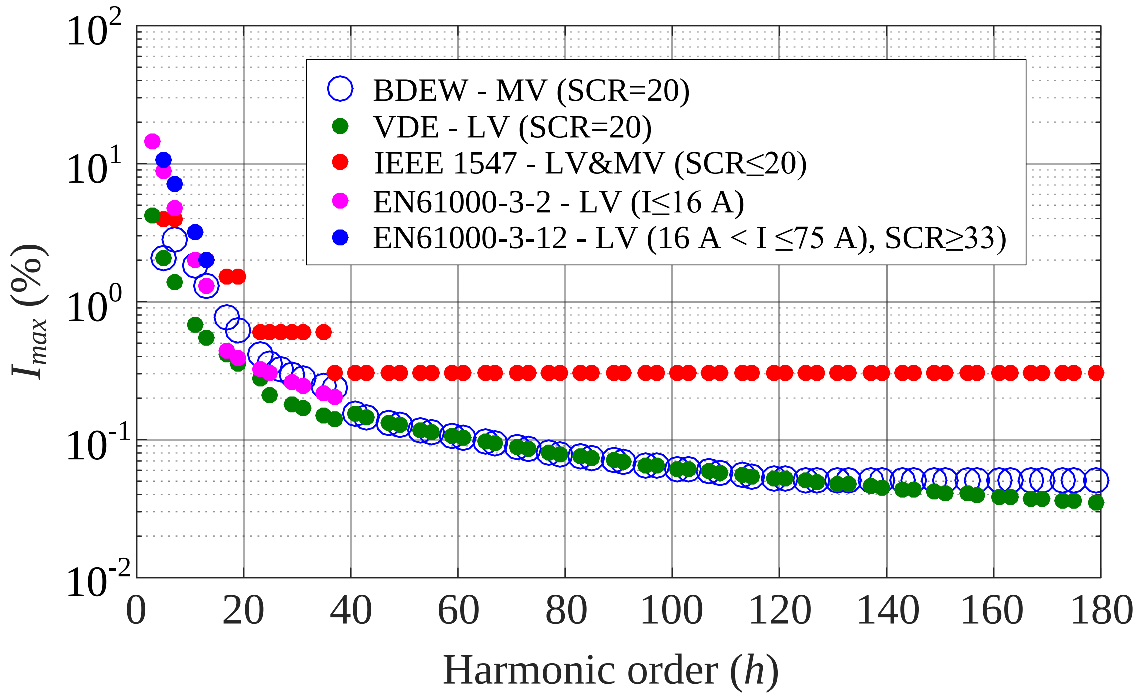
Harmonic standards and attenuation requirements

Individual current harmonic limits:

- 0.3 % HF limit specified by IEEE 1547
- 0.05 % HF limit specified by BDEW

Total harmonic distortion of the current:

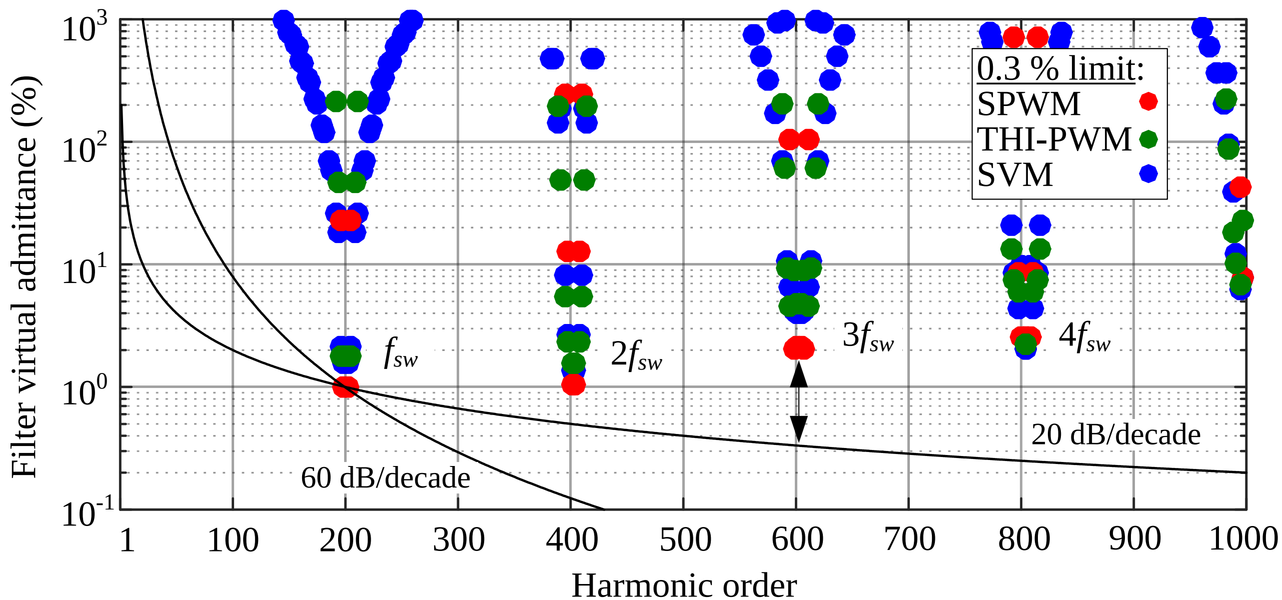
- Less than ~5 %



2. Characterization of Passive Filters

Influence of the PWM method and filter topology

Virtual harmonic filter admittance: $$Y_{vhf} = \frac{i_{\text{limit}}(h)}{v_{VSC}(h)}$$

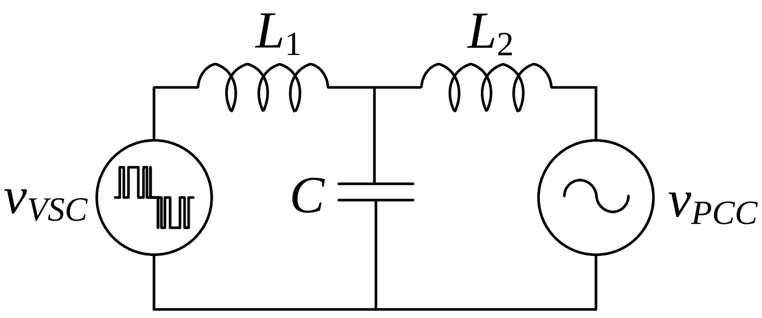


Selecting $\boldsymbol{Y_{21}} \leq \boldsymbol{Y_{vhf}}$ suffices performance criteria of passive filters!

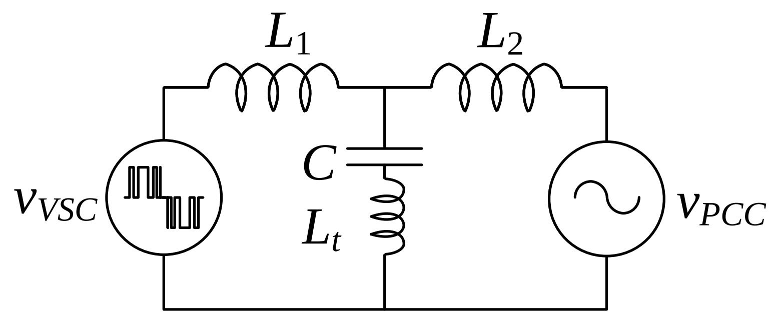
2. Characterization of Passive Filters

Alternative to LCL filter

LCL filter (3rd order low-pass)



LLCL filter (LCL + trap filter)



Filter <u>transfer admittances</u> (i_2/v_{VSC}):

$$Y_{21(LCL)}(s) = A_0 \frac{1}{\frac{s^2}{\omega_0^2}+1} = A_\infty \frac{1}{\frac{\omega_0^2}{s^2}+1}$$

$$Y_{21(trap)}(s) = A_0 \frac{\frac{s^2}{\omega_t^2}}{\frac{s^2}{\omega_0^2}+1} = A_\infty \frac{\frac{\omega_t^2}{s^2}}{\frac{\omega_0^2}{s^2}+1}$$

Selecting $\boldsymbol{Y_{21} \leq Y_{vhf}}$ suffices performance criteria of passive filters!

