Active damping of LCL filters

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Power electronic converters generate non-ideal current and voltage waveforms, which unavoidably include a broad spectrum of undesirable switching harmonics. In most applications, these harmonics must be mitigated, e.g. with passive or active damping, requiring the use of various types of filters. Among them, LCL-type filters are popular, thanks to their good trade-off between complexity, performance, size, and cost.

However, LCL filters have an inherent resonant frequency, which may cause instability, and therefore requires some sort of damping. Different damping approaches are available (passive [1], active [2], inherent [3], hybrid damping).

All damping techniques are based on the modification of the global impedance, shifting or reducing the admittance peak at the resonant frequency. Passive damping consists in modifying the LCL filter structure (mainly with resistors) in order to stabilize the current. Reciprocally, active damping makes use of the system-level control inputs in order to virtually alter the global impedance.

This technical note is focused on a possible method of active damping for LCL filter. It is mostly inspired by the work reported in [4].

Software resources

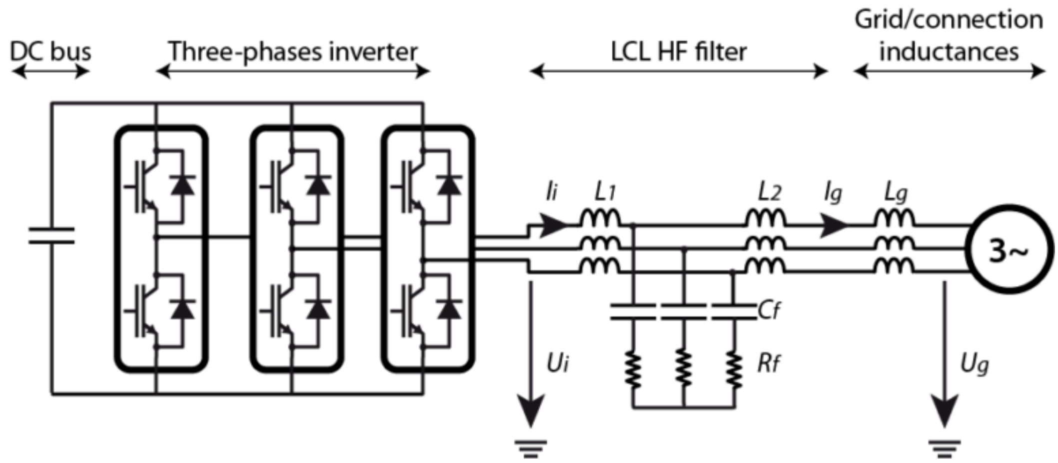
[Simulink model of gird-tie inverter with active control of aLCL filterDownload]

The file `TN123_ActiveDamping_Simulation.zip` contains the simulation/code generation files:

- `parameters.m`: Initialization file (system parameters and calculation of the closed-loop controllers).
- `TN123_ActiveDamping`: Base Simulink file.
- `TN123_ActiveDamping_PLECS_viewer`: Simulink file compatible with PLECS viewer.
- `TN123_ActiveDamping_PLECS_viewer_Matlab2015a`: Simulink file compatible with PLECS viewer and Matlab Simulink above 2015a.

Hardware configuration: LCL filter and grid-tie inverter

The following configuration is considered. The DC bus voltage is assumed to be constant and the control objective is to control the grid current I_g (energy transfer from DC bus to grid) while damping the filter.



Grid-tie inverter with LCL filter

LCL filter resonance and damping

Since the grid is assumed to be an ideal voltage source, the transfer function of the LCL filter is

$$\left.\frac{i_g(s)}{U_i(s)}\right|_{U_g(s)=0} = \frac{1}{(L_1 L_2 C_f)s^3 + (L_1 + L_2)s}$$

In this example (L_1=L_2=2.5 mH, C_f=3µF), the cutoff frequency is 2.6kHz. It reflects a natural resonance, which means that, at this frequency, the impedance is zero and the current tends to be infinite. In practice, as the grid voltage source isn't ideal and the cables and inductors have parasitic resistances, the current can't become infinite, but may be high enough to damage the system. Consequently, the system must be damped in order to avoid the impedance from being zero at this frequency.

