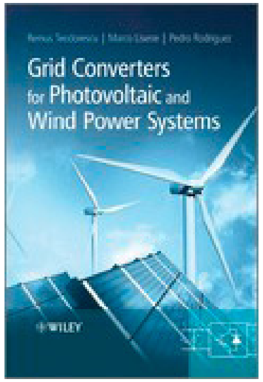

Grid Converters for Photovoltaic and Wind Power Systems

by R. Teodorescu, M. Liserre and P. Rodriguez

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Chapter 11

Grid Filter Design

Outline

- Filter topologies and model
- LCL-filter design
- Practical Examples of LCL Filters and Grid Interactions
- Resonance problems and damping solutions
- Non-linear behavior of the filter

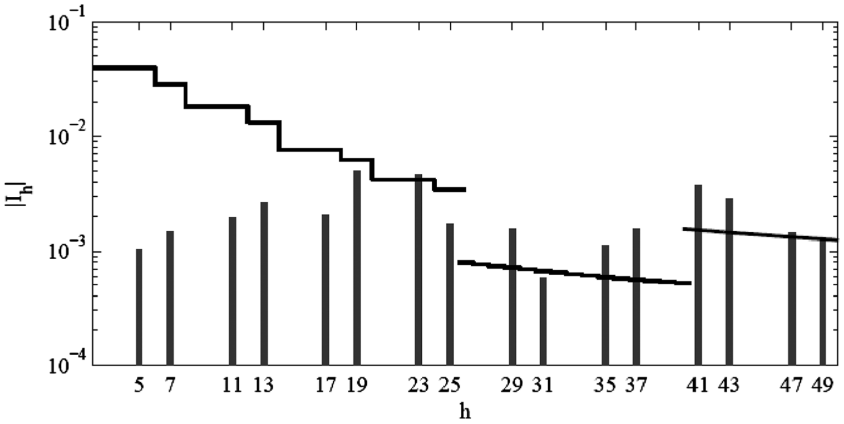
Filter topologies

The role of the grid filters in VSC-based grid converter operation is twofold:

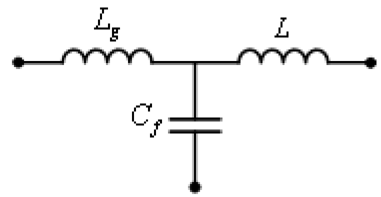
1. Allow the control of active and reactive power with the control of phase and magnitude of the voltage
2. Reduce PWM harmonics caused by the grid-converter

The two most adopted approaches are:

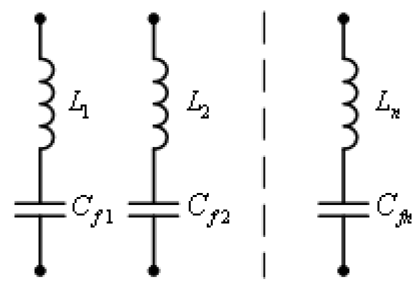
- L-filter plus tuned LC filters (typically at a system level to meet requirements related to the voltage quality)
- Low-pass LCL filter



Harmonic spectrum compared to German VDEW limit



Low-pass filter



Trap filter

Filter model

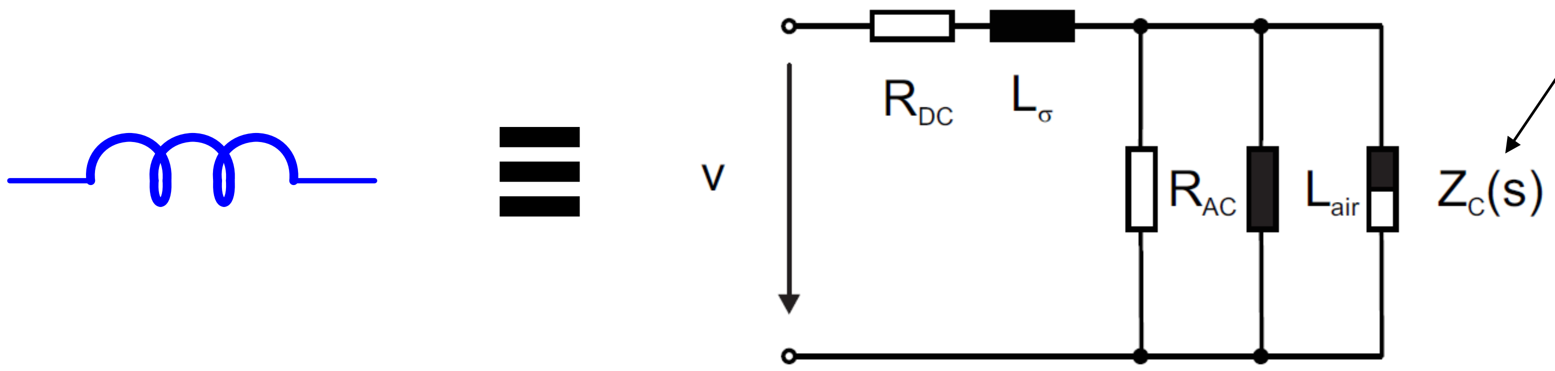
MAGNETIC PROPERTIES OF THE MOST COMMONLY USED CORE MATERIALS [5]

Material	laminated FeSi	Powdered iron	Ferrites
Contents	$3-6\%$ Si	95% Fe resin	MnZn, NiZn resin
μ_r	1000-10000	1-500	100-20000
B_{Sat} [T]	1.9	1 - 1.5	0,3-0,45
ρ [$\mu\Omega$m]	0.4 -0.7		10^3-10^4 MnZn 10^7-10^9 NiZn
Curie temp.	720	700	125-450

Materials used for the inductors

Complete model of the inductors

$$Z_C(s) = \frac{V_C(s)}{I_C(s)} = 2n\frac{b}{l}N^2 Z_0(s)\tanh\left(\gamma(s)\frac{d}{2}\right)$$

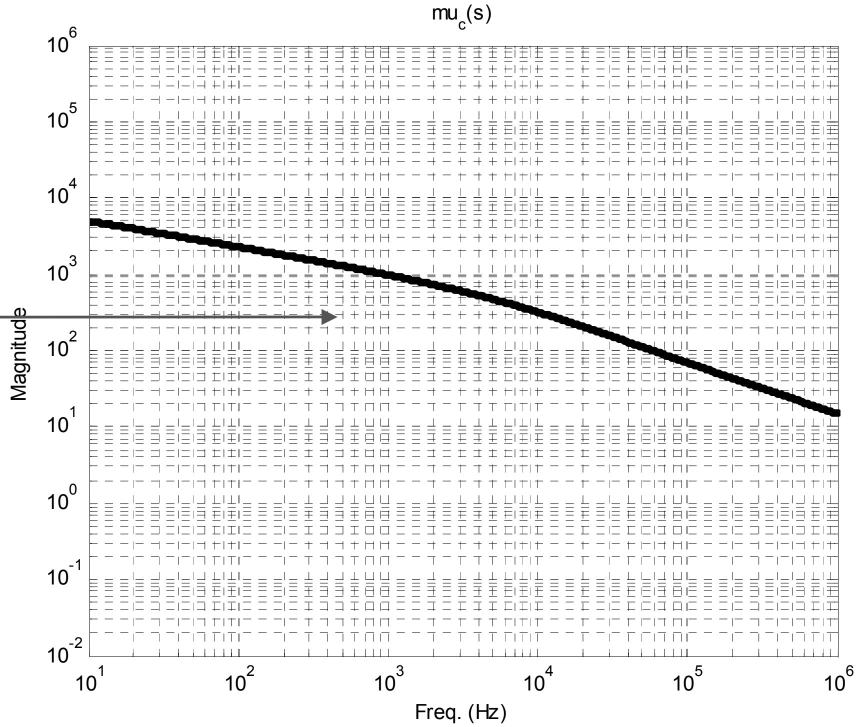


Filter model

- A fractional order model can explain the effects of frequency saturation in magnetic materials

$$\mu_h(s) = \frac{1}{s}\mu_h^{ref} s^{1-2\delta_h/\pi}$$

Saturation problems



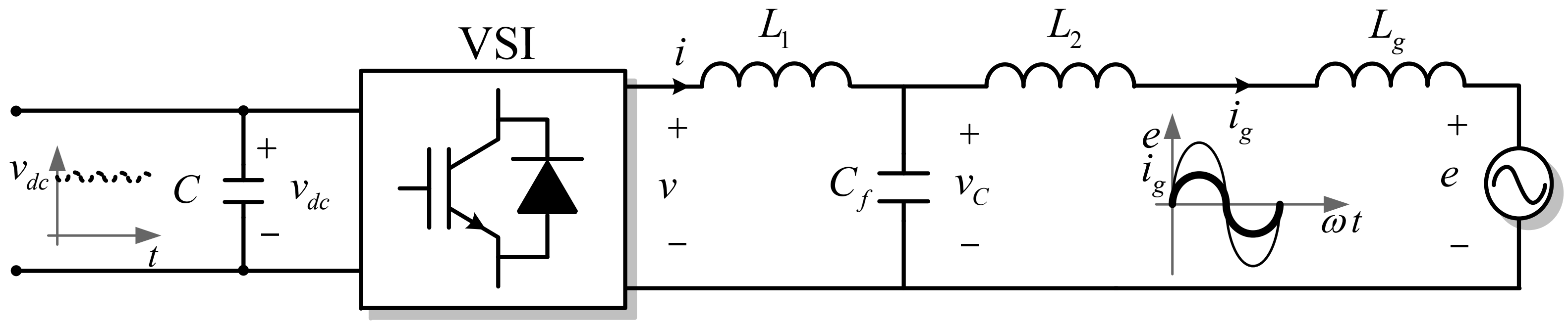
W.-T. Franke, J. Dannehl, F. W. Fuchs, M. Liserre, "Characterization of Differential-Mode Filter for Grid-Side Converters", IECON 2009, Oporto, Portugal, November 2009

LCL-filter design

The passive elements of the system have both storage and filtering functions

The elements on the ac side have mainly filtering function since the stored energy is typically less than 5% of all the energy stored

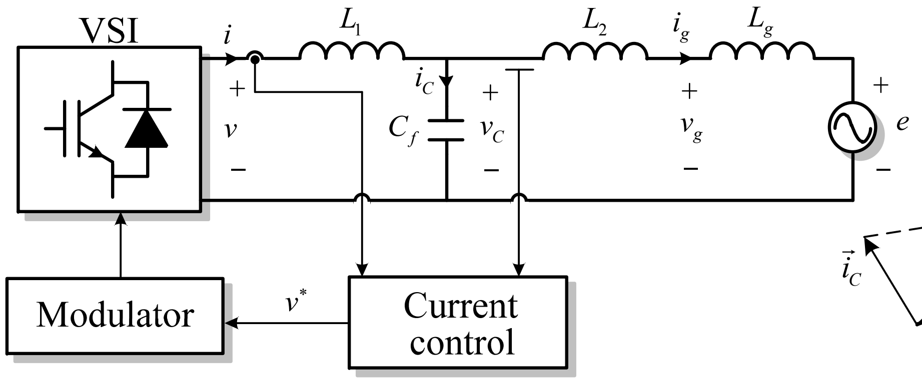
LCL-filter design is a trade-off between filtering and dynamics

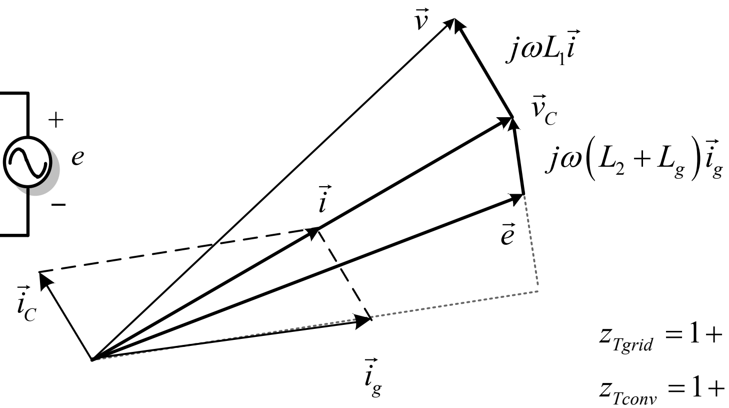


LCL-filter design: sensor position influence

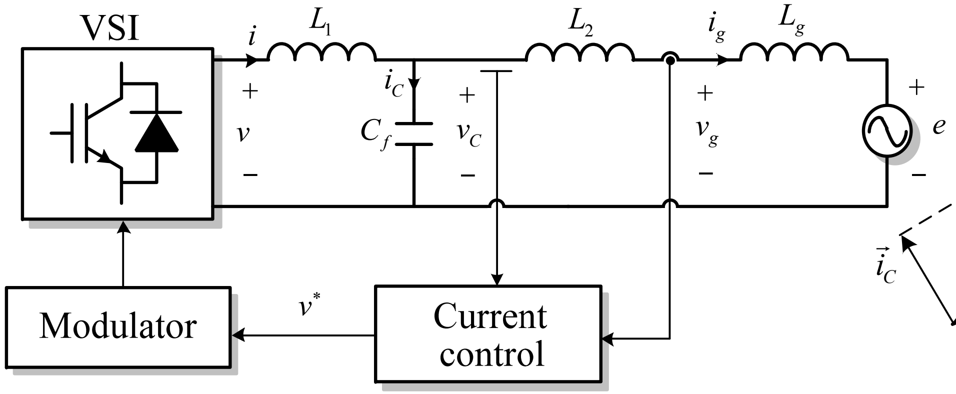
Sensors position has an effect on the equivalent impedance seen from the grid z_{Tgrid} or from the converter z_{Tconv}

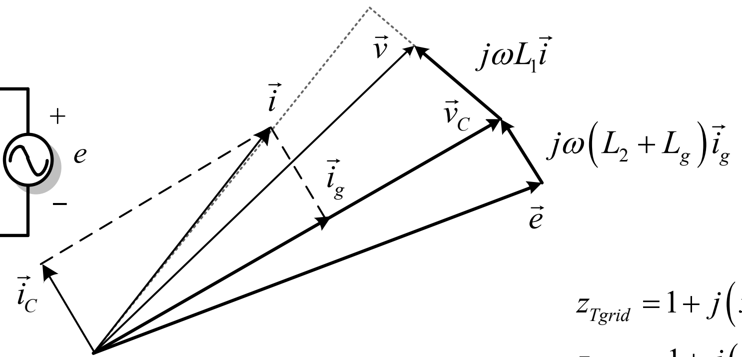
The energy stored in the filter can be seen also in terms of equivalent impedance to be minimized from the grid side to minimize the exchanged reactive power and from the converter side to minimize the rating of the converters





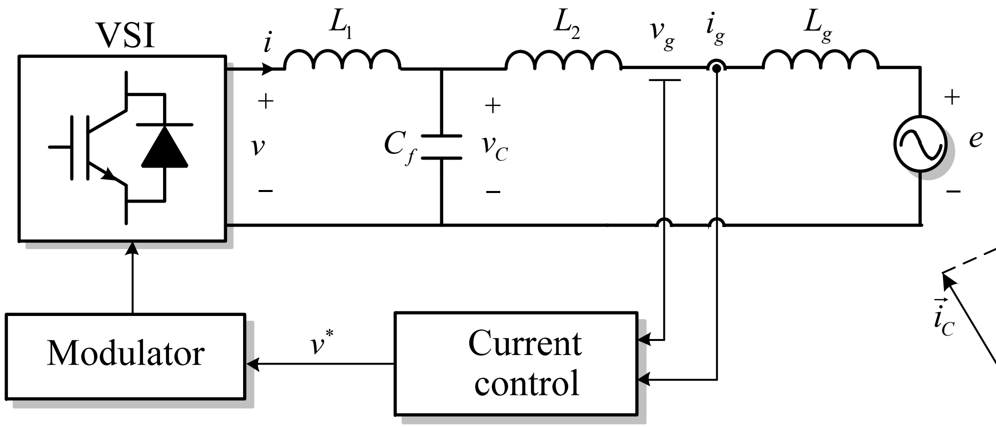
$$z_{Tgrid} = 1 + j\left(x_2 + x_g - x_C\right)$$
$$z_{Tconv} = 1 + jx_1$$