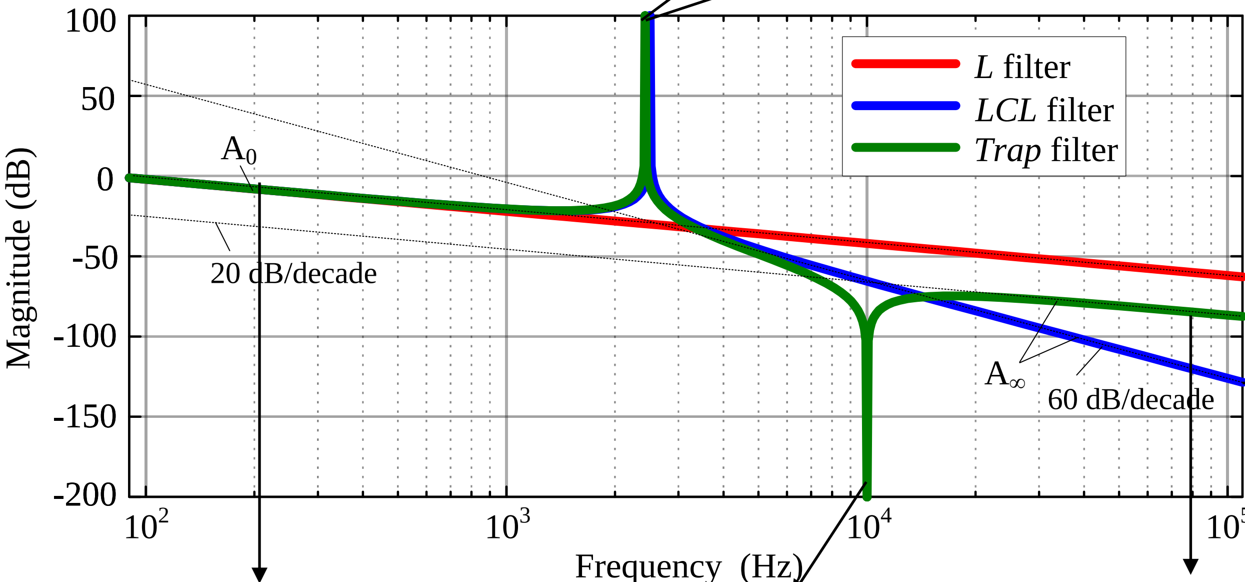
2. Characterization of Passive Filters

Attenuation characteristics

Filter <u>transfer admittances</u> (i_2/v_{VSC}):

$$\omega_{0(Trap)} = \sqrt{[L_1||L_2 + L_t]C)^{-1}}$$

$$\omega_{0(LCL)} = \sqrt{(L_1 + L_2)/(L_1 L_2 C)}$$



$$A_{\infty(LCL)} = 1/(s^3 L_1 L_2 C)$$

$$A_0 = 1/[s(L_1 + L_2)]$$

$$\omega_t = \sqrt{(L_t C)^{-1}}$$

$$A_{\infty(Trap)} = L_t/[s(L_1 L_2 + L_1 L_t + L_2 L_t)$$

Selecting $\boldsymbol{Y_{21} \leq Y_{vhf}}$ suffices performance criteria of passive filters!

2. Characterization of Passive Filters

Attenuation characteristics

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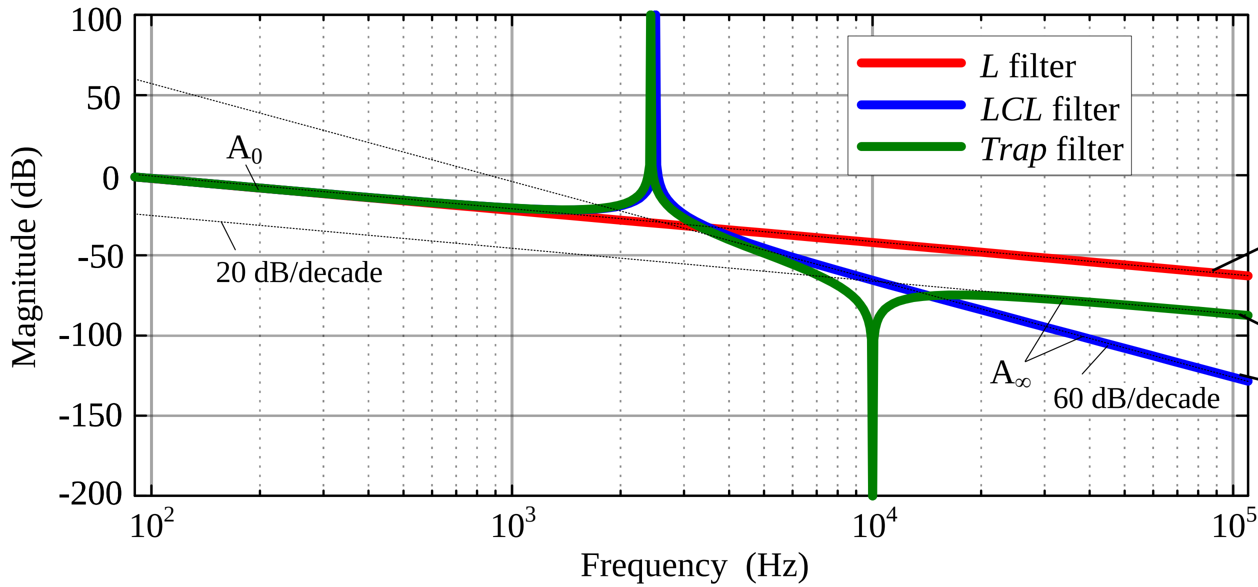
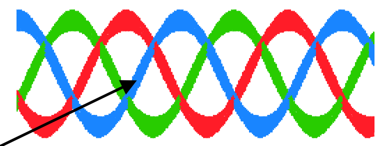
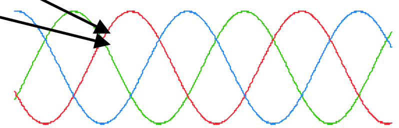


L filter



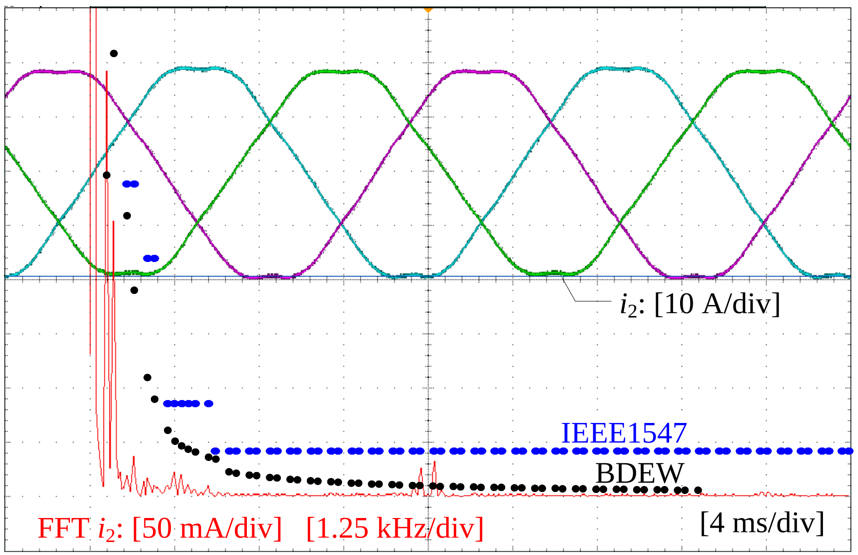
LCL & trap filters



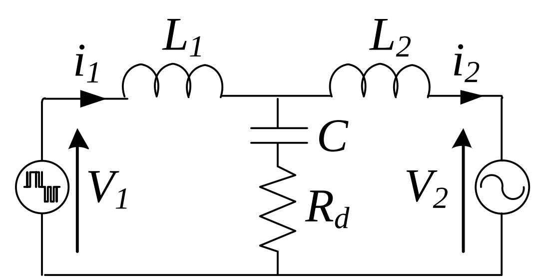
Selecting $\boldsymbol{Y_{21} \leq Y_{vhf}}$ suffices performance criteria of passive filters!

Conventional passive damping method

Experimental waveforms – conservative design, fsw=5 kHz [4]



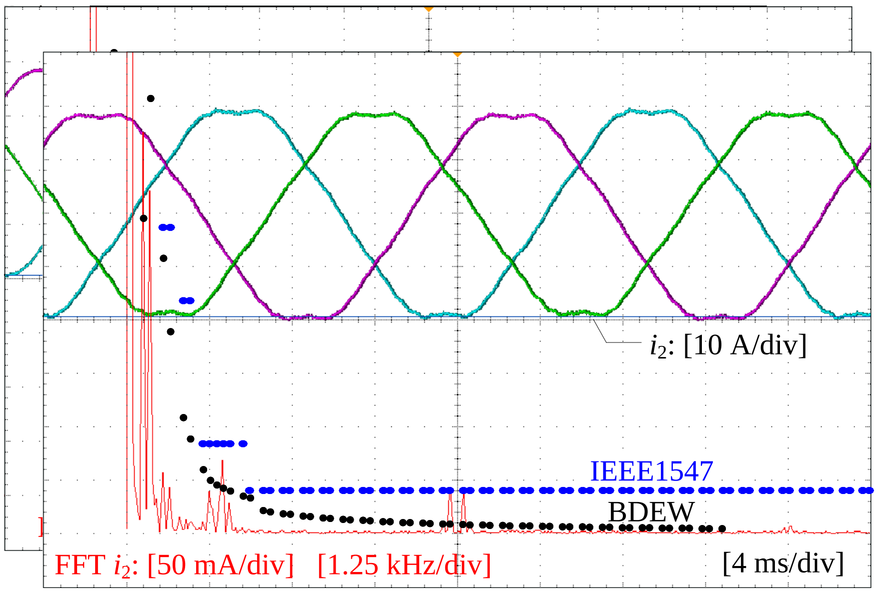
L_1 = 3.5 mH (**7 %**), L_2 = 1.5 mH (**3 %**),
C = 9.5 µF (**5 %**), R_d =1.4 Ω (0.13 %),
P_d = 0.03 %
k_p = 8.5, k_i = 450



[4] R. Beres, X. Wang, M. Liserre, F. Blaabjerg, and C. L. Bak, "A Review of Passive Power Filters for Three Phase Grid Connected Voltage-Source Converters," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 1, 2016, pp. 54–69.