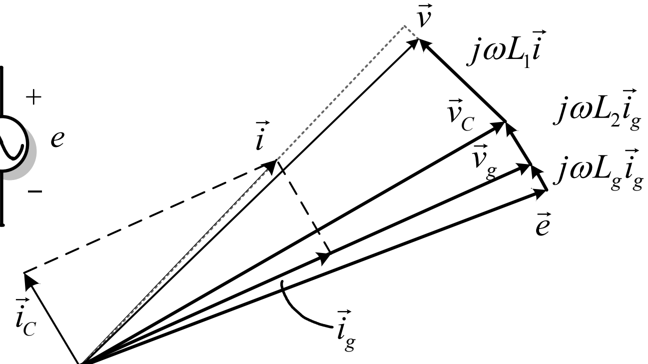




$$z_{Tgrid} = 1 + j\left(x_2 + x_g\right)$$
$$z_{Tconv} = 1 + j\left(x_1 - x_C\right)$$

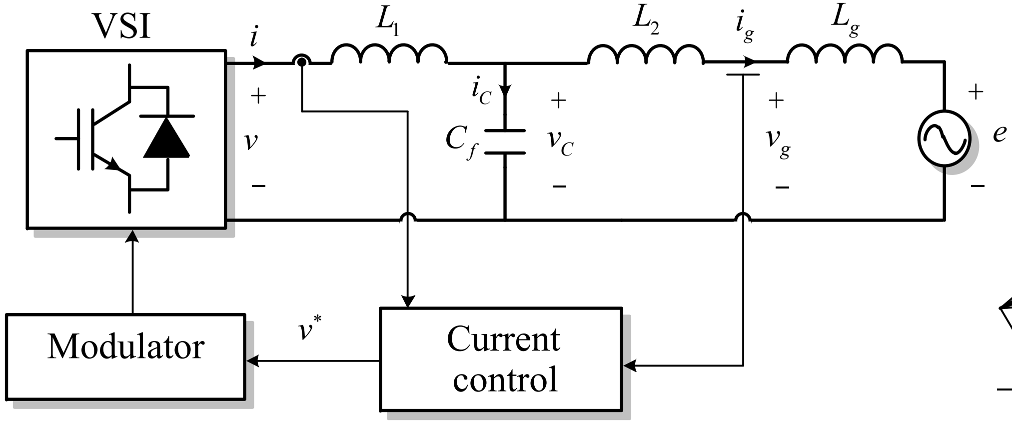
LCL-filter design: sensor position influence

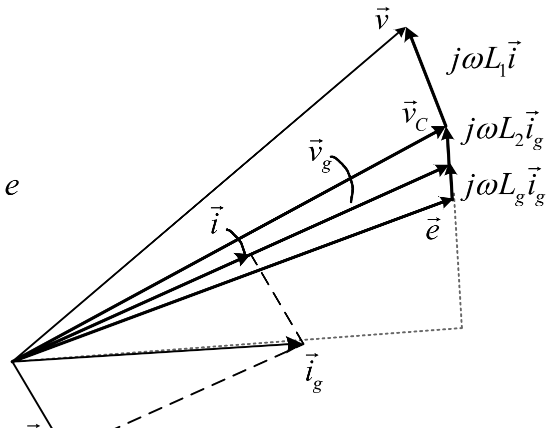




$$z_{Tgrid} = 1 + jx_g$$

$$z_{Tconv} = 1 + j\left(x_1 - x_2 - x_g - x_c\right)$$





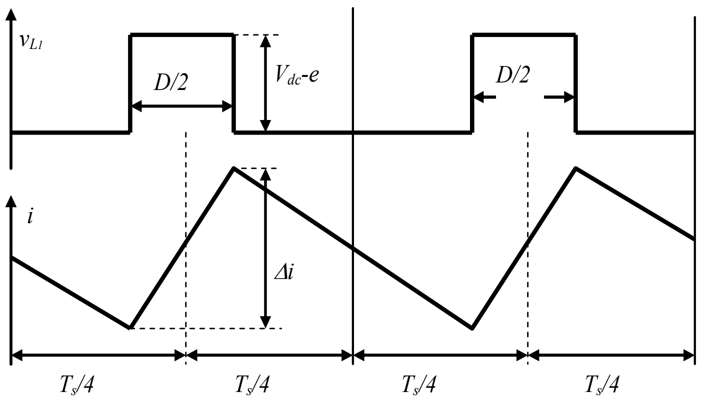
$$z_{Tgrid} = 1 + j\left(x_g - x_C\right)$$

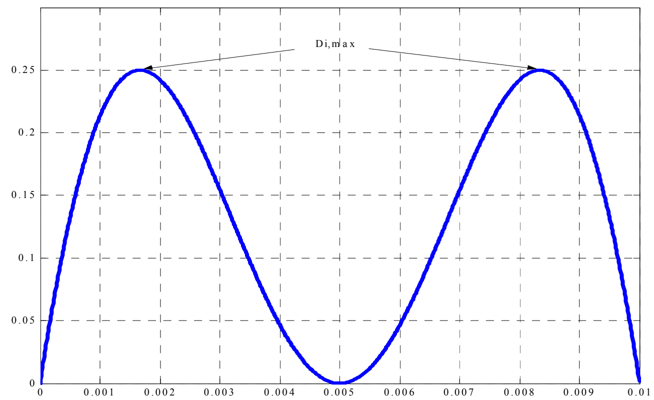
$$z_{Tconv} = 1 - j\left(x_1 + x_2\right)$$

LCL-filter design: choice of L_1

Current ripple in the inverter-side inductor L_1 in case of unipolar modulation

$$\Delta i'(\omega t) = \frac{\Delta i(\omega t)}{\dfrac{V_{dc}\cdot T_s}{2L_1}} = \left(1-\left|M\cdot\sin(\omega t)\right|\right)\cdot\left|M\sin(\omega t)\right|$$

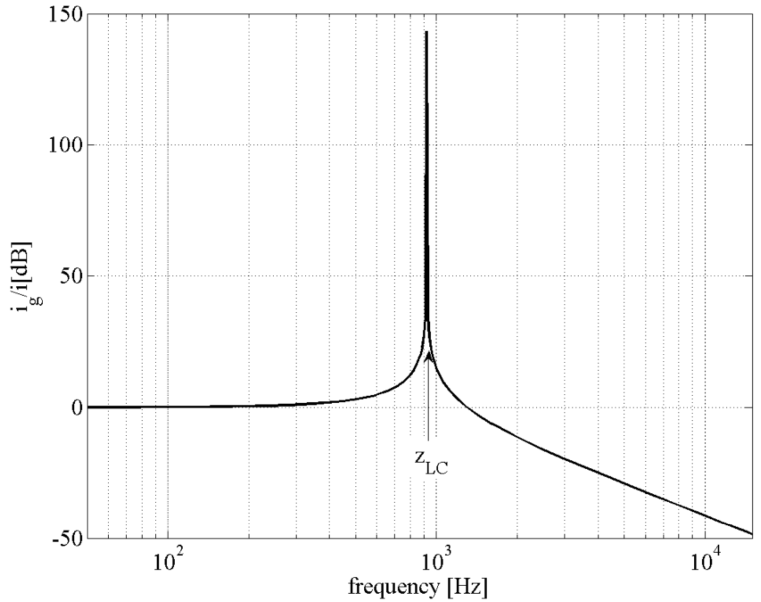


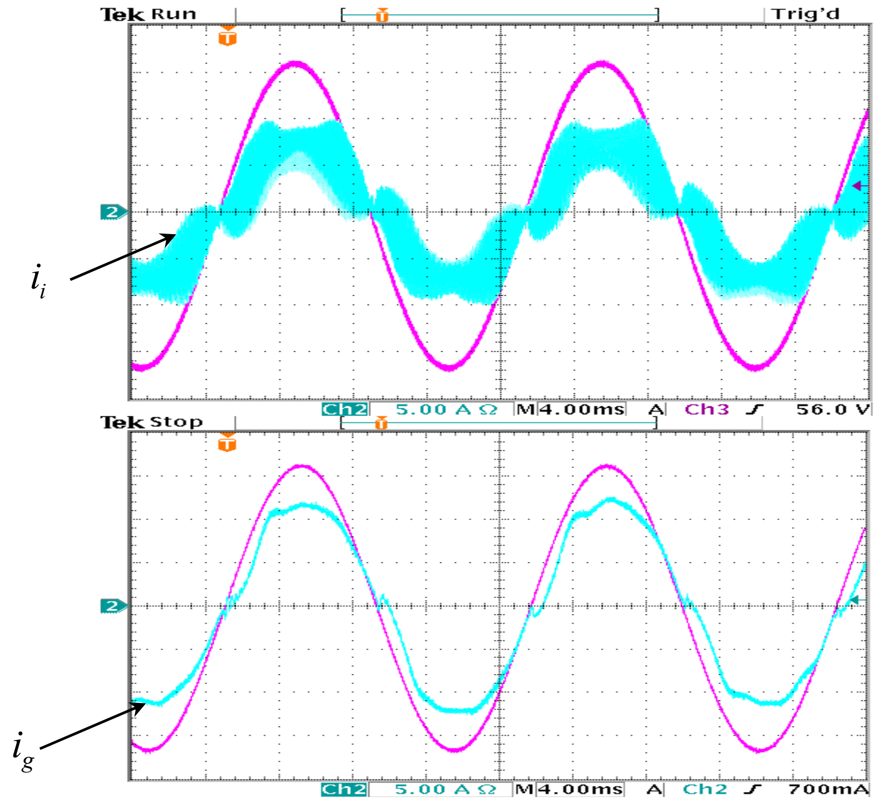


- For a generic type of modulation the maximum ripple is $\Delta I_{MAX} = \frac{1}{n}\frac{V_{dc}}{L_1 f}$ where n depends on the modulation
- The inductor side inductor L_1 is first determined by limiting the max. current ripple at a certain value for a given dc voltage and switching frequency
- Knowing the maximum ripple, the peak current can be calculated and used for the choice of the IGBTs, design of the current protection and design of L_1 magnetic

LCL-filter design: choice of L_2C_f

$$\frac{i_g(s)}{i_i(s)} = \frac{1}{1 + C_f \cdot \left(L_2 + L_g\right) \cdot s^2}$$





Ripple attenuation

$$\frac{i_g(\omega)}{i(\omega)} = \frac{z_{LC}^2}{\left|z_{LC}^2 - \omega^2\right|}$$

where $z_{LC}^2 = \dfrac{1}{\left(L_g + L_2\right)C_f}$ is selected on the basis of the needed attenuation of the current ripple at the frequency ω

Design of LCL filter: choice of C_f and L_2

- C_f is then sized with two goals:

  1. Minimize the installed reactive power of the filter or z_{Tconv} and z_{Tgrid}

  2. Robustness of the resonance frequency and as a consequence of the filter attenuation to the grid impedance variation

$$\Delta\omega_{res} = \frac{1}{2\omega_{res} C_f}\left(\frac{1}{L_2 + L_{g1}} - \frac{1}{L_2 + L_{g2}}\right)$$

- Finally, the L_2 is determined

- The effect of passive damping on the filter attenuation should be calculated

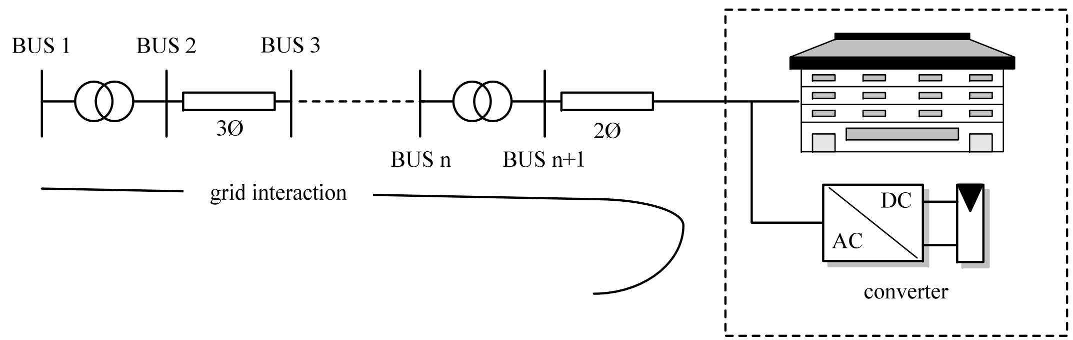
Practical Examples of LCL Filters and Grid Interactions

- The possible wide range of grid impedance values (distributed generation is suited for remote areas with radial distribution plants) challenge:
  1. the stability of the system
  2. the effectiveness of the LCL-filter

- The topic will be discussed both for PV and WT systems

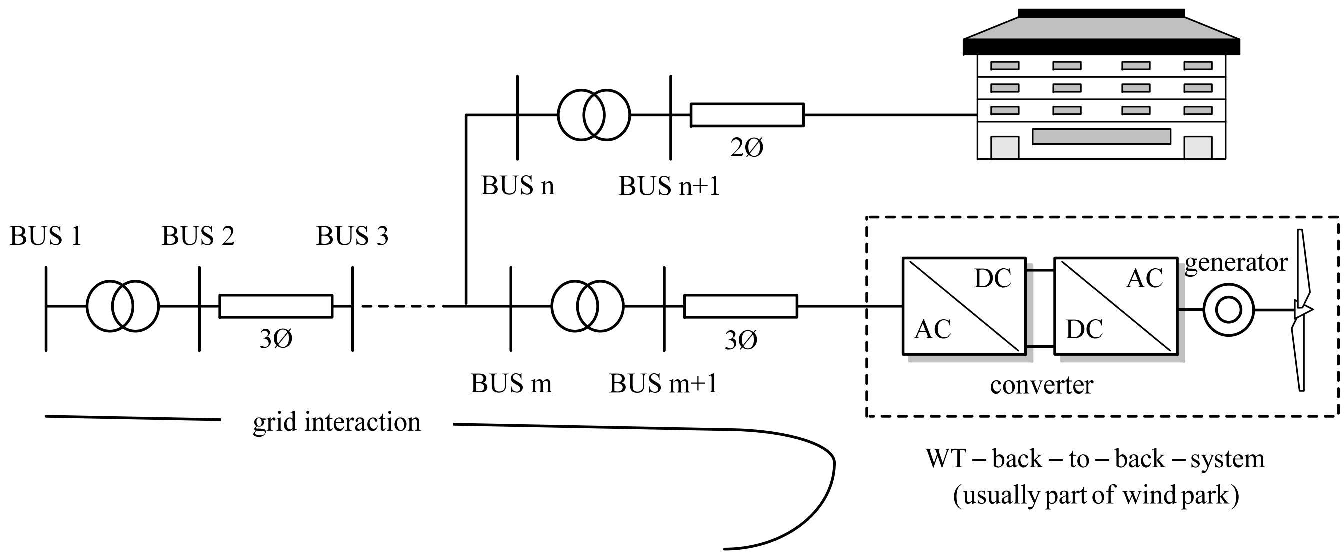
Practical Examples: PV-system

- The High-Voltage/Medium-Voltage transformer as well as a three-phase cable to the MV transformer introduce only a small impedance
- If the PV-house is located in a remote area the medium voltage line can be very extended (hundreds of km's) and its cables can introduce reactive reactance
- The MV/LV transformer introduces a reactance that could be considerably higher in locations where the transformer rated power is considerable lower
- Then the low voltage cable introduces a prevalently resistive impedance that varies with the distance of the PV-inverter from the transformer
- Capacitive loads (e.g. refrigerators) could introduce a capacitive impedance that can create low frequency resonances



Practical Examples: WT-system

- The system is similar to the previous one (hence also in this case a radial plant typical of a rural zone can introduce a very high impedance) up to the MV/LV transformer, to which the wind turbine converter is connected
- Hence the impedance seen by the grid connected inverter can be mainly inductive and can be different depending on the plant configuration
- However, the system present less interaction with domestic loads, avoiding possible low frequency resonances