Conventional passive damping method

Experimental waveforms – optimal design, fsw=5 kHz [4]



L_1 = 2 mH (**4 %**), L_2 = 1.5 mH (**3 %**)
C = 20 μF (**10 %**), R_d =1.6 Ω (0.3 %),
$\boldsymbol{P_d}$ **= 0.4 %,**
k_p = 5, k_i = 250

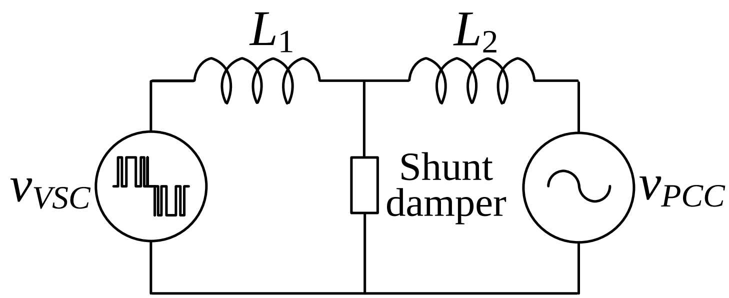
Filter size/cost is reduced with 30 %!

Damping losses increases by a factor of 13!

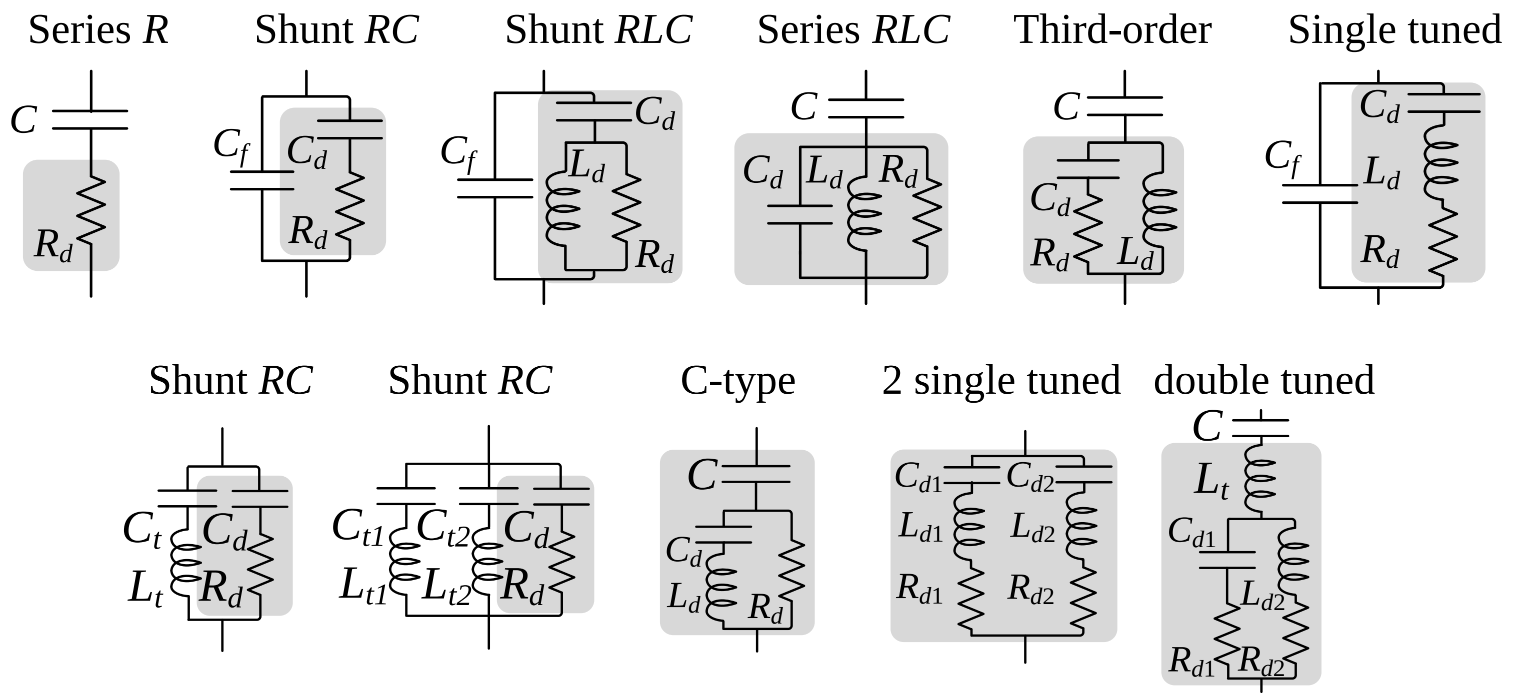
[4] R. Beres, X. Wang, M. Liserre, F. Blaabjerg, and C. L. Bak, "A Review of Passive Power Filters for Three Phase Grid Connected Voltage-Source Converters," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 1, 2016, pp. 54–69.

3. Damping Methods and Loss Optimization

Passive damping methods

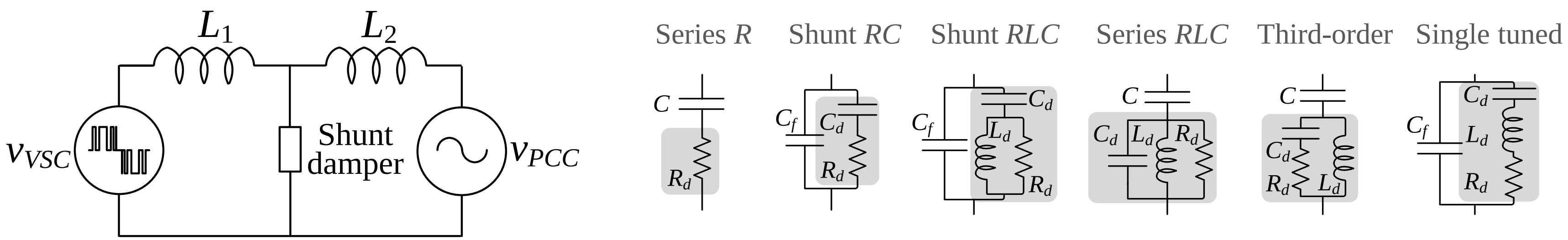


Shunt dampers:

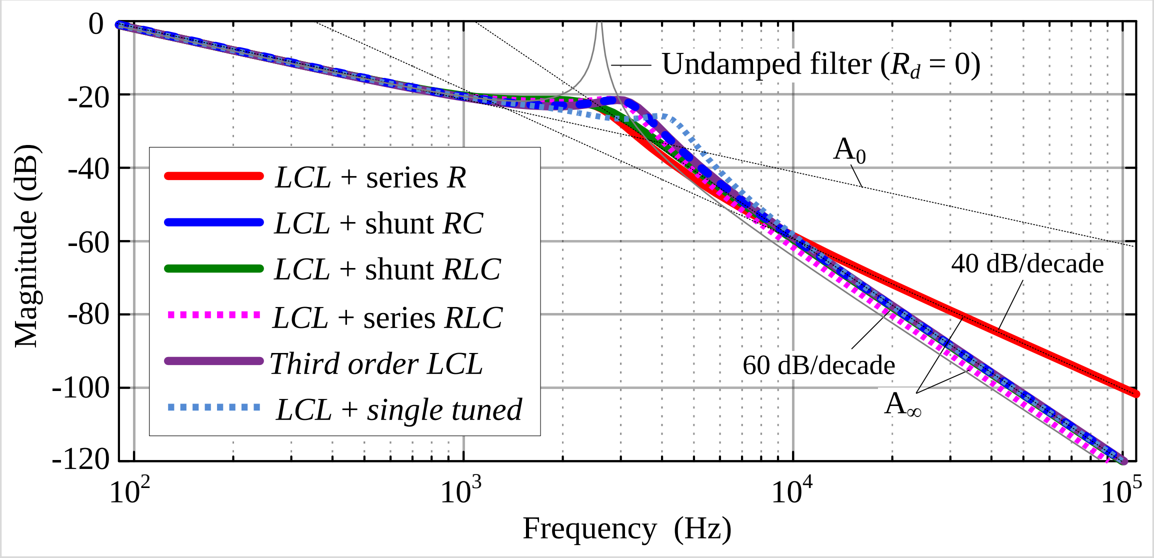


3. Damping Methods and Loss Optimization

Shunt passive damped filters for *LCL* filter



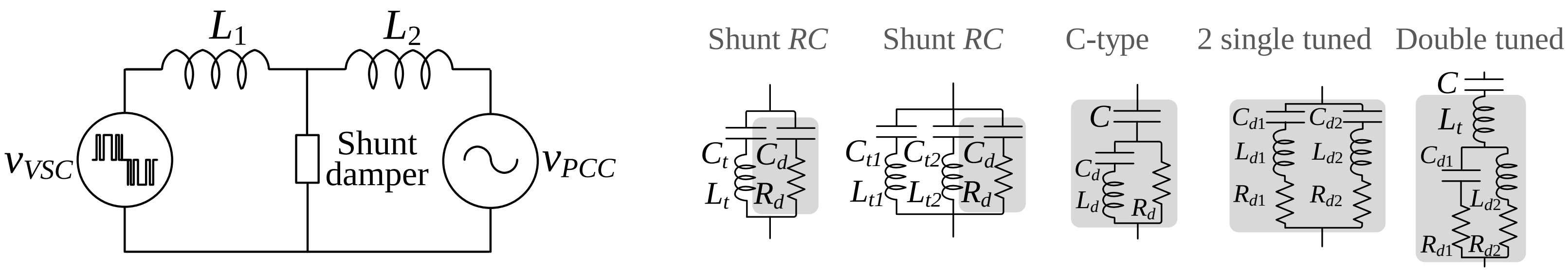
Filter transfer admittance:



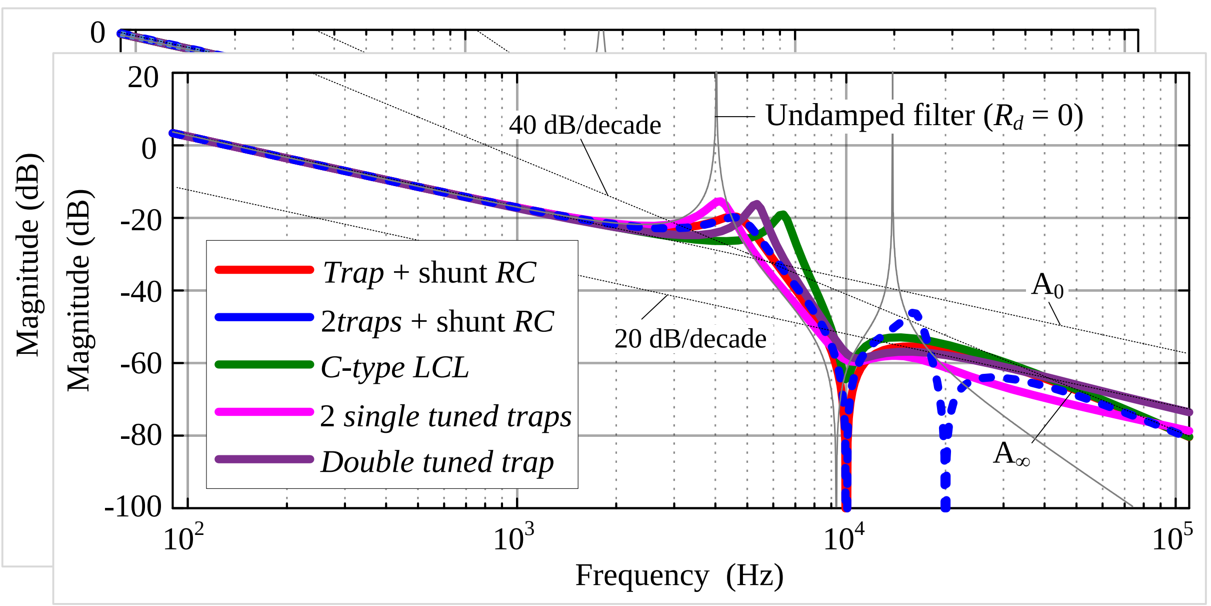
Mainly the resonance frequencies are affected!

3. Damping Methods and Loss Optimization

Shunt passive damped filters for *Trap* filter



Filter transfer admittance:



Mainly the resonance frequencies are affected!

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Shunt passive damped filters – optimal design concept [5]

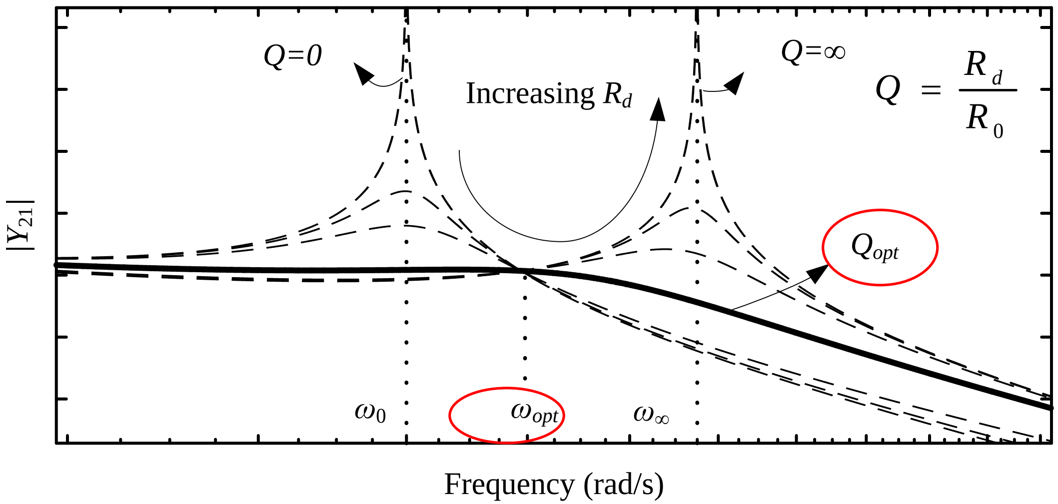
Optimal frequency:

$$\left|Y_{21}(s)\right|_{\substack{R_d=0 \\ s=j\omega_{opt}}} = \left|Y_{21}(s)\right|_{\substack{R_d=\infty \\ s=j\omega_{opt}}} \rightarrow \omega_{opt}$$

Optimal quality factor:

$$\left[\frac{d}{d\left(x^2\right)}\left|Y_{21}\right|^2\right]_{\begin{cases} s=j\omega_{opt} \\ x=\frac{\omega_{opt}}{\omega_0}\end{cases}} = 0 \rightarrow Q_{opt} = f(n)$$

$$n = \frac{C_d}{C_f} \qquad R_d = Q_{opt} R_0 = Q_{opt}\sqrt{L/C}$$



[5] R. Beres, X. Wang, F. Blaabjerg, M. Liserre, and C. L. Bak, "Optimal Design of High-Order Passive-Damped Filters for Grid-Connected Applications," IEEE Trans. Power Electron., vol. 31, no. 3, 2016, pp. 2083–2098.

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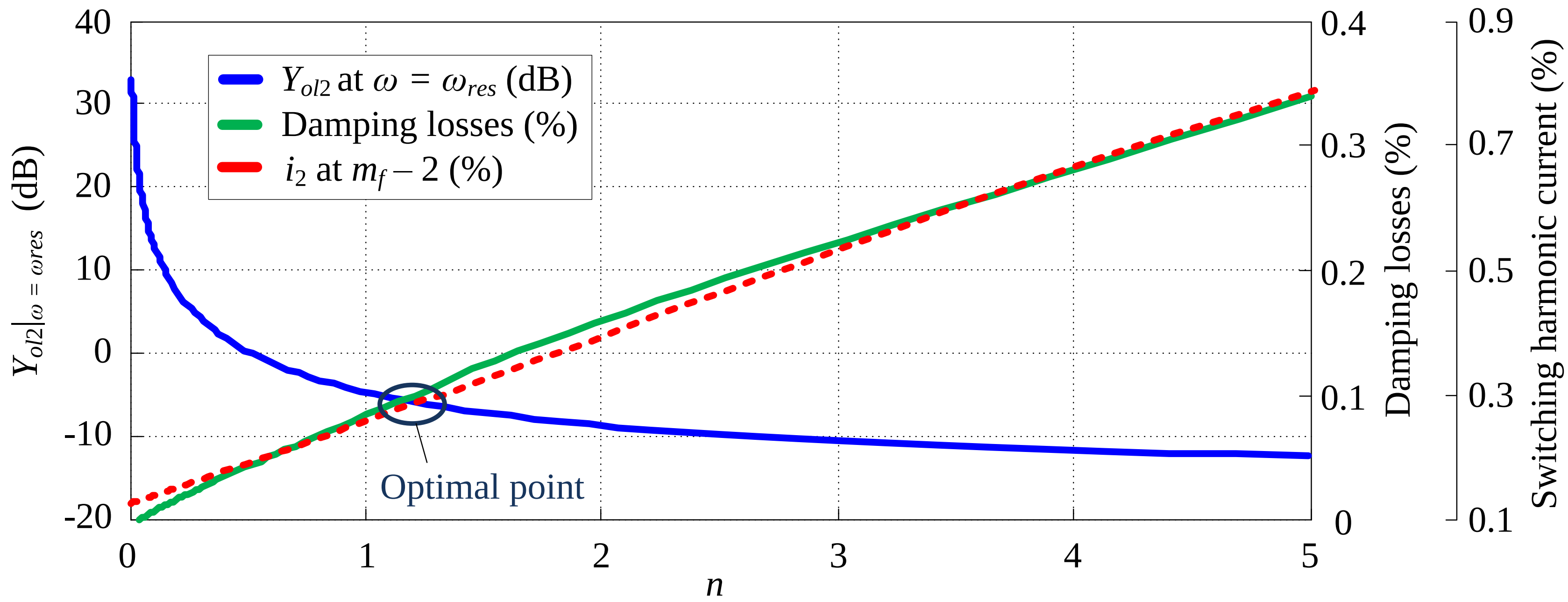
Optimal selection of filter parameters