Practical Examples: issues

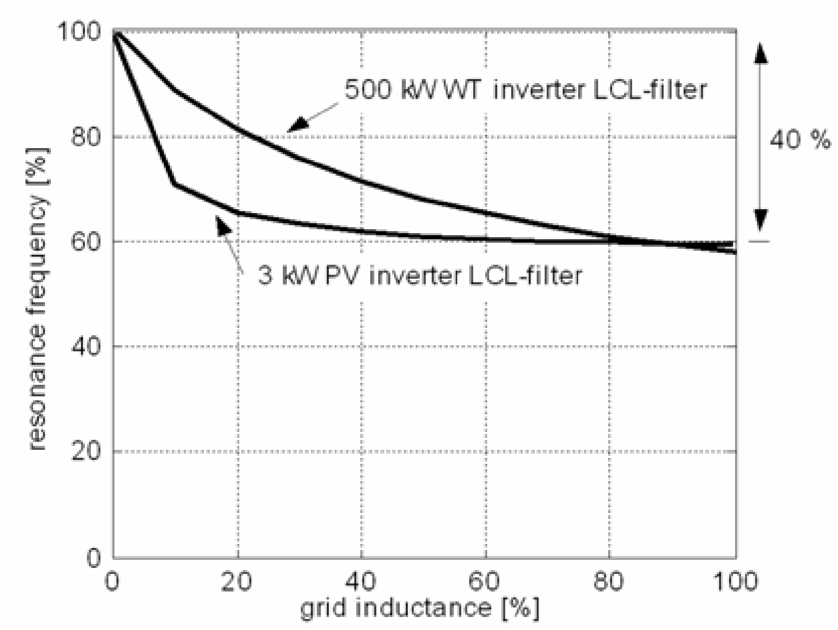
The impedance variation leads to dynamic and stability problems:

- in the low frequency range (around the current controller bandwidth frequency), it challenges the design of harmonic compensators adopted to mitigate the effect of the grid harmonic distortion on the grid current. In fact if the proportional gain of the current loop is chosen such as the low frequency complex conjugate poles, that depend on the grid side time constant, are optimally damped, when the inverter is connected to a highly inductive grid, i.e. with a higher time constant, the selected proportional gain is insufficient, the system is too slow and the harmonic controllers stay outside the bandwidth, making the system unstable.
- in the high frequency range (around the LCL-filter resonance frequency) it influences the frequency characteristic of the filter and the design of passive or active damping (to ensure stability) becomes more difficult

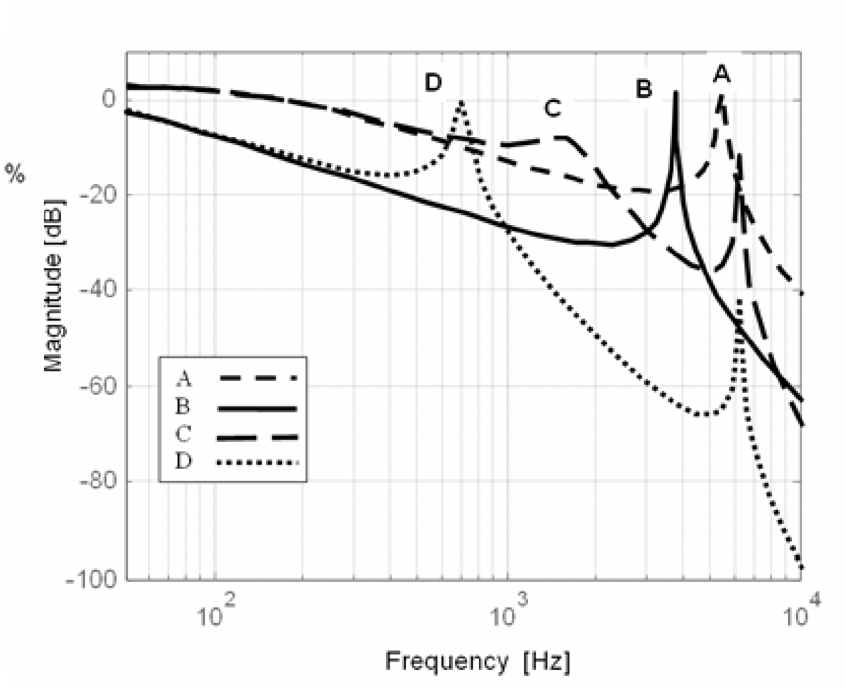
Example of two systems 500 kW WT and 3 kW PV

		500 kW WT system		3 kW PV-system	
LCL-filter	Boost inductance	0.2 mH	23 %	0.4 mH	1 %
	Grid side inductance	0.03 mH		0.2 mH	
	Filter capacitor	83 μF	1 %	5 μF	3 %
Grid impedance	Maximum value (weak grid)	0.03 Ω (inductive)	10 %	2.7 Ω (41% inductive)	15 %
	Minimum value (stiff grid)	0.003 Ω (inductive)	1 %	0.4 Ω (resistive)	2 %

Example of two systems 500 kW WT and 3 kW PV



Variable inductance

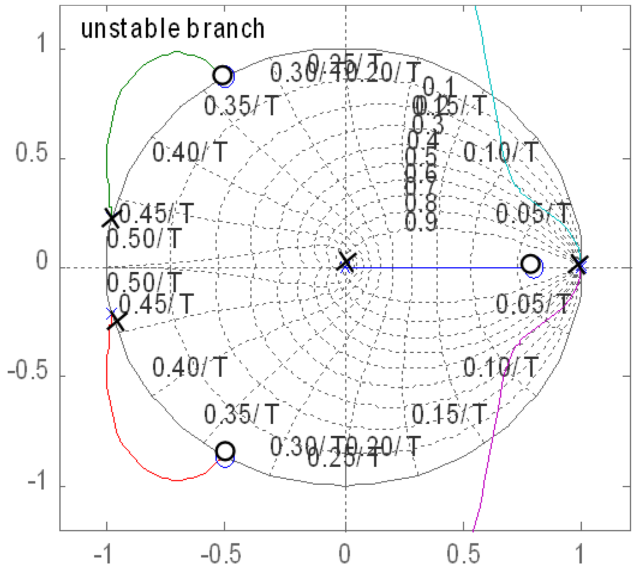


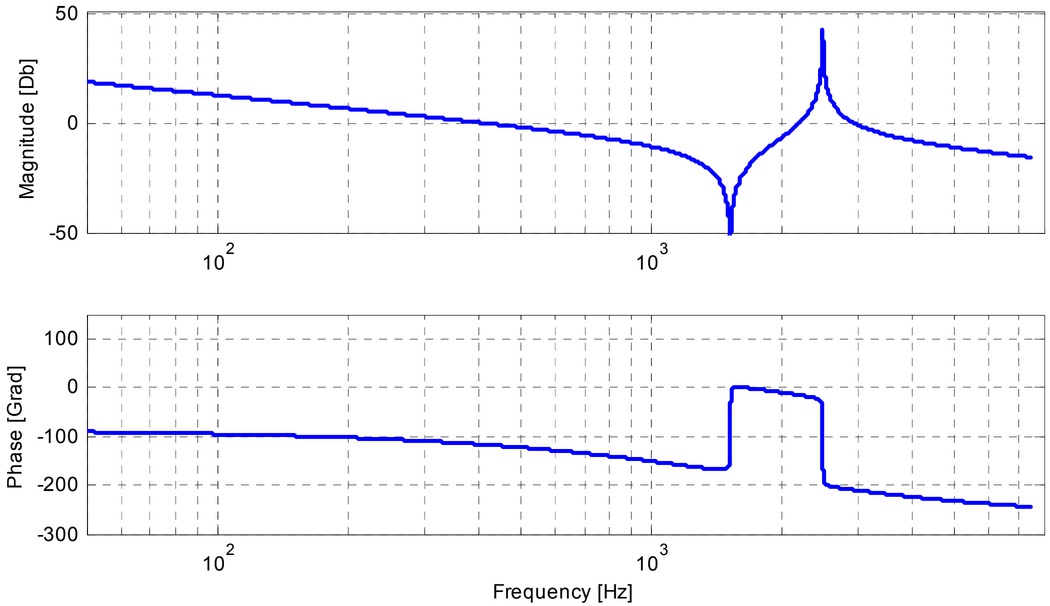
Introduction of $100\ \mu F$ capacitance

Considerations

- LCL-filter effectiveness changes with the grid stiffness
- Damping is difficult since the plant changes with the grid stiffness (active one is more flexible)
- The grid stiffness influence can be limited using more inductance in the filter but it leads to a bulky inverter and to packaging problems (i.e. the automatic mounting of the components is not possible) in case of PV systems
- The presence of capacitive loads create other resonance peaks, active damping can be effective also in these cases

Resonance problems and damping solutions



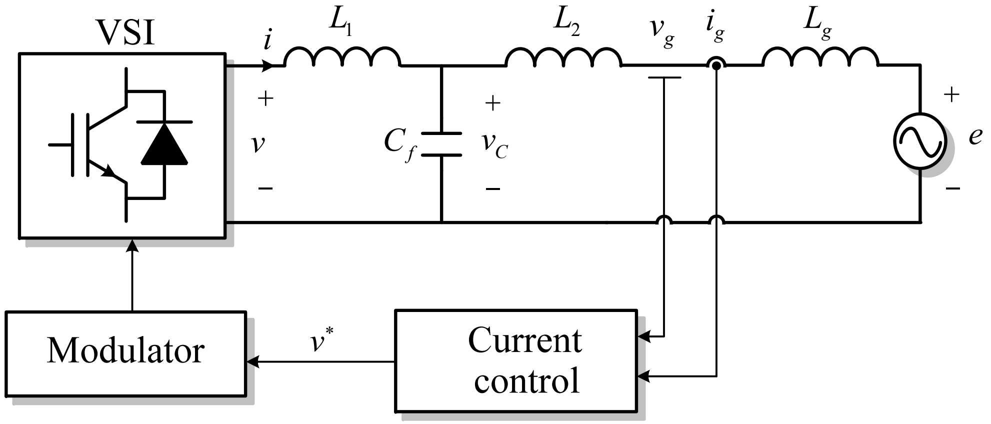


- The LCL-filter challenges the system stability
- There is a resonant peak associated to two resonant poles
- Their position changes as the grid inductance changes

Resonance problems and damping solutions

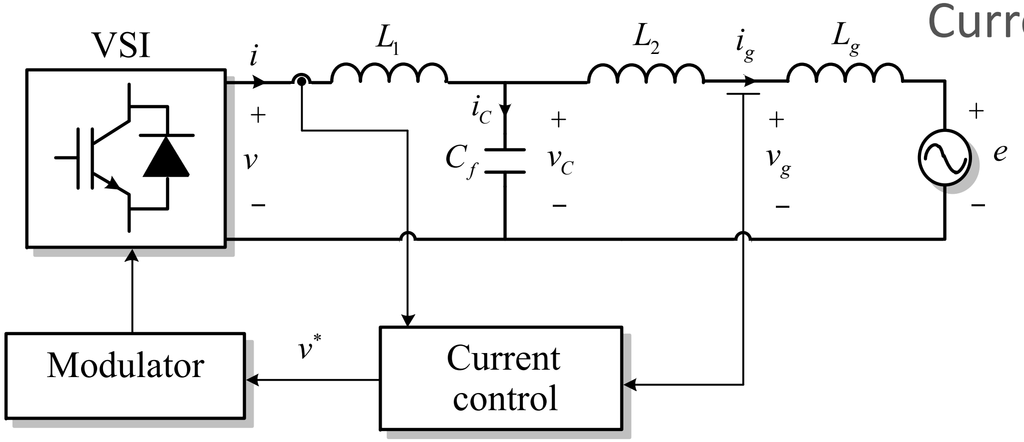
- The plant depends on the position of the current sensors: grid-side (more typical in low power PV-system) or converter-side (more typical in high power WT-system)

Current sensors on the grid side



$$G_f(s) = \frac{i(s)}{v(s)} = \frac{1}{Ls} \frac{z_{LC}^2}{\left(s^2 + \omega_{res}^2\right)}$$

Current sensors on the converter side

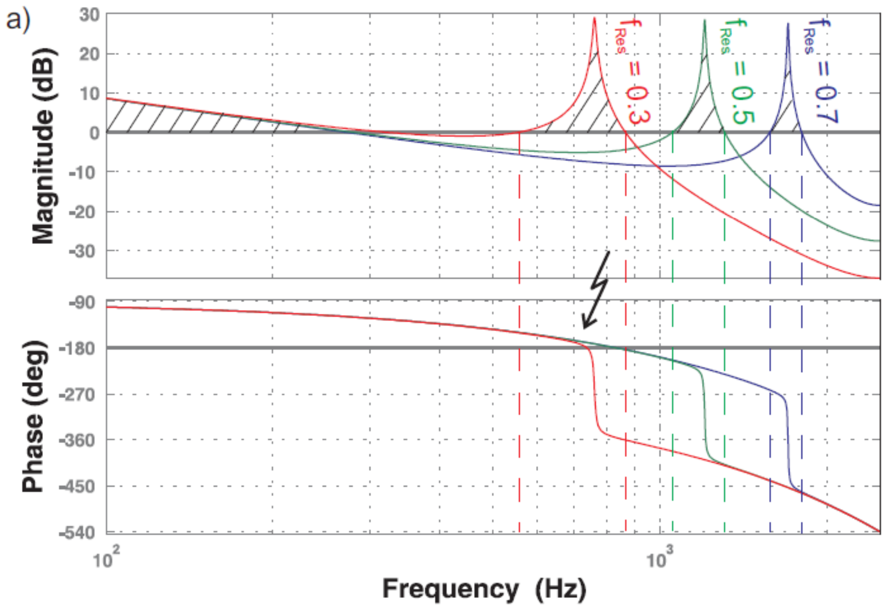


$$G_f(s) = \frac{i(s)}{v(s)} = \frac{1}{Ls} \frac{\left(s^2 + z_{LC}^2\right)}{\left(s^2 + \omega_{res}^2\right)}$$

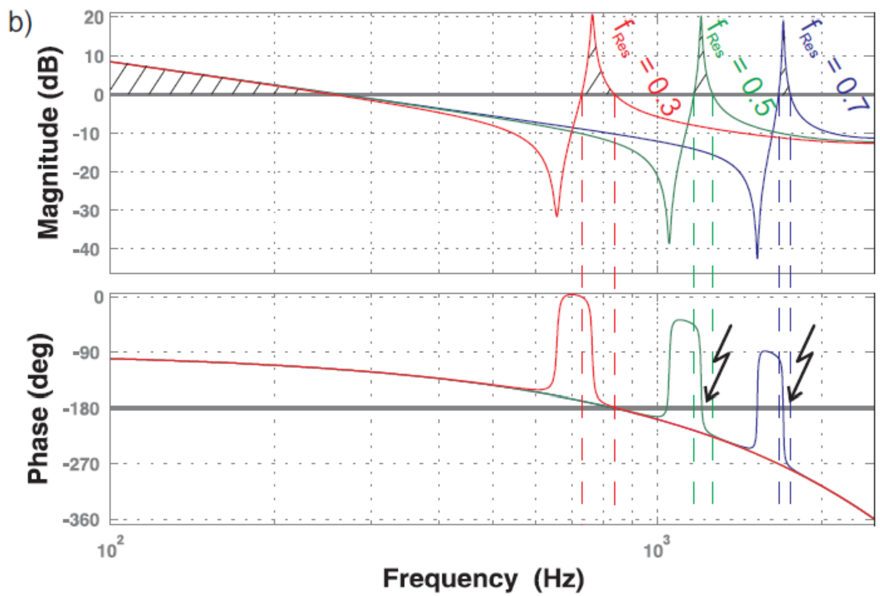
Resonance problems and damping solutions

- Sensing the grid current create conditions more favorable for the stability if the resonance frequency is high

Current sensors on the grid side



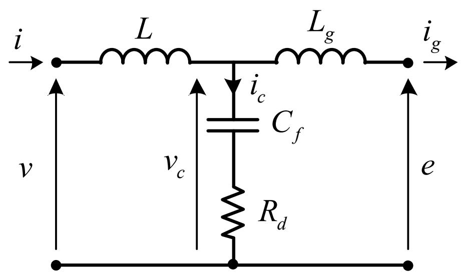
Current sensors on the converter side

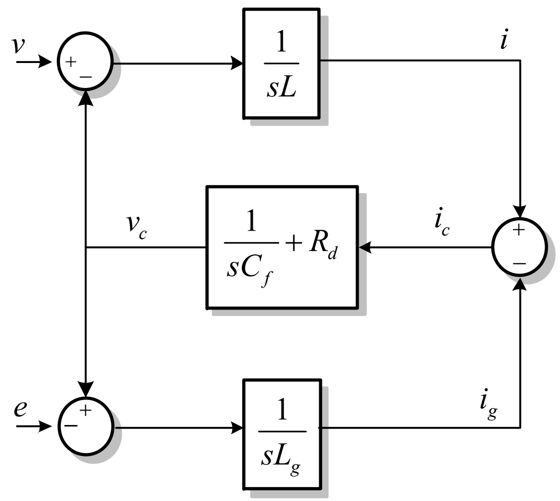


J. Dannehl, M. Liserre, F. Fuchs, F.; , "Filter-based Active Damping of Voltage Source Converters with LCL-filter," IEEE Transactions on Industrial Electronics, 2011.