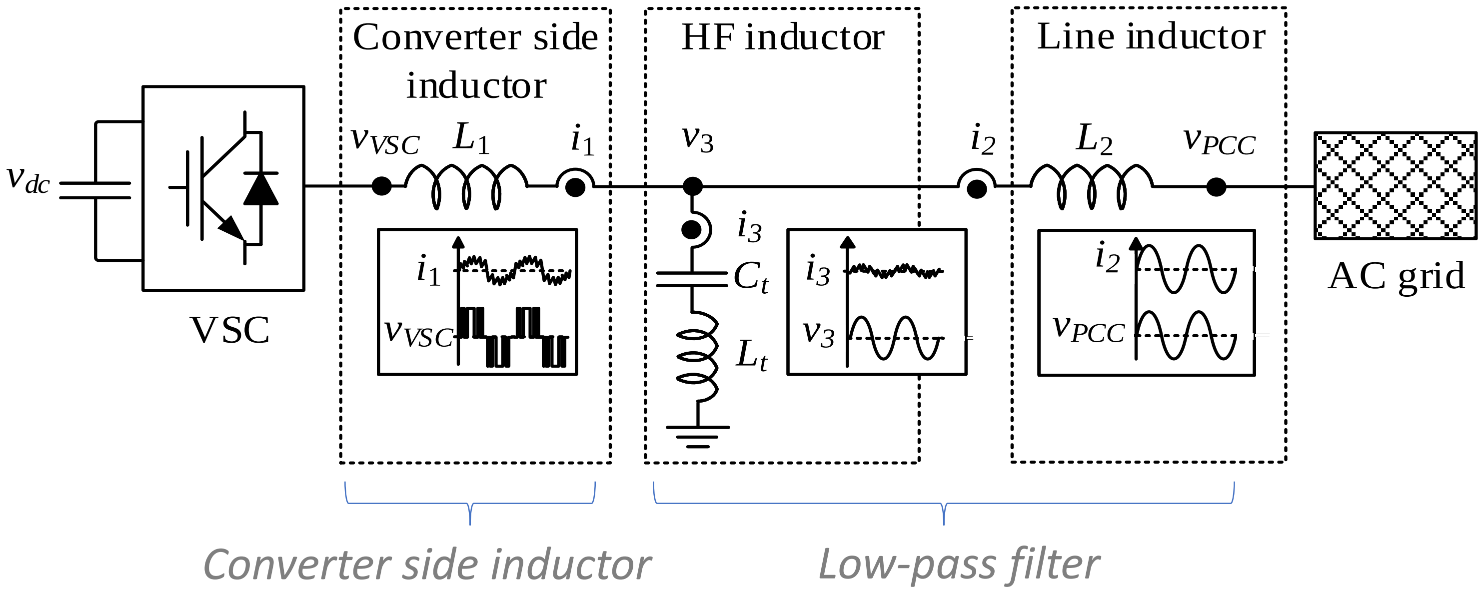
- Control loop also has to be included for $\omega_{opt} < \omega_{Nq}$
- Optimal selection results as a trade-off between filter resonance, damping losses and filter attenuation



4. Characterization of Inductive Components

Filter components [3]

- Converter side inductor
- Shunt capacitor in series with switching frequency inductor
- Line inductor



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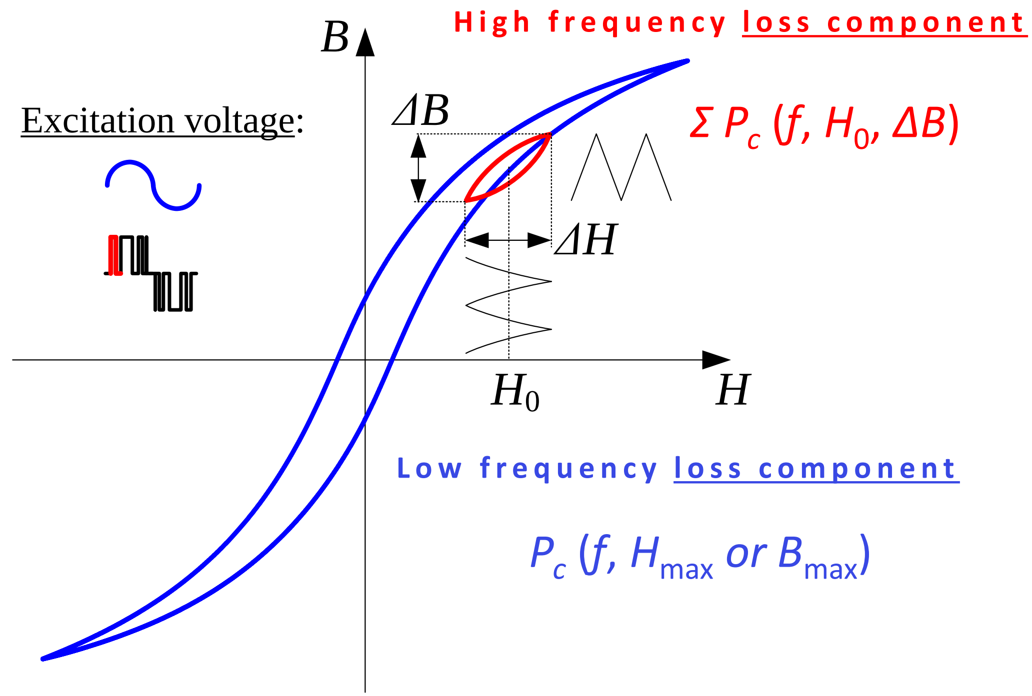
Design of the converter side inductor



Inductance rating:

$$L_1 = \frac{V_{dc}}{r \Delta i_{1pk} f_{sw}}$$

Current rating:

$$I_{1pk} = \max\left(i_{1LF}(t) + i_{1HF}(t)\right) = \frac{A_c B_{\max} N}{L_1}$$

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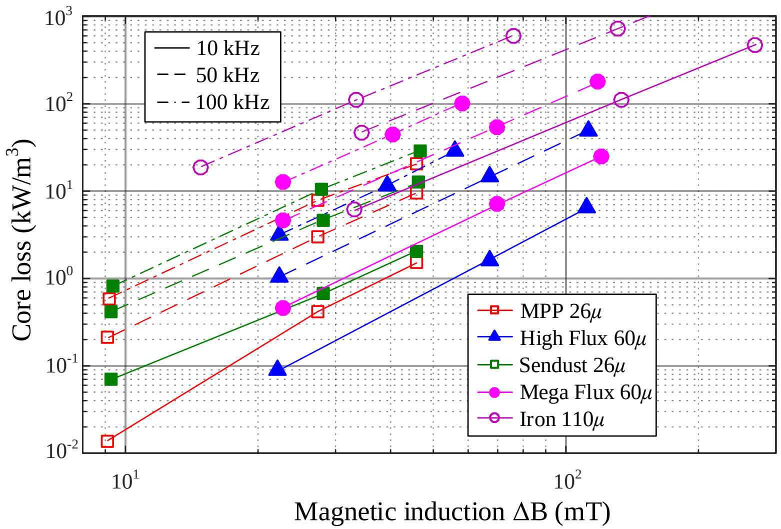
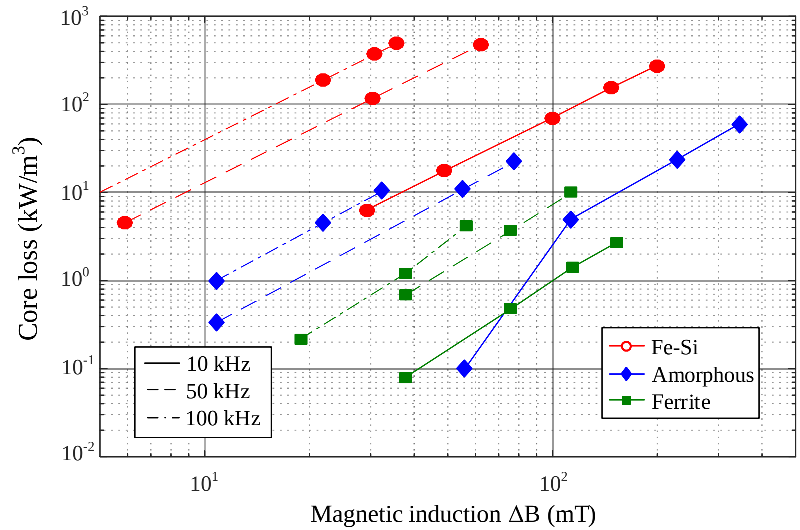
High frequency loss component [3]

Rectangular voltage excitation, P_{cv} (f, H_0=0, ΔB)





Total high frequency loss = Σ P_c (f, H_0, ΔB)!

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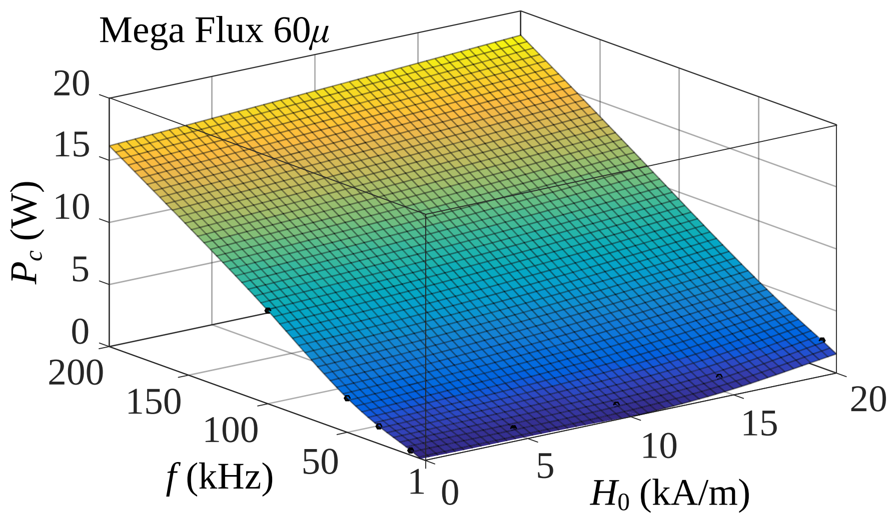
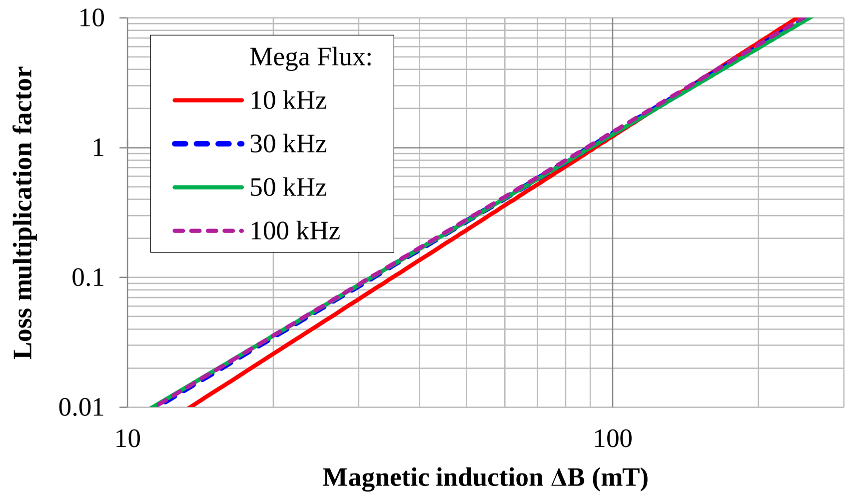
High frequency loss component

Rectangular voltage excitation, Loss map of P_{cv} (f, H_0, ΔB = ct. = 0.09 T) [6]





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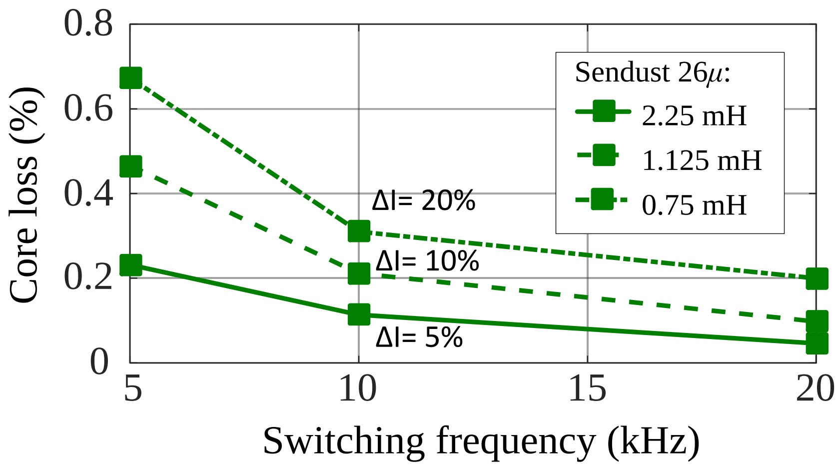
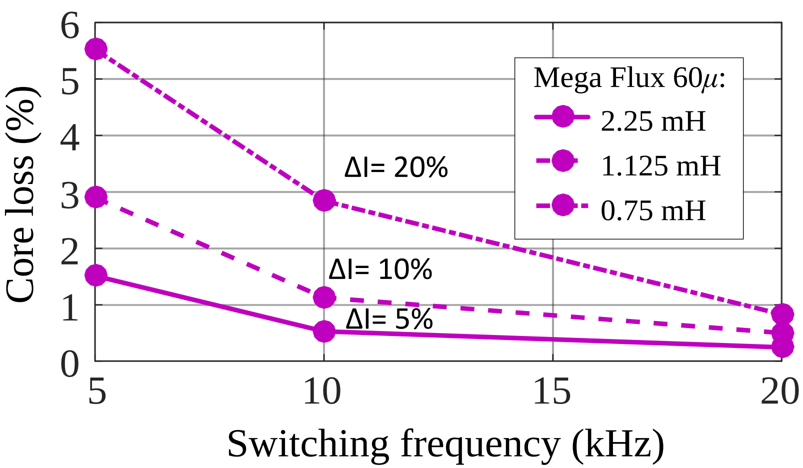
[6] R. N. Beres "Optimal design of passive power filters for grid-connected voltage-source converters" PhD thesis, Aalborg University, 2016.

Core loss vs. current ripple [6]

Single phase inverter results for 5 %, 10 % and 20 % current ripple @ 5 Apk & @ 10 kHz, unipolar modulation with ma=0.9





Total high frequency loss = $\Sigma P_c (f, H_0, \Delta B)$!

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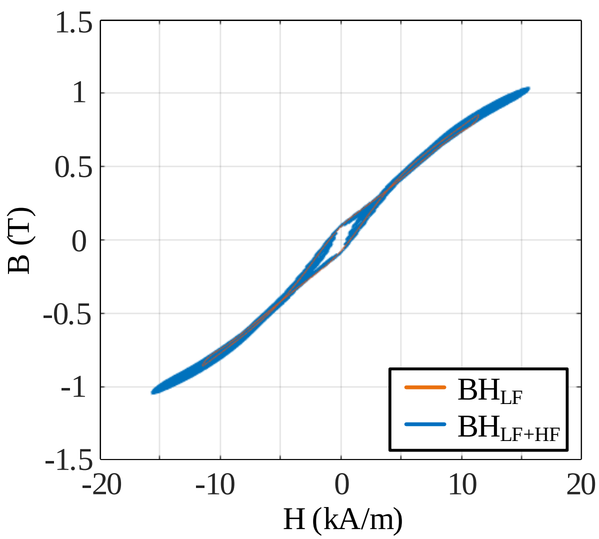
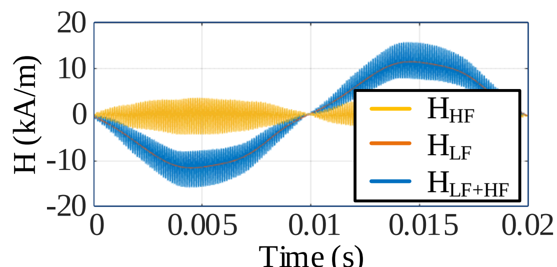
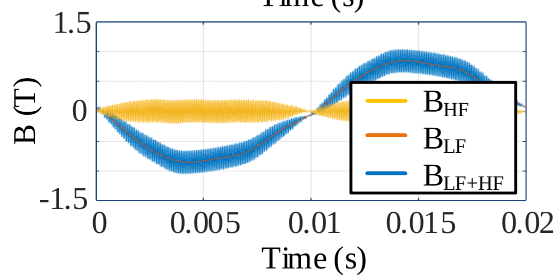
4. Characterization of Inductive Components

Actual operating waveforms and total core loss

Single phase inverter results with Mega Flux µ60 converter side inductor with L=2.25 mH @ 10 A_{pk}, 5 kHz unipolar modulation and m_a=0.5:







<u>Low frequency core loss</u>:

P_{cvLF} is 37.5 kW/m³

→ line inductor design is not loss limited!