Passive damping

- As the damping resistor increases, both stability is enforced and the losses grow but at the same time the LCL-filter effectiveness is reduced





Losses

$$P_d = 3R_d \sum_h \left[i(h) - i_g(h) \right]^2$$

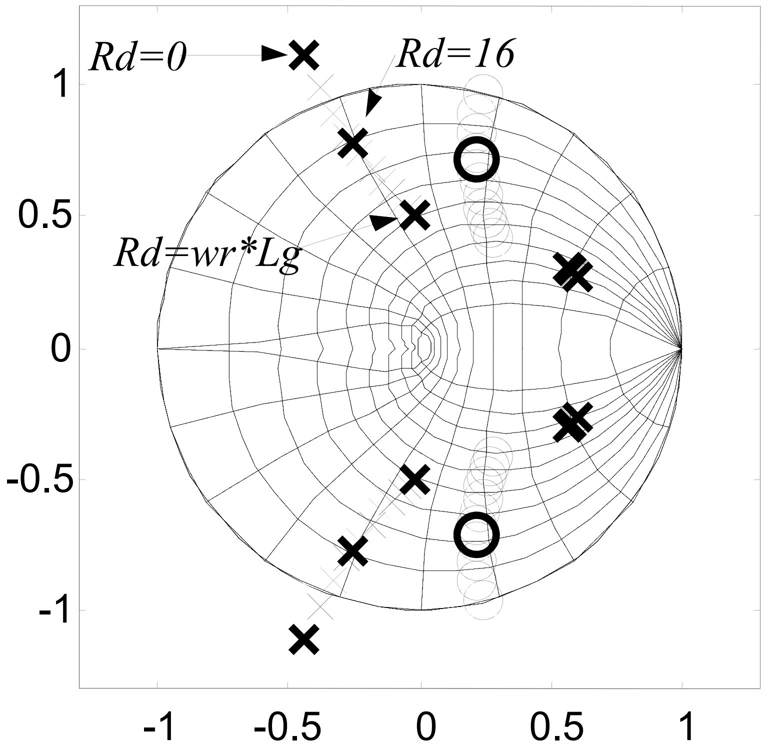
- Main terms of the sum are for the index h near to the multiples of the switching frequency order

f_{sw}	5 kHz	6 kHz	7kHz	8 kHz
abs value	32 W	20 W	13 W	10 W
% of rated power	0.8 %	0.5 %	0.3 %	0.2 %

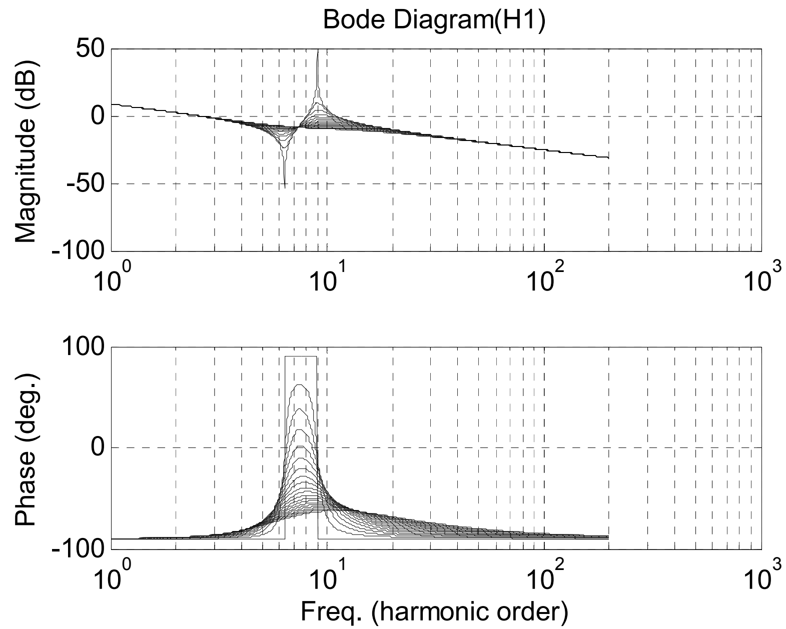
Increasing the switching/sampling frequency, the losses decrease but at the same time the damping becomes less effective

Passive damping

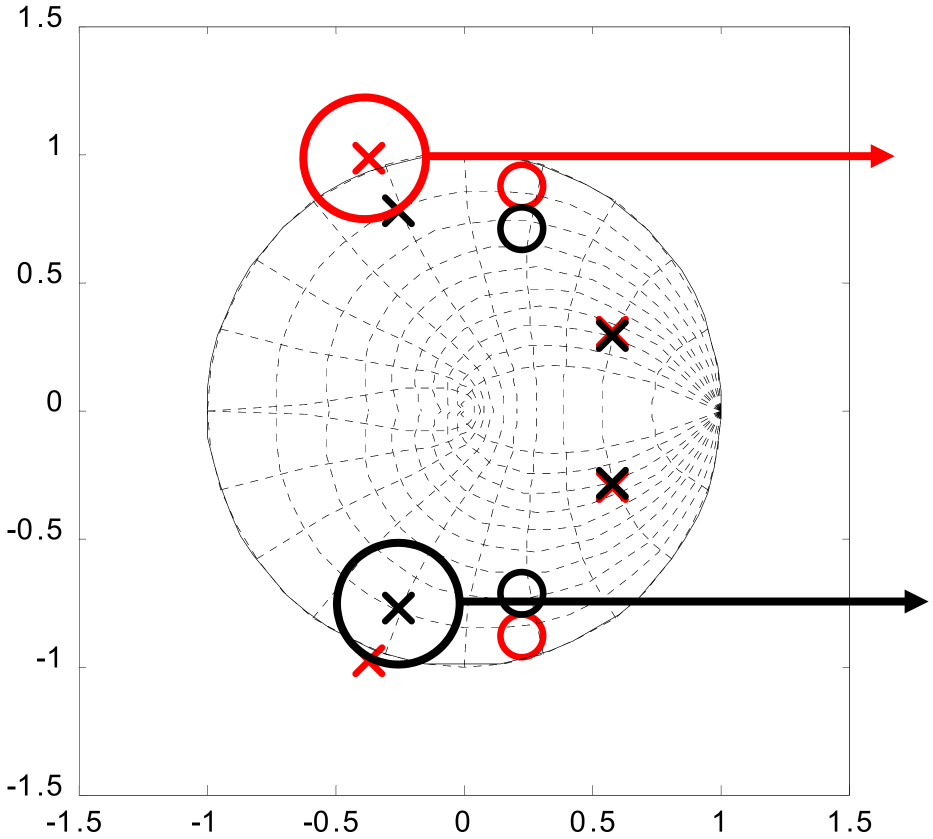
Root locus

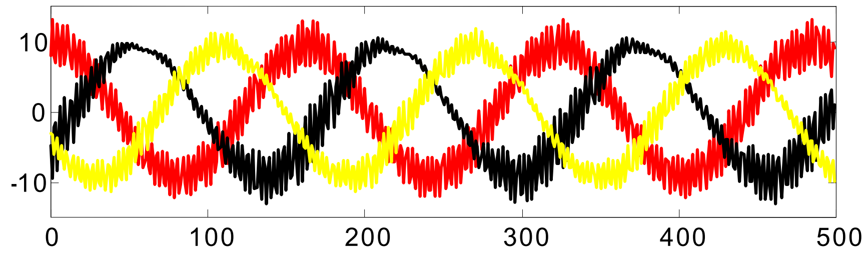


Bode plot

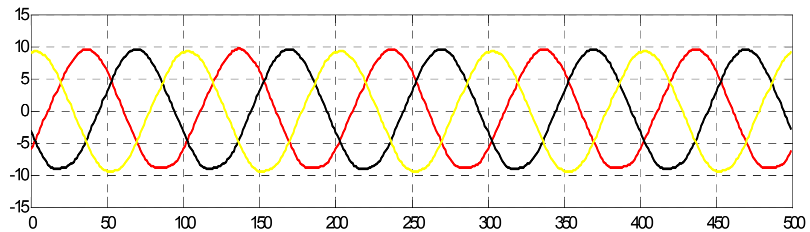


Passive damping



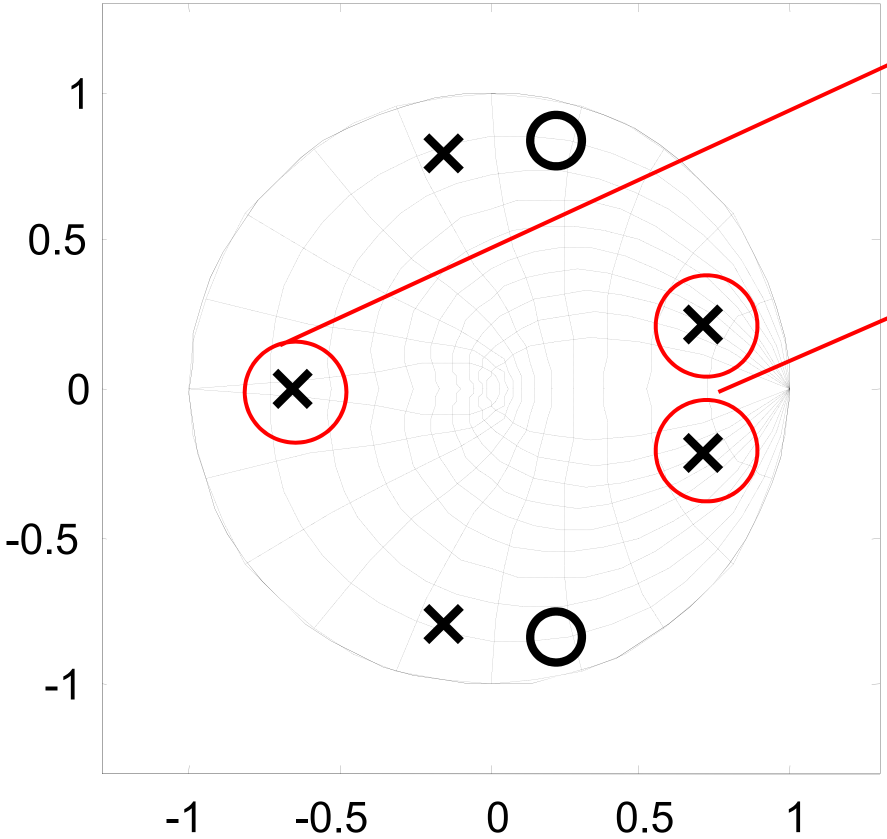


Converter side current



Passive damping in case of one delay in the control loop

Root locus

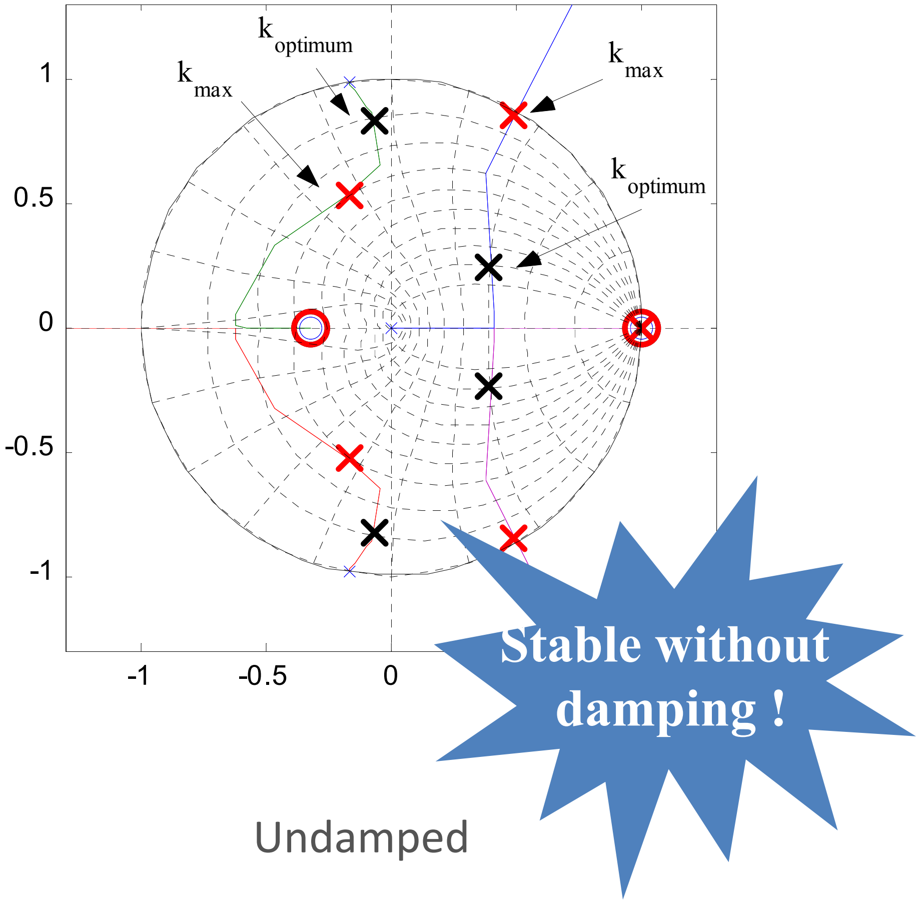


Pole introduced by the delay

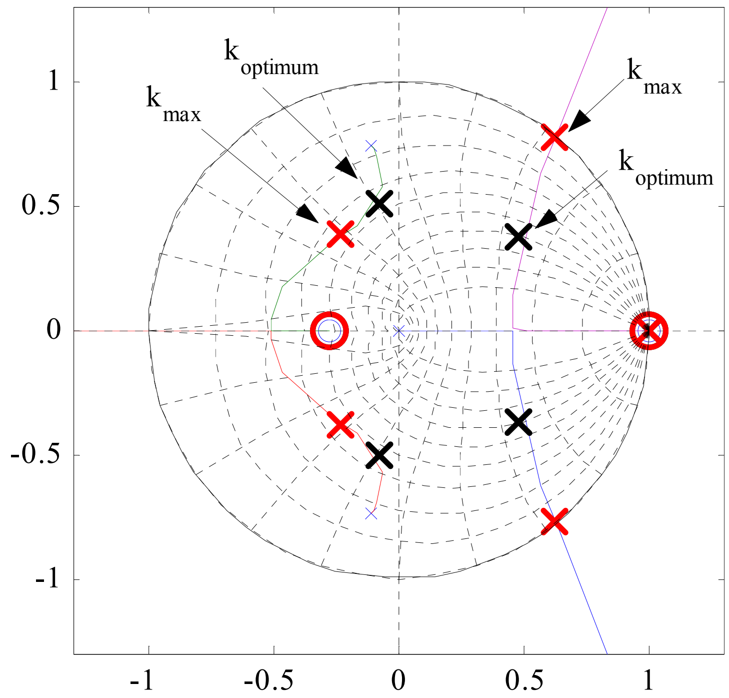
Reduction of the bandwidth from 350 Hz to 200 Hz

Good method to reduce losses in high power applications at the price of a slow down of the dynamic, as a consequence in case of voltage sag an higher overcurrent is obtained