<u>Total core loss</u>:

P_{cv} is 1000 kW/m³ (1.75 %)

→ High frequency core loss are dominant!

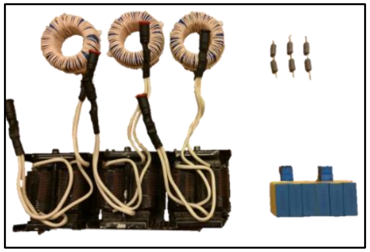
Total high frequency loss = $\Sigma P_c (f, H_0, \Delta B)$!

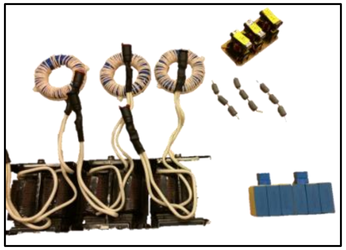
[6] R. N. Beres "Optimal design of passive power filters for grid-connected voltage-source converters" PhD thesis, Aalborg University, 2016.

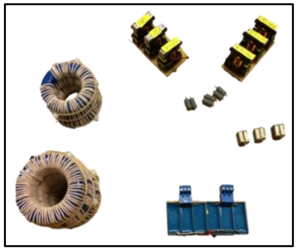
5. Design Examples

Design example and loss evaluation of 10 kW - 10 kHz LCL filter [5]

Description	LCL+RC	Trap+RC	2 traps+RC
Total Losses (%)	1	1	0.95
Damping Losses (%)	**0.075**	**0.071**	**0.053**
THD_{vPCC} (%)	0.45	0.45	0.39
THD_{iPCC} (%)	1.27	1.12	2.67
$i_{2(mf-2)}$ (%)	0.083	0.0083	0.0328
Volume (dm^3)	0.76	0.67	0.37
Magnetic materials	Fe-Si + Sendust	Fe-Si + Sendust + Ferrite	Sendust + Ferrite





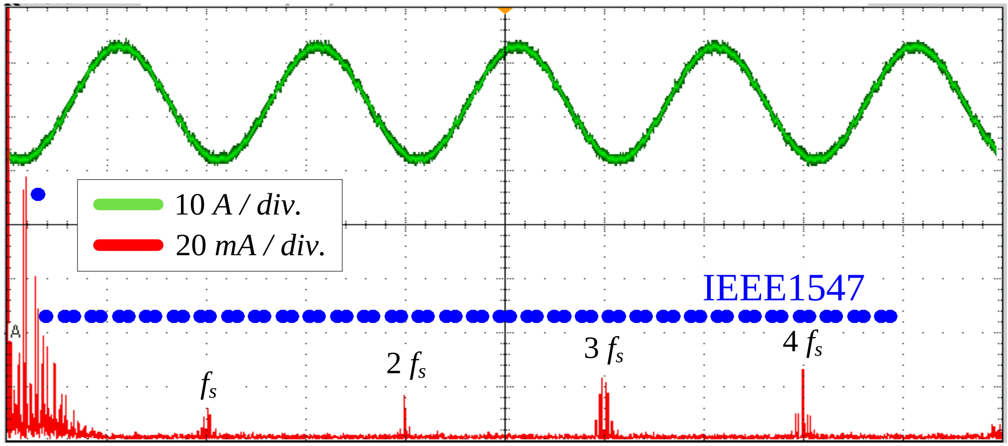


Half size!

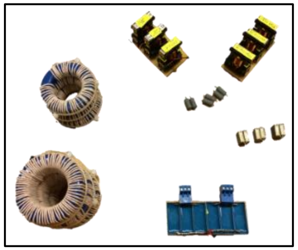
[5] R. Beres, X. Wang, F. Blaabjerg, M. Liserre, and C. L. Bak, "Optimal Design of High-Order Passive-Damped Filters for Grid-Connected Applications," IEEE Trans. Power Electron., vol. 31, no. 3, 2016, pp. 2083–2098.

5. Design Examples

Current waveforms in 10 kW - 10 kHz LCL+2 traps filter [5]



Grid current waveforms!



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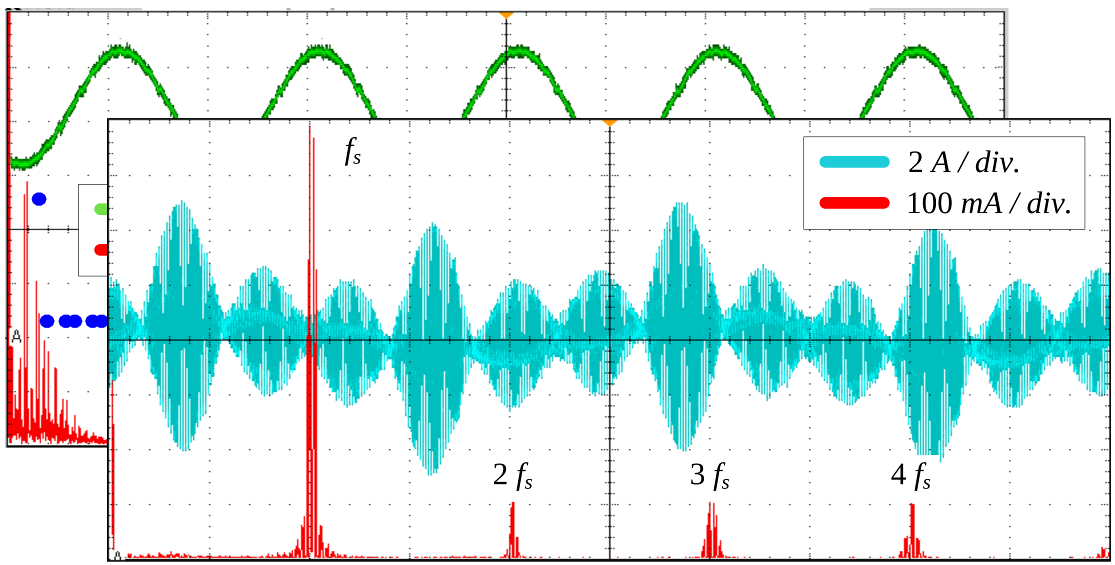
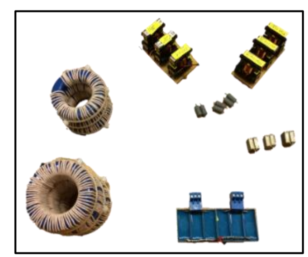


First trap current waveforms!



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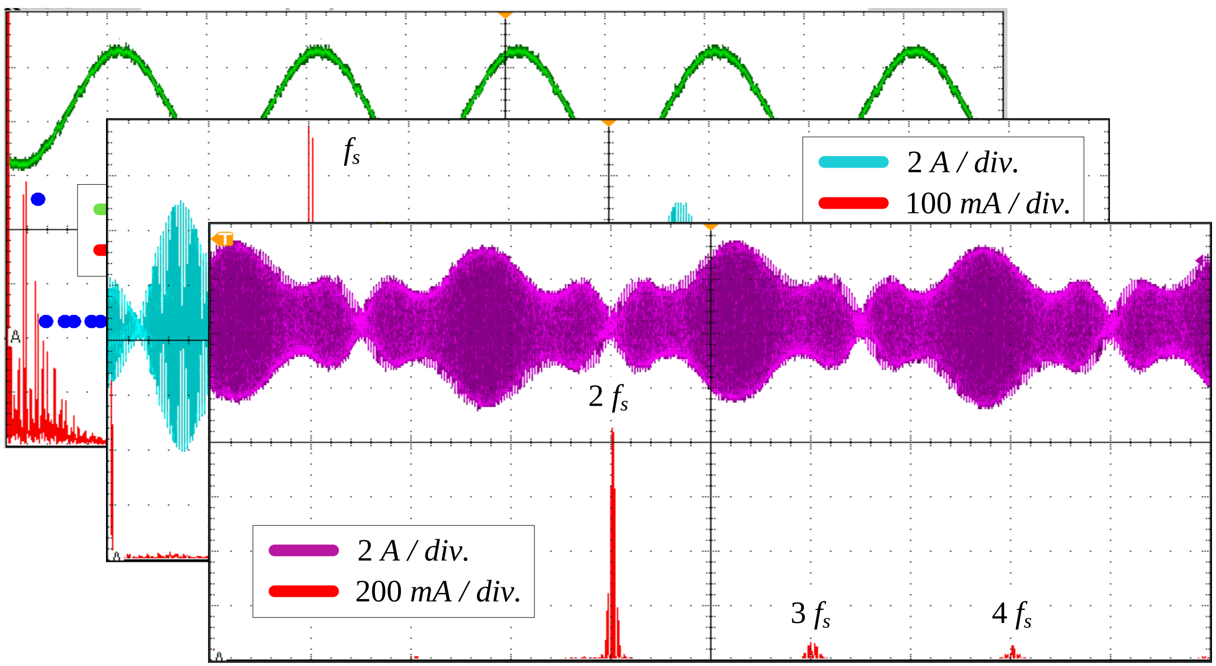

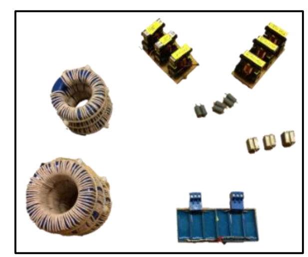

Half size!