Passive damping in case of control of the grid current



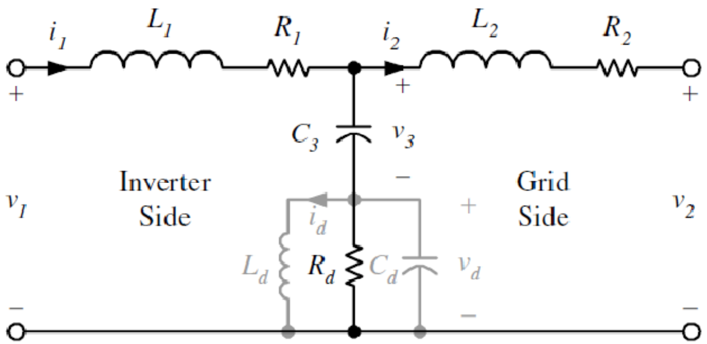
Undamped

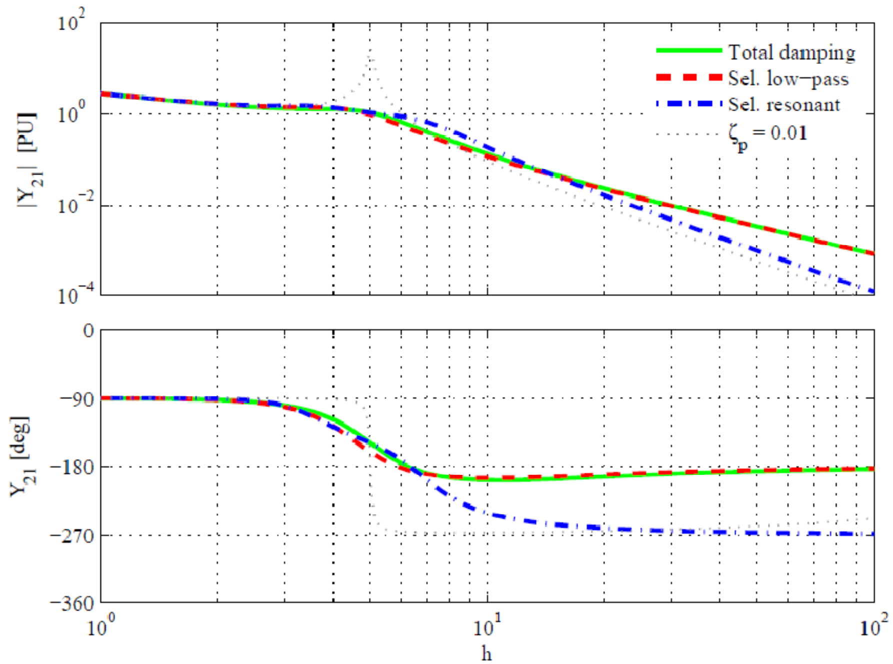


Passively damped

Passive damping: selective damping

Higher power DPGS (like MW WT-systems) switch at low frequency and resonance frequency needs to be damped selectively

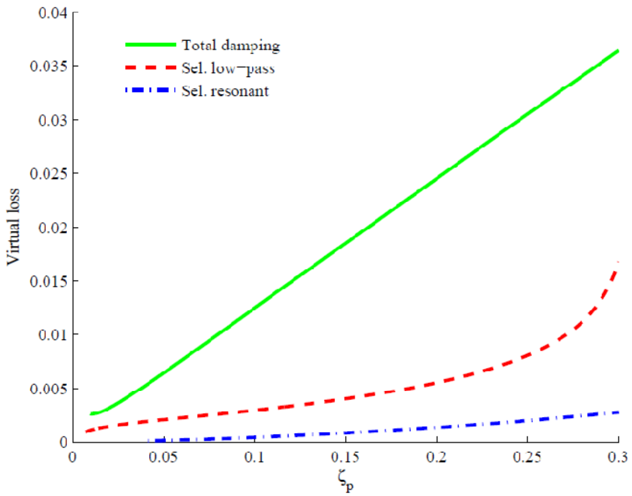




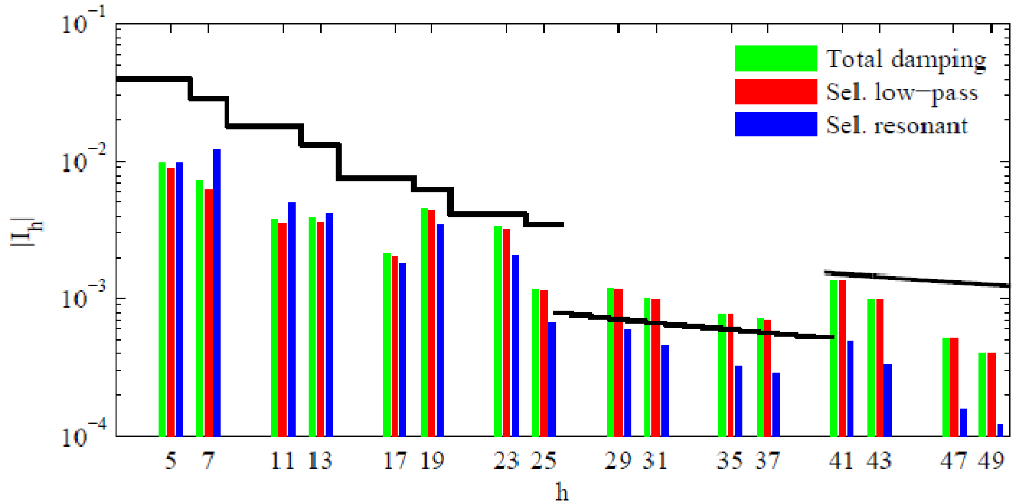
Damping resistor in parallel with inductor and capacitor to achive selective damping

Passive damping: selective damping

Virtual Losses



Harmonic Spectrum

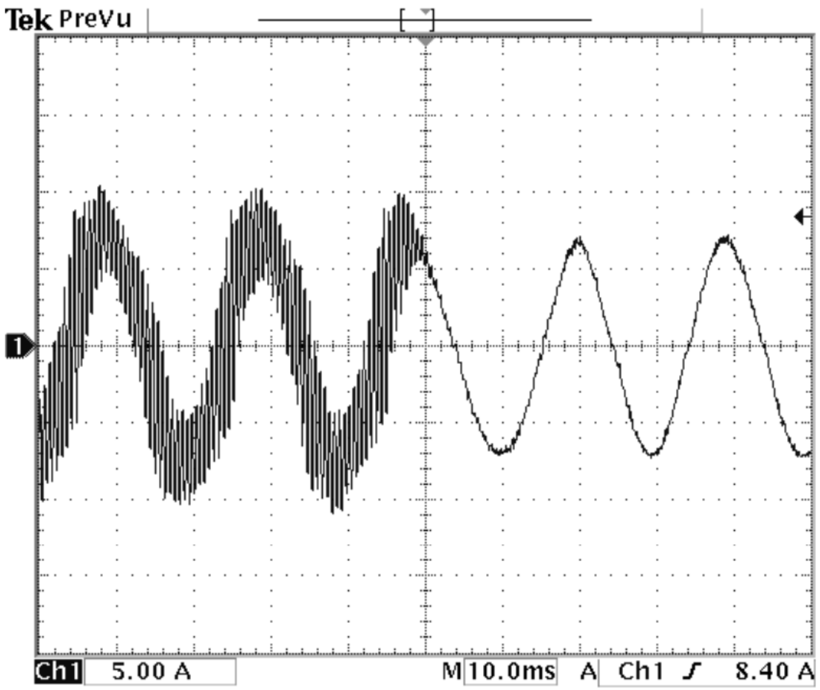


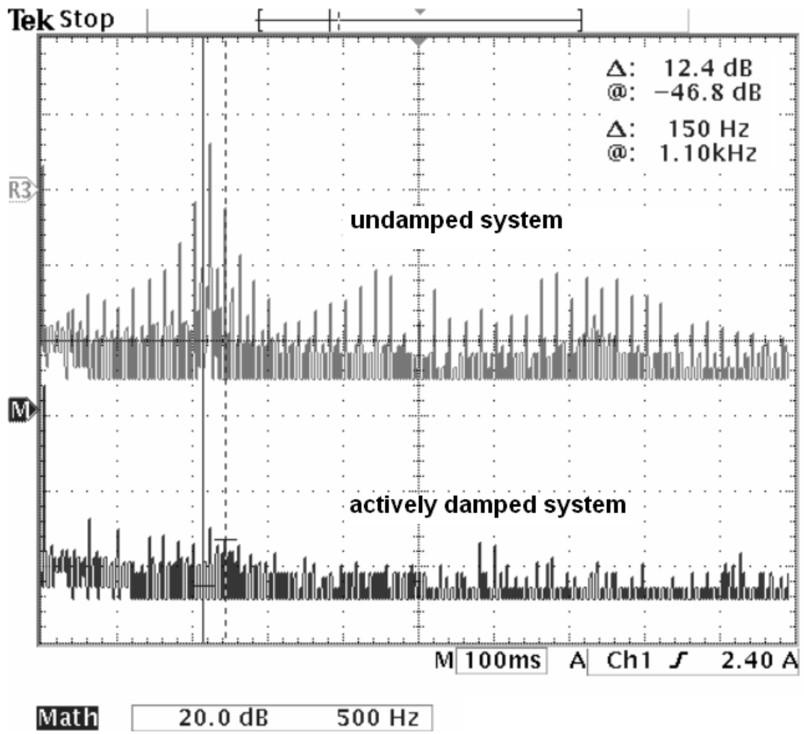
A. Rockhill, M. Liserre, R. Teodorescu, P. Rodriguez, "Grid Filter Design for a Multi-Megawatt Medium-Voltage Voltage Source Inverter," IEEE Transactions on Industrial Electronics, 2011.

Active damping

- Obtain stability without additional losses
- Modify the control algorithm
- Various techniques based also on the use of more sensors
- Two main possibilities:
  - Multiloop
  - Filter-based

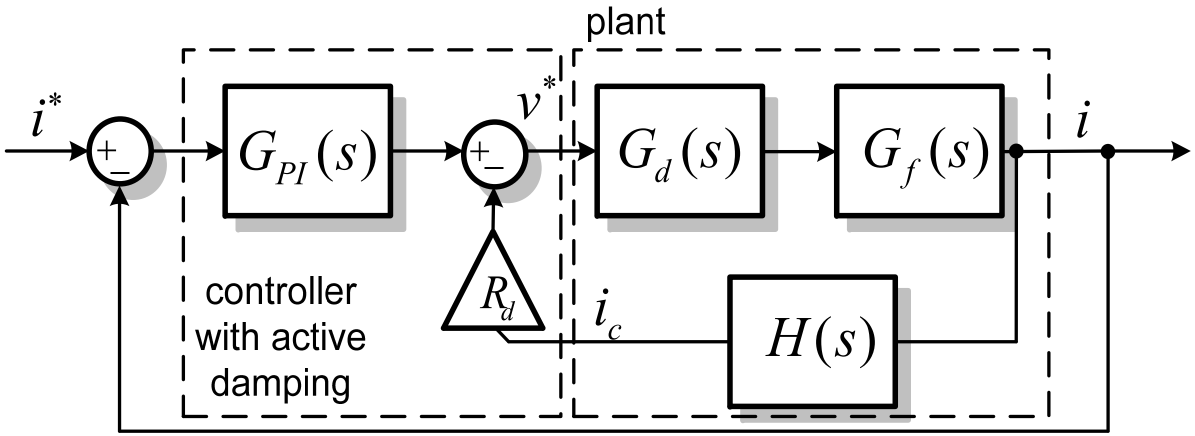
Active damping

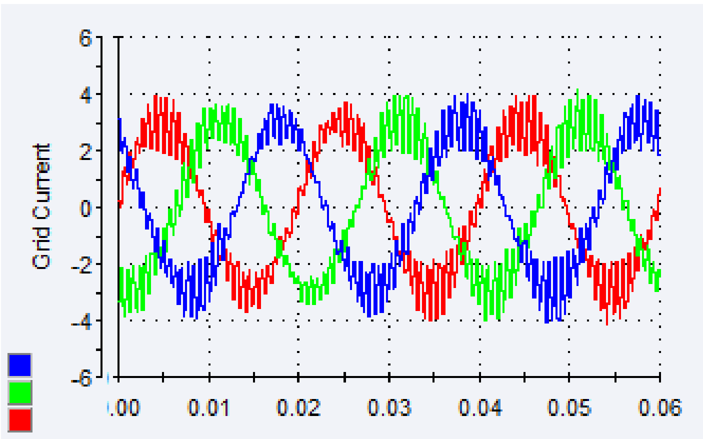




Active damping plug-in

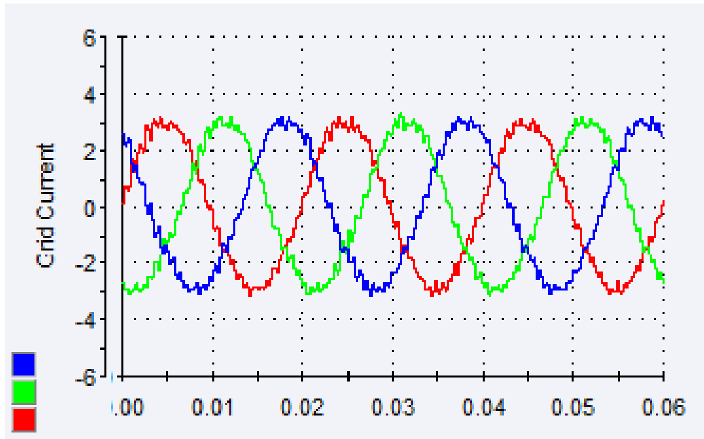
Multiloop methods: Virtual resistor



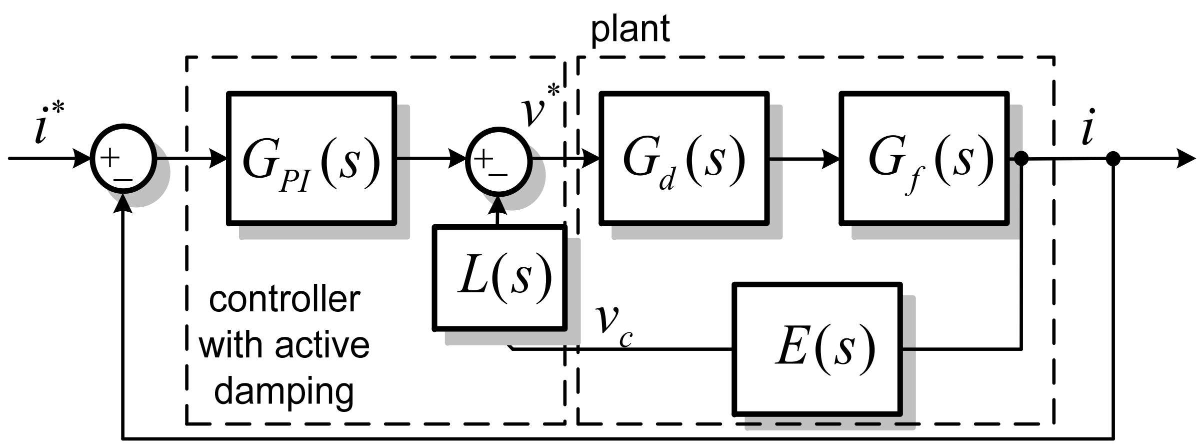


$R_d = 4$

$R_d = 14$



Multiloop methods: lead network

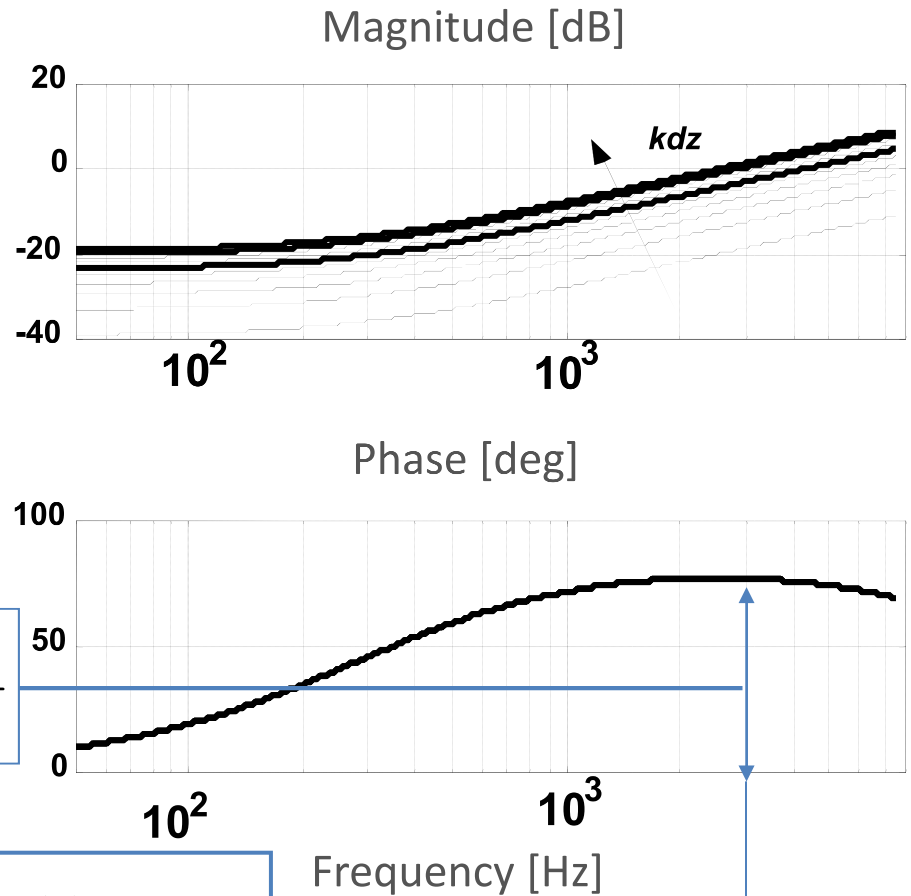


- The LCL-filter capacitor voltage should be measured or estimated
- A lead network is used to create the control action that should damp the resonance adding phase lead

Multiloop methods: lead network

Lead network

$$L(s) = k_d \frac{T_d s + 1}{\alpha T_d s + 1}$$



Principle of operation

$$\phi_{MAX} = arcsin \frac{1-\alpha}{1+\alpha}$$

$$f < \frac{1}{T_d} \rightarrow L(s) = k_d \qquad f \geq \frac{1}{\alpha T_d} \rightarrow L(s) = 10 k_d$$

$$f_{MAX} = \frac{1}{T_d \sqrt{\alpha}}$$

Multiloop methods: lead network

- The increase of the lead ratio $\boxed{1/\alpha}$ increases the phase lead but it produces higher amplifications at higher frequencies
- Adopting a low-pass filter, it is possible to select a high phase margin ($80°$) around the resonance frequency (2.5 kHz)

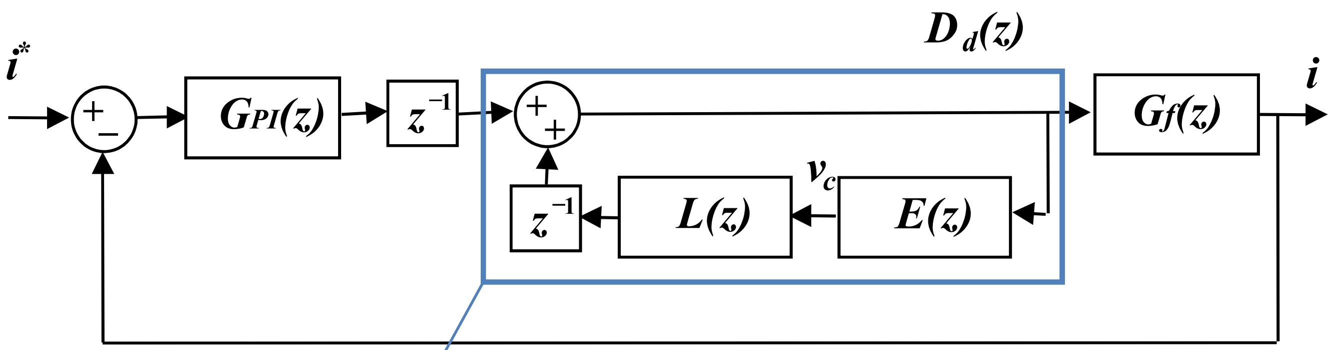
$$T_d = 5.6*10^{-4} \qquad a = 1.2*10^{-2}$$

k_d has to be chosen both on damping and dynamic considerations

Discretization → $L(z) = k_{dz} \dfrac{z + z_o}{z + p_o}$

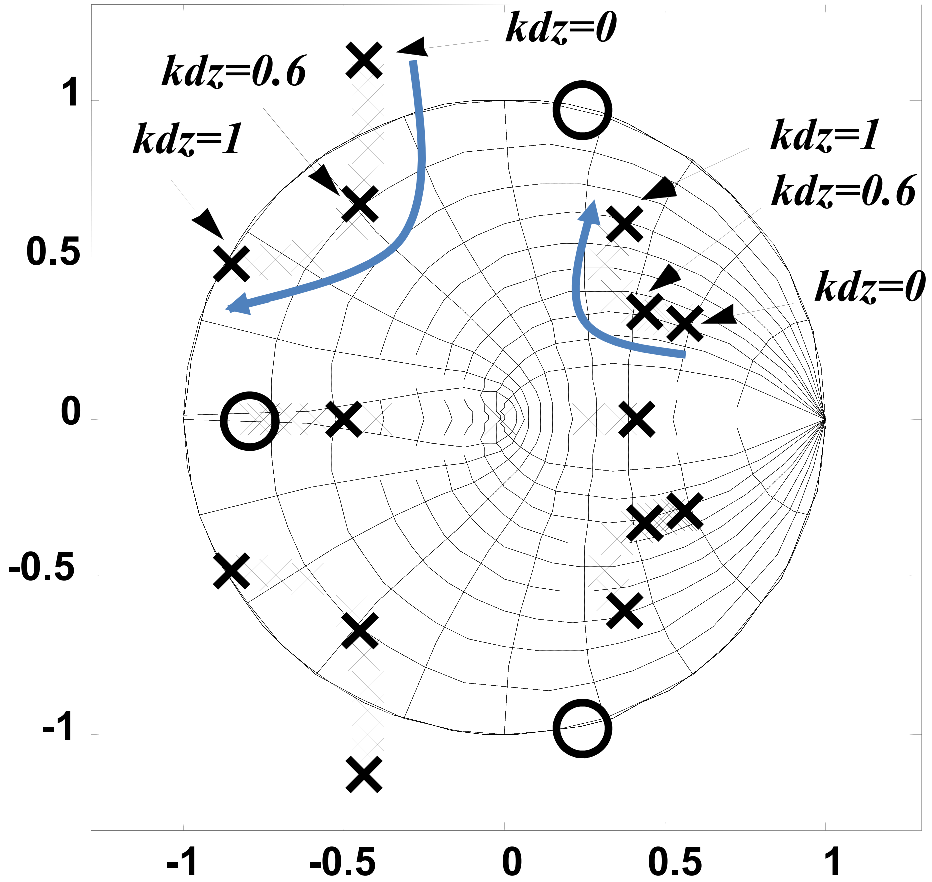
Multiloop methods: lead network

- Instead of a low-pass filter it is enough to select carefully the lead network position



$$\boxed{D_d(z) = \frac{1}{1 - z^{-1}L(z)E(z)}} = \begin{cases} 1 \text{ for } f < 1.8 \text{ kHz because of the lead network} \\ \text{introduce phase lead for } f \in [1.8 \div 4] \text{ kHz} \\ 1 \text{ for } f > 4 \text{ kHz because of } \quad E(s) = \dfrac{1}{LC_f}\dfrac{1}{\left(s^2 + \omega_{res}^2\right)} \end{cases}$$