Second trap current waveforms!

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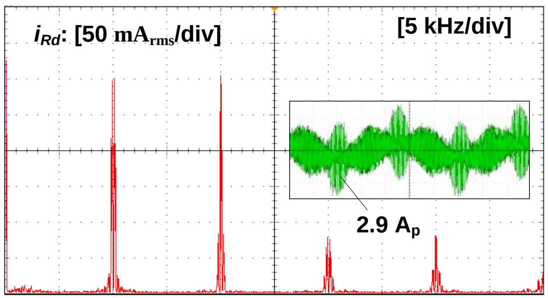
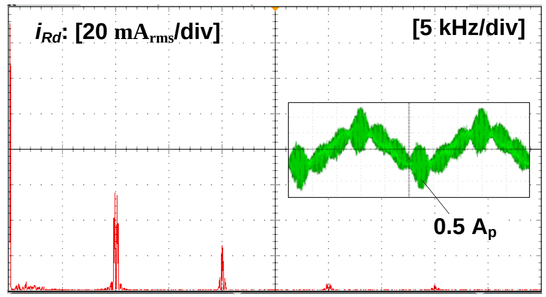
5. Design Examples

Damping loss evaluation in 10 kW - 10 kHz filter with different damping methods [4]

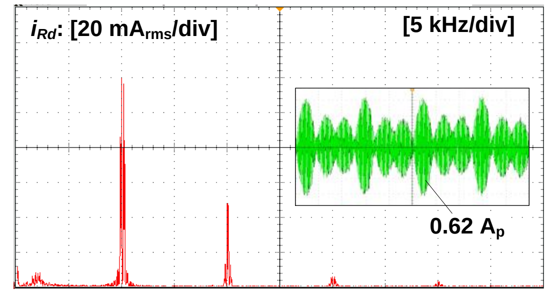
LCL + series *R* (0.12%)



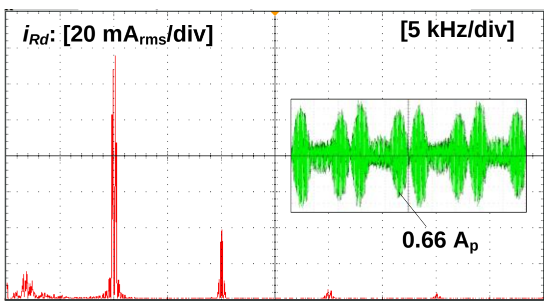
LCL + shunt *RC* (0.045%)



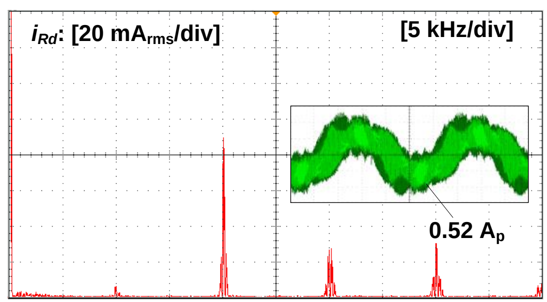
LCL + shunt *RLC* (0.028 %)



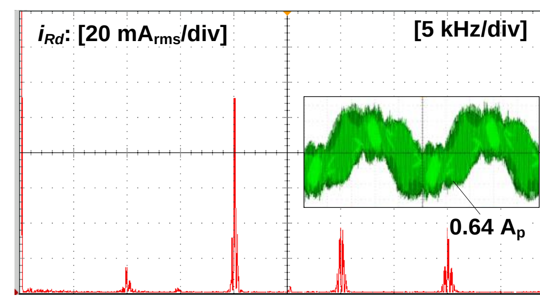
LCL + series *RLC* (0.01%)



Trap + shunt *RC* (0.03%)



2Traps + shunt *RC* (0.03 %)



[4] R. Beres, X. Wang, M. Liserre, F. Blaabjerg, and C. L. Bak, "A Review of Passive Power Filters for Three Phase Grid Connected Voltage-Source Converters," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 1, 2016, pp. 54–69.

5. Design Examples

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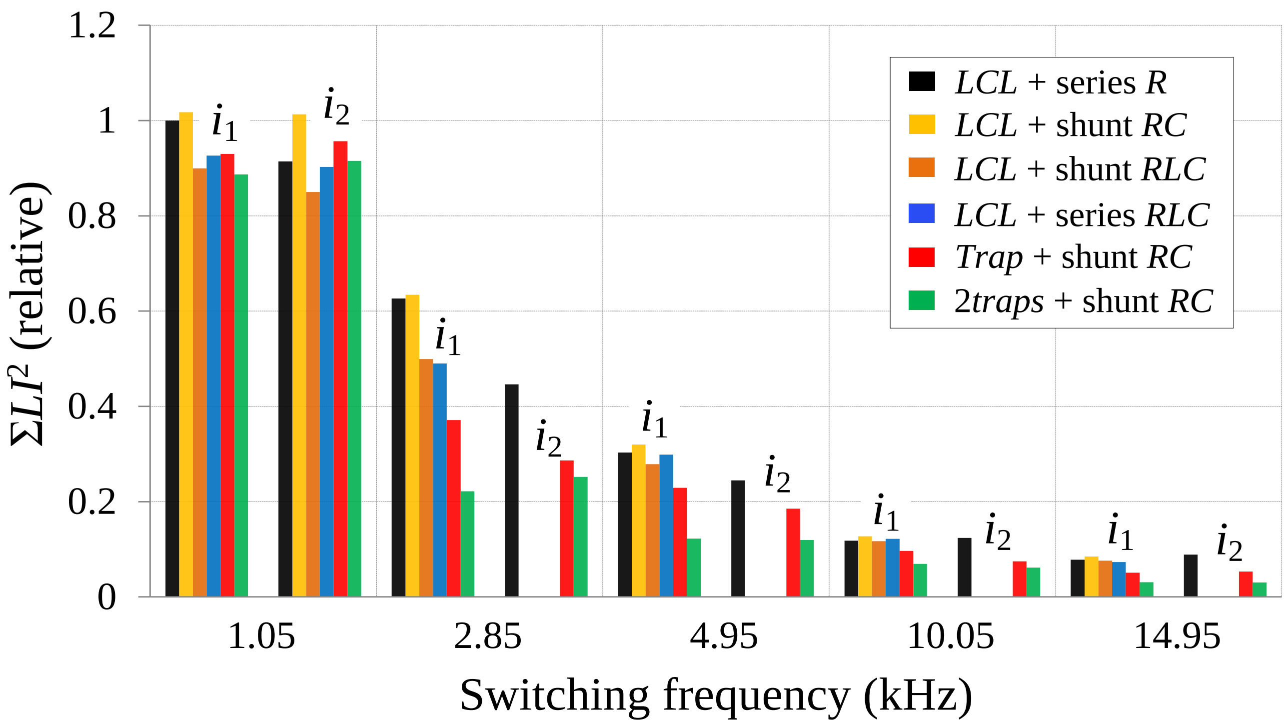
Filter size for different switching frequency and damping methods



i_1 – Converter current feedback

i_2 – Grid current feedback

6. Conclusions

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- The chosen magnetic material and current ripple level in the converter side inductance of the filter dictates on the cost, size and efficiency of the passive filter
- The harmonic current flow in the filter increases with decreasing the inductance and accurate damping is needed
- Accurate core loss for rectangular voltage excitation under dc-bias is also needed for accurate filter design and loss characterization
- Passive damped filters with RLC circuits in different configurations can be tuned to obtain very low damping losses over a wide range of operating conditions
- With tuned traps, the filter size can be reduced by up to 3 times depending on the switching frequency (at a price of increased component count and complexity)

7. Questions

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