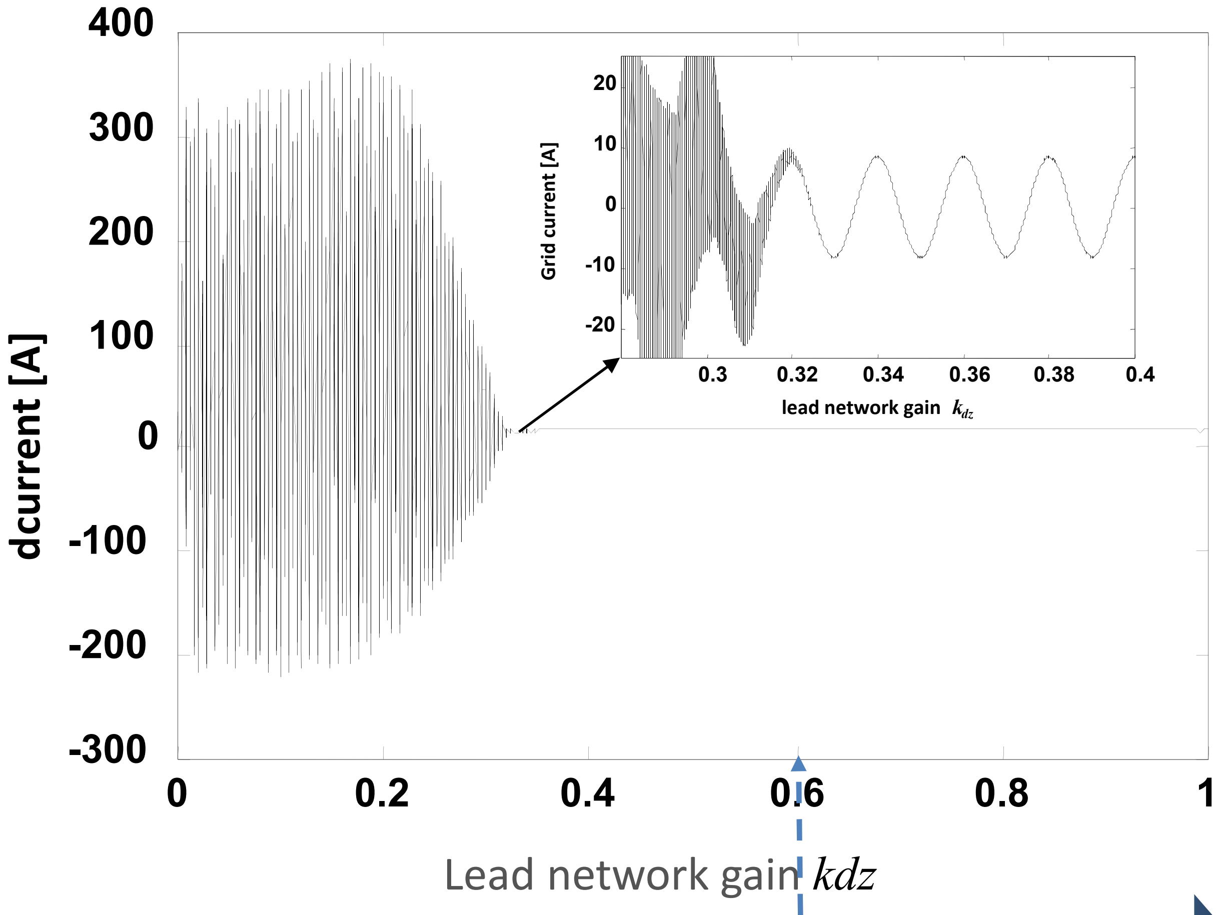
Multiloop methods: lead network



$kdz = 0.6$

- Best damping
- Good dynamic

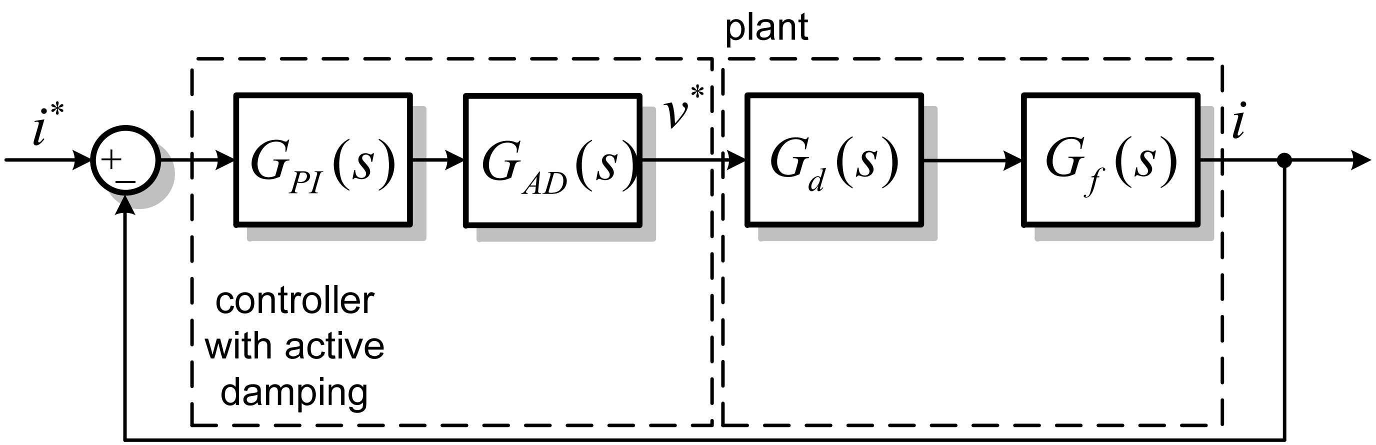
Multiloop methods: lead network



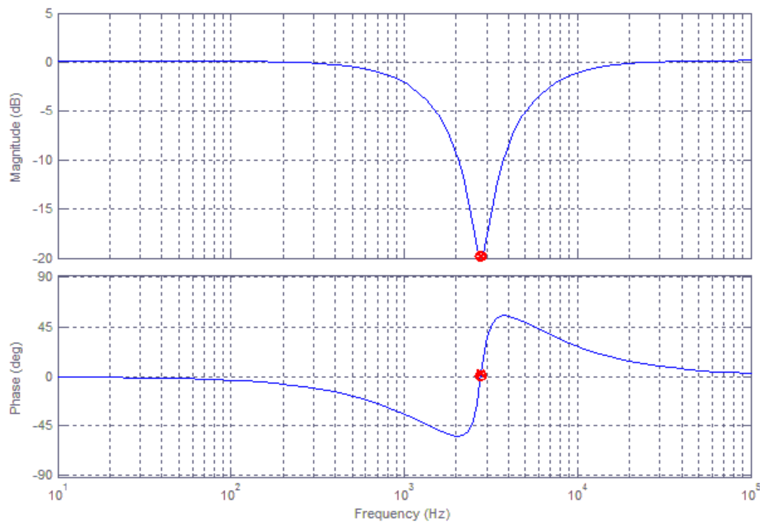
$$THD = 1.6\%$$
$$THFHD = 0.6\%$$

Optimum steady-state performance

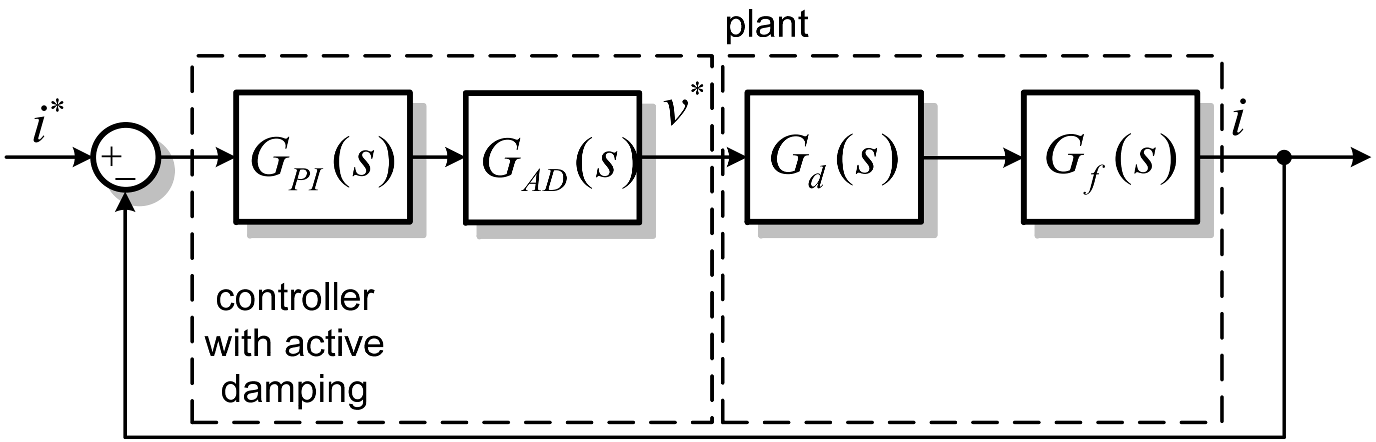
Filter-based methods: Notch filter



- The notch filter is tuned at the resonance frequency



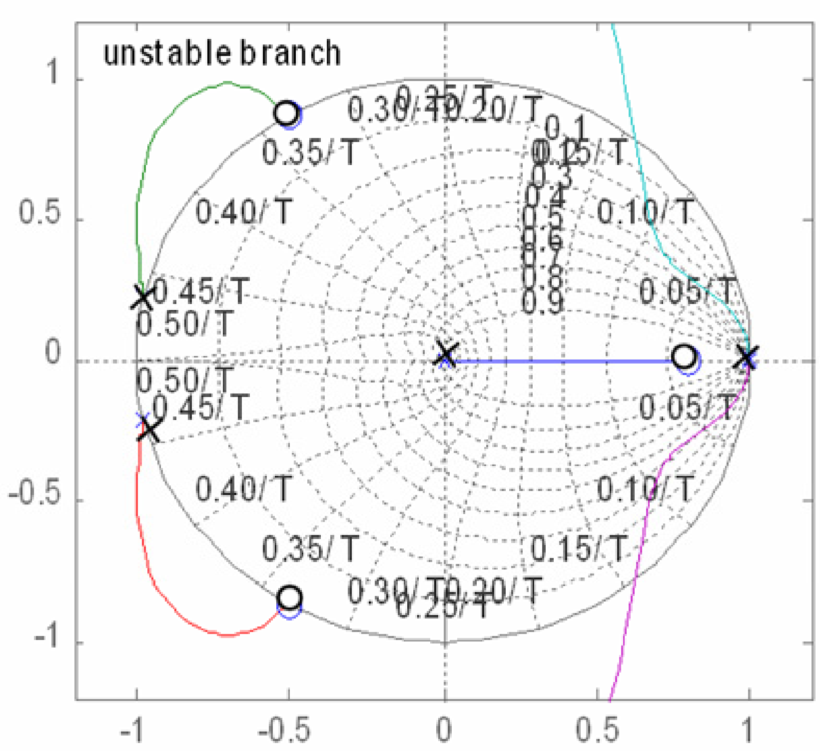
Filter-based methods: Bi-quad filter



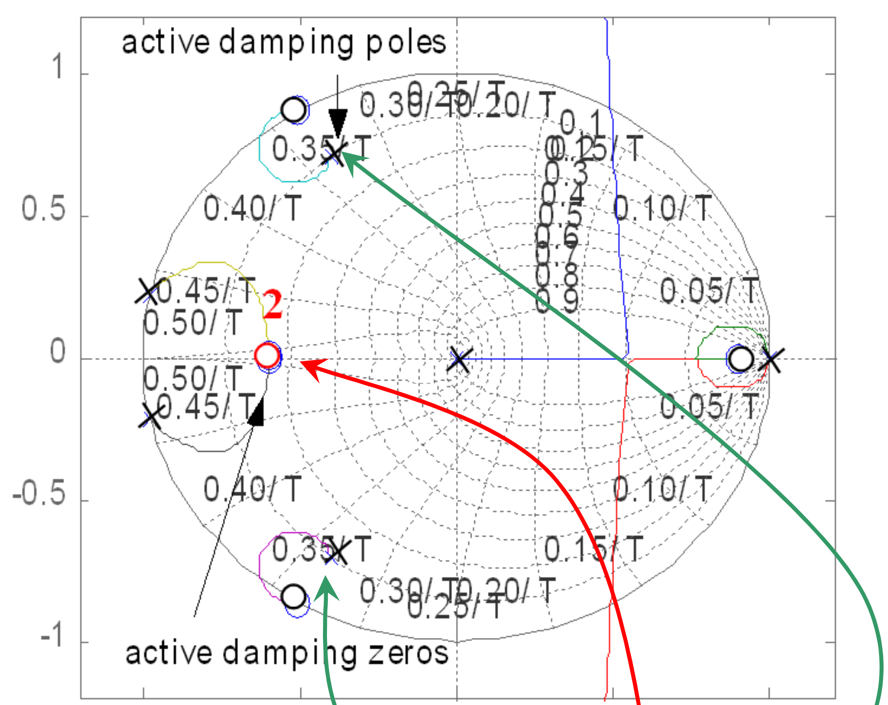
- The bi-quad filter complex conjugate zeros and poles have different frequencies
- They can be used to cancel resonance and anti-resonance

$$G_{AD}(s) = \frac{s^2 + 2D_p\omega_p s + \omega_p^2}{s^2 + 2D_z\omega_z s + \omega_z^2}$$

Filter-based methods: Bi-quad filter



Undamped



$$G_{AD}(z) = \left[\frac{z^2 - z_o^2}{z^2 - p_o^2}\right]$$

Non-linear behavior of the filter: average model

- The describing function method has been widely used to determine the dynamic behaviour of nonlinear systems. The describing functions method can be used to linearise the nonlinear characteristic of the inductor and estimate the average inductance value

$$L = \frac{\Phi(i)}{i}$$

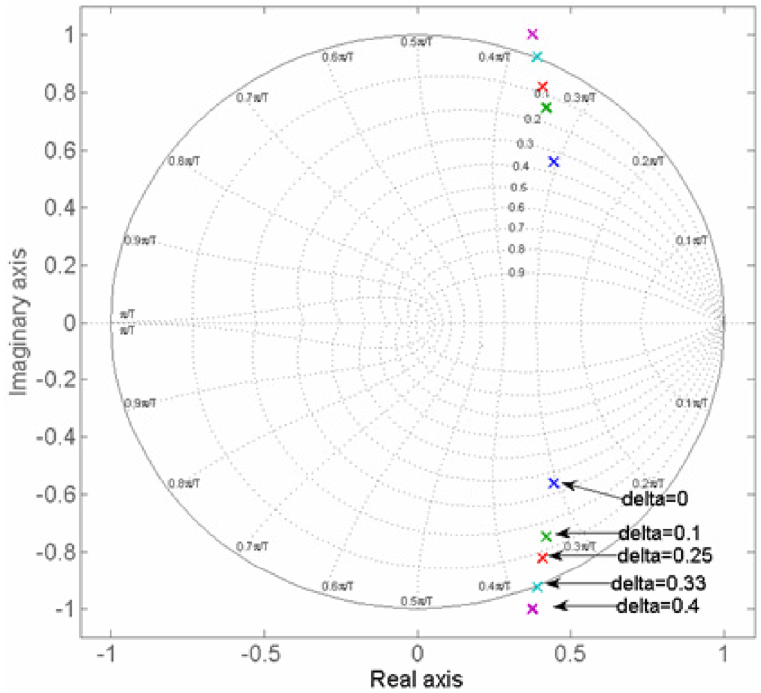
$$\int_0^T \frac{1}{L} dt = \left(\frac{\delta}{L_{sat}} + \frac{(1-\delta)}{L} \right) T$$

Where the interval of integration T can be chosen to be one period of the ac input current and δ is the portion of fundamental period (expressed in p.u.) for which the inductance has value L_{sat}

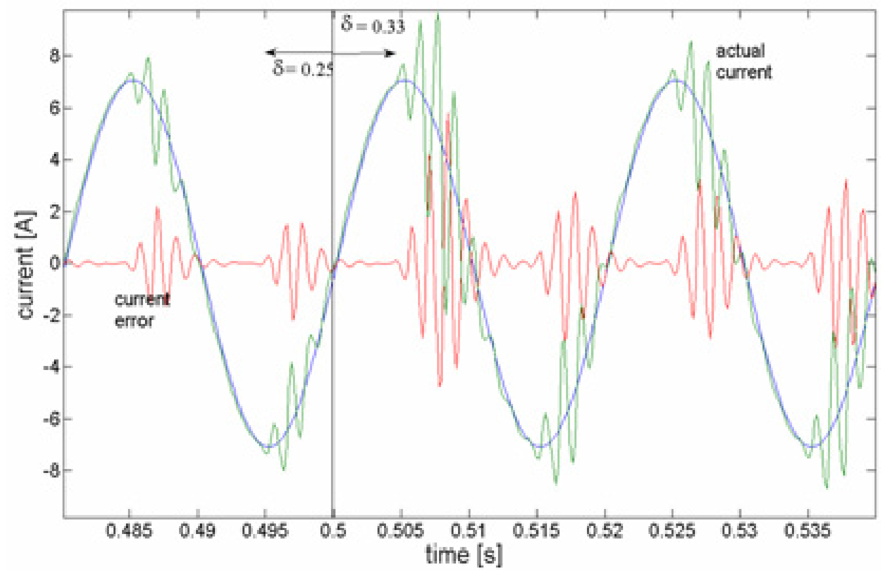
$$\frac{1}{L_{eq}} = \left(\frac{\delta}{L_{sat}} + \frac{(1-\delta)}{L} \right)$$

REF S.C. Chung, S.R. Huang and E.C. Lee, “Applications of describing functions to estimate the performance of nonlinear inductance”, IEE Proceedings-Science, Measurement and Technology, vol.48, no. 3, May 2001, pp.108-114

Non-linear behavior of the filter: Average inductor model results



Real and imaginary part of the closed loop of the PWM inverter system (with PI current controller) for variations of the degree of filtering inductance saturation from $\delta = 0$ to $\delta = 0.4$



Grid current (reference, actual and error) with resonant controller in case of increment of saturation from $\delta = 0.25$ to $\delta = 0.33$

saturation -> instability

Non-linear behavior of the filter: Piecewise linearizated inductor model

- A time-variant current dependent model can be developed on the basis of the piecewise linearization
- Two different cases of nonlinearities are considered: the saturation of the inductor, which occurs for high values of current, and a light nonlinearity of the first portion of the magnetization curve which occurs for very low value of current

$$\phi(i) = sat(i) = \begin{cases} Li_{sat} & i > i_{sat} \\ Li & i_{sat} \geq i \geq -i_{sat} \\ -Li_{sat} & -i_{sat} > i \end{cases}$$

$$\phi^*(i) = sat(i) = \begin{cases} L_1 i & i \leq i_s^* \\ L_2 i & i > i_s^* \end{cases}$$

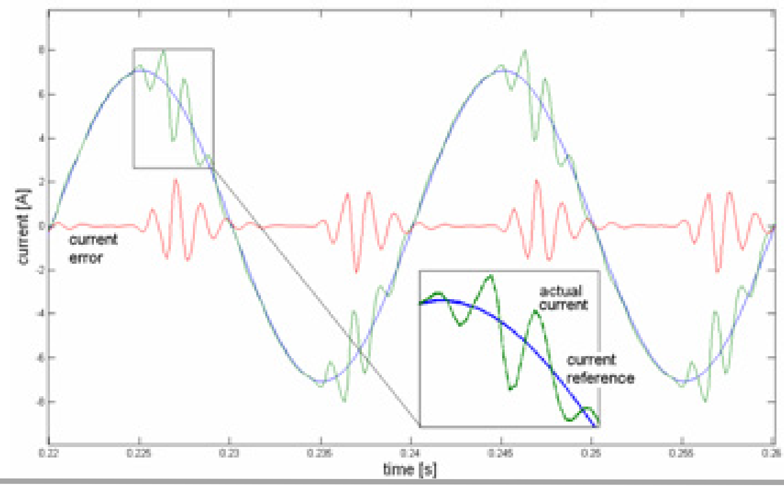
$$\frac{d(Li)}{dt} = e(t) - Ri(t)$$

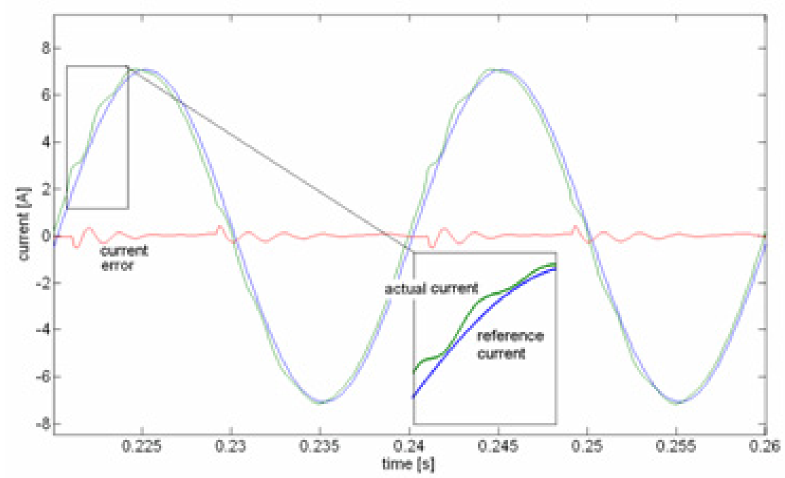
Non-linear behavior of the filter: Piecewise linearizated inductor results

$$\phi(i) = sat(i) = \begin{cases} Li_{sat} & i > i_{sat} \\ Li & i_{sat} \geq i \geq -i_{sat} \\ -Li_{sat} & -i_{sat} > i \end{cases}$$

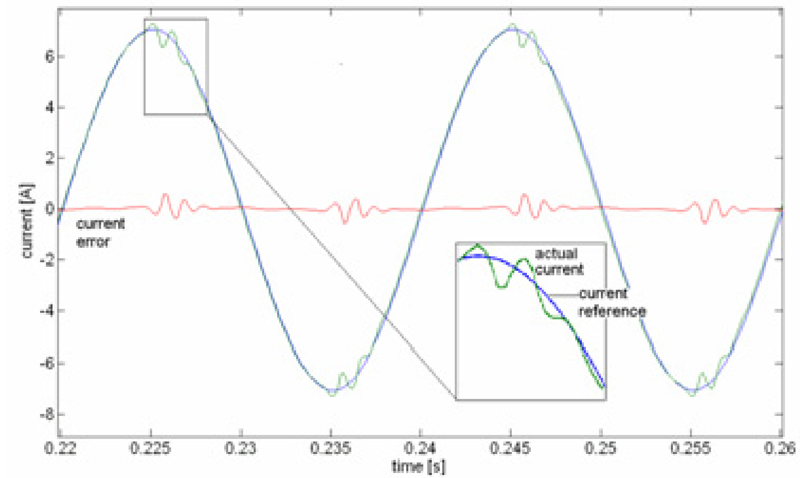
$$\phi^{*}(i) = sat(i) = \begin{cases} L_1 i & i \leq i_s^{\,*} \\ L_2 i & i > i_s^{\,*} \end{cases}$$

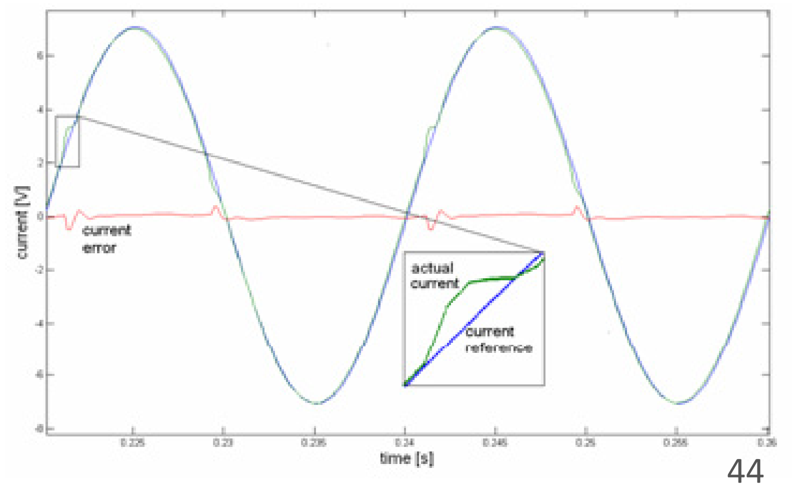
Resonant





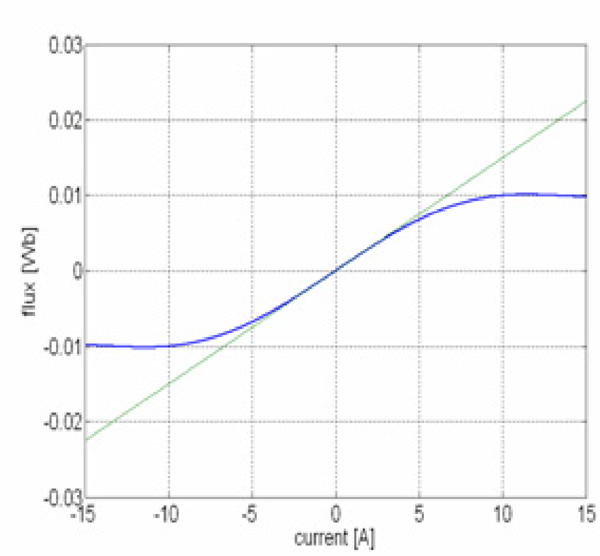
Repetitive





Non-linear behavior of the filter: Volterra-series expansion inductor model

- The frequency behaviour of the non-linear inductance can be studied splitting the model in a linear part and a non-linear part in accordance with the Volterra theory



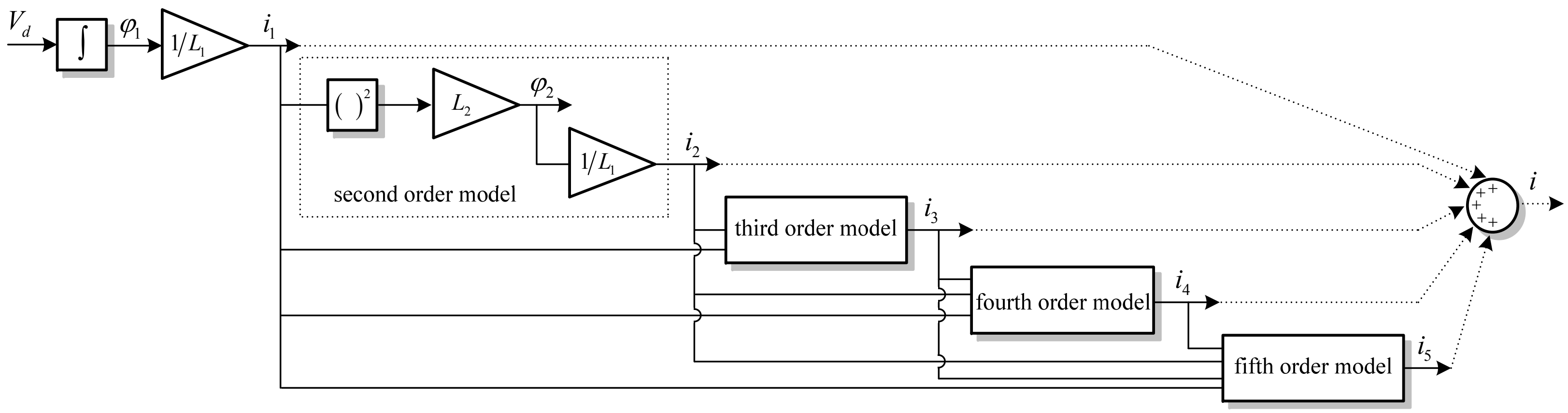
The Volterra-series expansion of the flux is $\varphi(t) \approx \sum_{i=1}^{5} \varphi_i(t)$

$$
\begin{cases}
\varphi_1(t) = L_1 i_1(t) \\
\varphi_2(t) = L_2 i_1^2(t) \\
\varphi_3(t) = 2L_2 i_1(t) i_2(t) + L_3 i_1^3(t) \\
\varphi_4(t) = 2L_2 i_1(t) i_3(t) + L_2 i_2^2(t) + 3L_3 i_1^2(t) i_2(t) + L_4 i_1^4(t) \\
\varphi_5(t) = 2L_2 i_1(t) i_4(t) + 3L_3 i_1^2(t) i_3(t) + 3L_3 i_1(t) i_2^2(t) + 4L_4 i_1^3(t) i_2(t) + L_5 i_1^5(t)
\end{cases}
$$

$\varphi_1(t)$ Is the first order response of the inductor which describes the behaviour in the linear case

$\varphi_i(t)$ Is the non-linear response of the inductor obtained using an appropriate excitation which is function of the lower order excitation

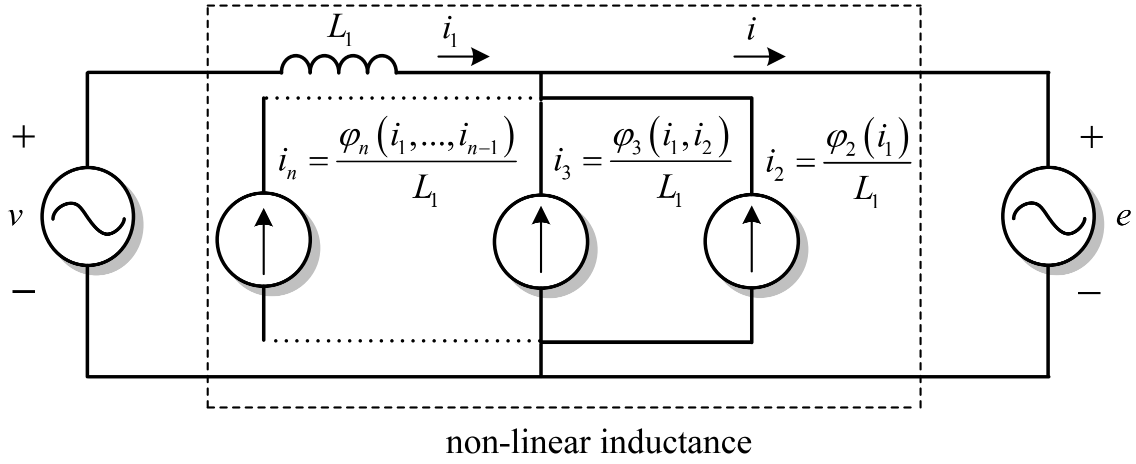
Non-linear behavior of the filter: Volterra-series expansion inductor model



Implementation of the non-linear inductance model

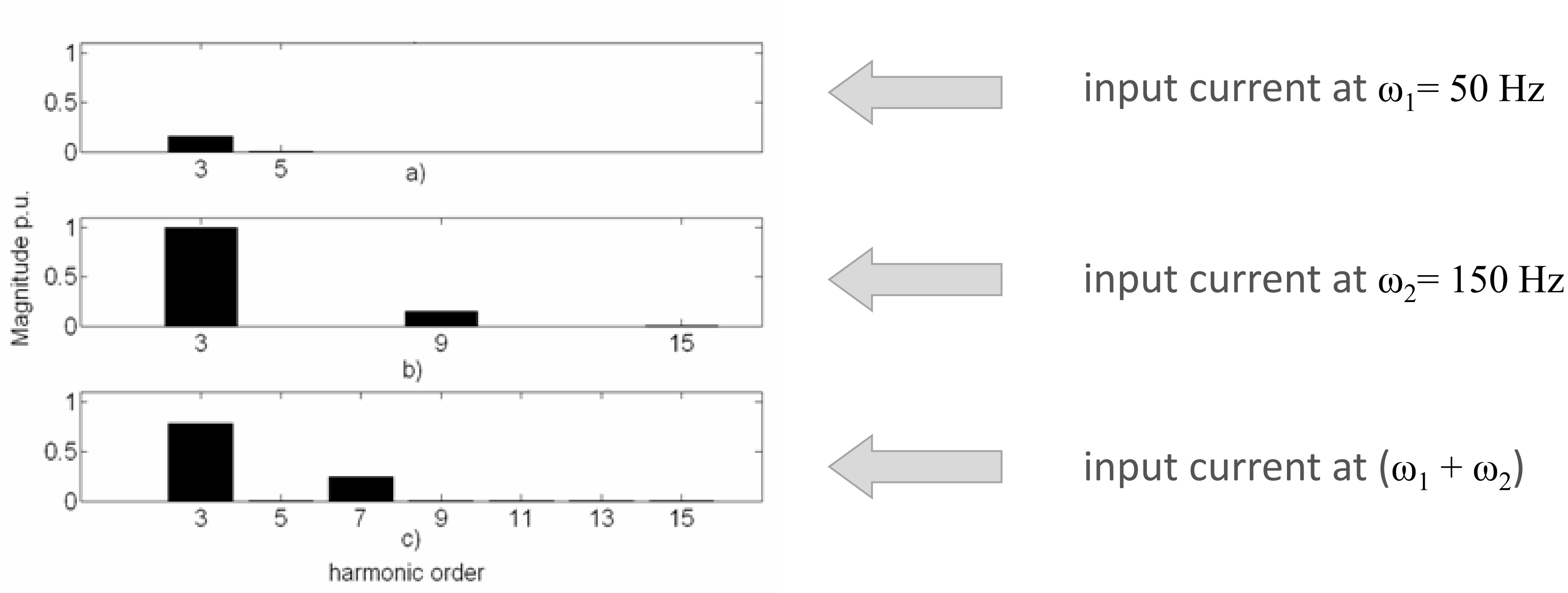
- The Volterra model allows calculating harmonics which are introduced in the systems as effect of the filter inductance saturation
- These harmonics can be modelled as external disturbances, hence they can be compensated by the resonant and repetitive controllers similarly to grid voltage harmonics
- This explains theoretically the effectiveness of the resonant and repetitive controllers in case of non-linear inductance

Non-linear behavior of the filter: Volterra-series expansion inductor model



- $i_i(t)$ through the non-linear inductor acts as an external source exciting the linear circuit
- It can be represented as an external source of current which is connected to the system between the converter and the grid

Non-linear behavior of the filter: Volterra-series expansion inductor results



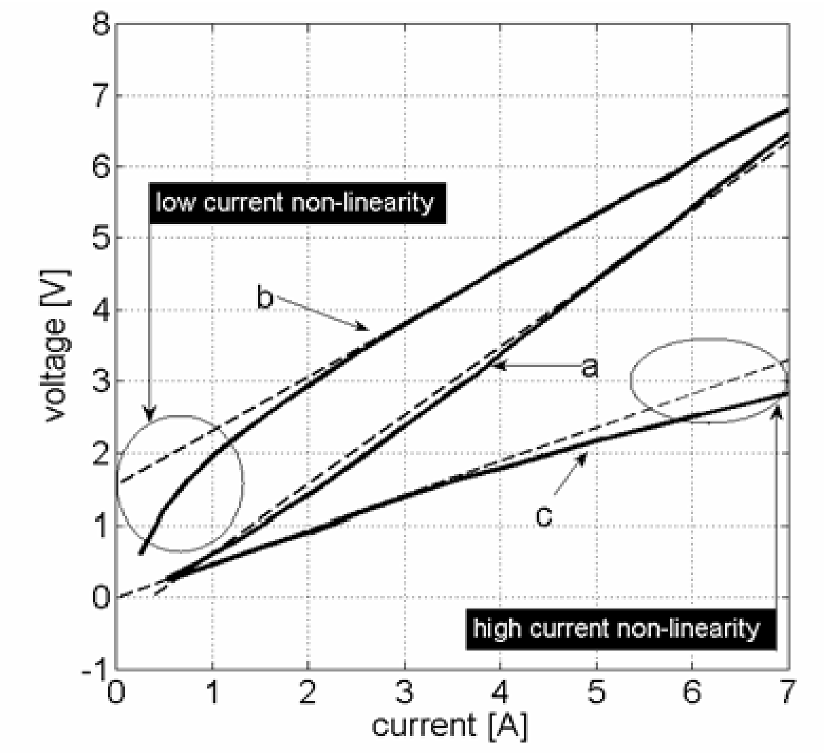
Flux spectrum of the non-linear inductance $i_1^5(t) = I_1^5 sen^5 \omega_1 t = \frac{I_1^5}{16}(10 sen\omega_1 t - 5 sen 3\omega_1 t + sen 5\omega_1 t)$

- When two sinusoids of different frequencies are applied simultaneously intermodulation components are generated
- They increase the frequency components in the response of the system and the complexity of the analysis

Experimental results

Three different kind of of single-phase filtering inductance have been tested:

- 3 mH and 1.5 mH toroidal inductor with a powdered metal core
- A 2.6 mH air-gap based inductor with a ferrite core



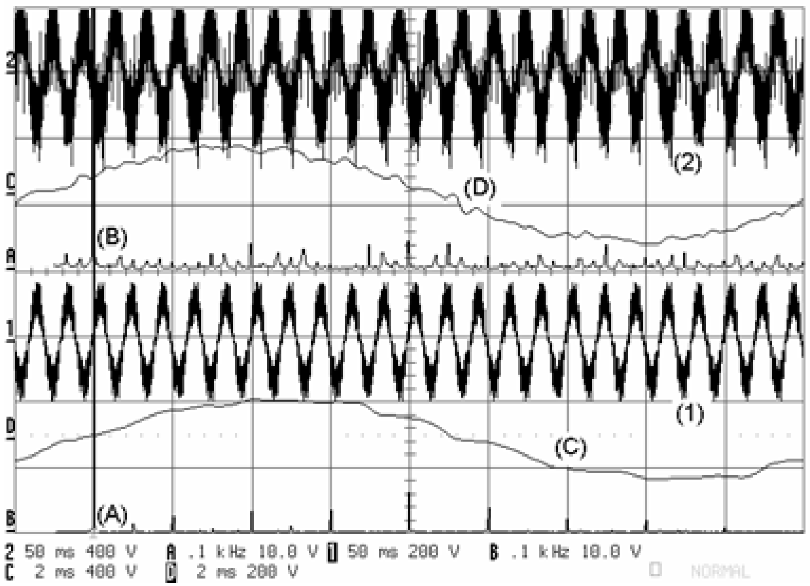
For low currents the air-gap based inductor characteristic is more non-linear

- a – 3 mH toroidal inductor characteristic
- b – 2.6 mH air-gap inductor characteristic
- c – 1.5 mH toroidal inductor characteristic

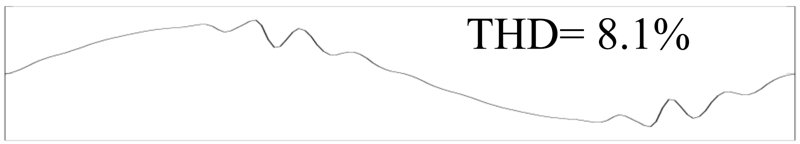
Experimental results: high current non-linearity

Resonant controller

a)



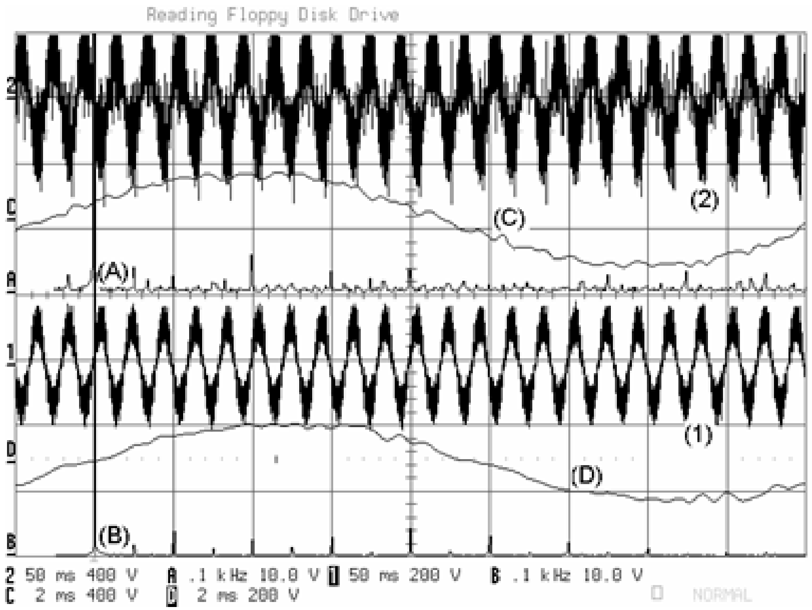
b)



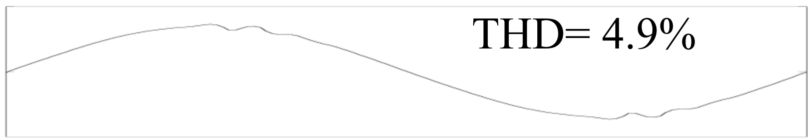
Grid current with non-linear inductor and resonant controller: a) (1) grid current [10A/div]; (2) grid voltage [400V/div]; (A) grid voltage spectrum [10V/div]; (B) grid current spectrum [0.5A/div]; (C) a period of the grid voltage; (D) a period of the grid current; b) a period of the grid current (simulation results) [10A/div]

Repetitive controller

a)



b)



Grid current with non-linear inductor and repetitive controller: a) (1) grid current [10A/div]; (2) grid voltage [400V/div]; (A) grid voltage spectrum [10V/div]; (B) grid current spectrum [0.5A/div]; (C) a period of the grid voltage; (D) a period of the grid current; b) a period of the grid current (simulation results) [10A/div]

Conclusions

- LCL-filter is used to reduce the switching ripple but it challenges the stability of the current control loop
- The different sensors position changes the 50 Hz impedance of the filter and the plant of the current control loop
- Passive damping can solve stability problems but it has been proven how the excessive damping leads to low frequency ripple, reduced filter effectiveness and high losses
- A reduced passive damping can be used if: the converter current is controlled with one sample delay or the grid current is controlled without delays
- A selective passive damping can be an interesting solution in MW range
- Active damping is an interesting alternative to passive damping, two approaches are possible: multiloop or notch filter
- Robustness to parameters variation, use of more sensors and tuning problems are open issues
- Many methods exist: virtual resistor is straightforward, filter-based methods are also intuitive and do not need more sensors