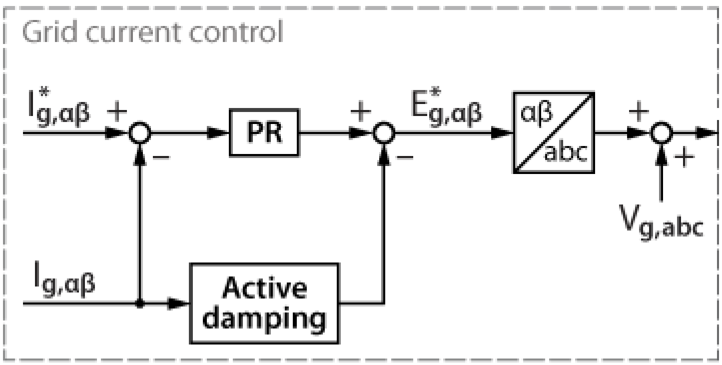
Active damping of a LCL filter

The damping of the LCL filter can be achieved with several approaches (passive, active, hybrid)[1-3]. Active damping consists in modifying the closed-loop transfer function to remove the resonance phenomenon.

Feedback control techniques are generally used for this alteration of the transfer function, relying on either the inverter current, the capacitor voltage, or the grid current. Notably, the feedback of the grid current is interesting as it can modify the closed-loop transfer function to be **equivalent to that of an LCL filter with a resistor** on the grid side. This equivalence authorizes a simple understanding of the damping dynamics.

Following this approach, the control of the LCL filter can be subdivided into two parts:

- A proportional and resonant controller in the stationary reference frame,
- The active damping that uses feedback on the grid current.



Overview of LCL active damping implementation

Grid current control

First, a proportional and resonant controller is developed for the grid current fed by the inverter. This topic is further detailed in TN110. The base circuit equations yield:

$$V_{reg,\alpha\beta}(s) = G_{I\alpha\beta}(s)\left(I^*_{g,\alpha\beta} - I_{g,\alpha\beta}\right)$$

$$G_{I\alpha\beta}(s) = k_p + k_r \frac{s}{s^2 + \omega_{grid}^2}$$

The discretization with sample time T_s gives:

$$G_{I\alpha\beta}(z) = k_p + k_r \frac{\sin(\omega_{grid}T_s)}{2\omega_{grid}} \frac{1 - z^{-2}}{1 - 2z^{-1}\sin(\omega_{grid}T_s) + z^{-2}}$$

Current feedback loop

Second, the damping is achieved using a feedback loop on the grid current, as proposed in [4].

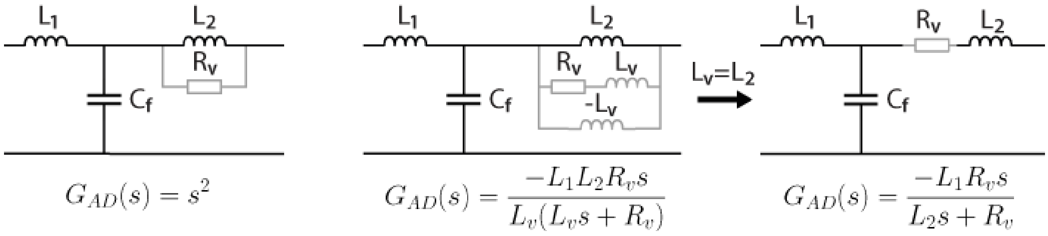
A feedback with the transfer function s^2 allows inserting a virtual resistor in parallel with the inductor L_2. However, the implementation of a double derivative is uneasy. Alternatively, the following transfer function can be used, which replaces the virtual *resistor* with a virtual *inductor*, itself being in parallel with an inductor and a resistor.

$$G_{AD\alpha\beta}(s) = -\frac{L_1 L_2 R_v s}{L_v(L_v s + R_v)}$$

If the added virtual inductor is chosen equal to the grid-side inductor L_2, the added grid-side part (L_2 L_v R_v) is virtually replaced by a virtual resistor R_v in series with the grid-side inductor L_2.

$$G_{AD\alpha\beta}(s) = -\frac{L_1 R_v s}{L_2 s + R_v} = -\frac{k_{ad} s}{s + \omega_{ad}}$$

The following illustration shows the possible circuits to be added in parallel to L_2.



Possible damping circuits

The discretization with sample time Ts gives:

$$G_{AD\alpha\beta}(z) = \frac{-2k_{ad}\left(z^{-1} - 1\right)}{(\omega_{ad}T_s + 2) + (\omega_{ad}T_s - 2)z^{-1}}$$

Active damping simulation results

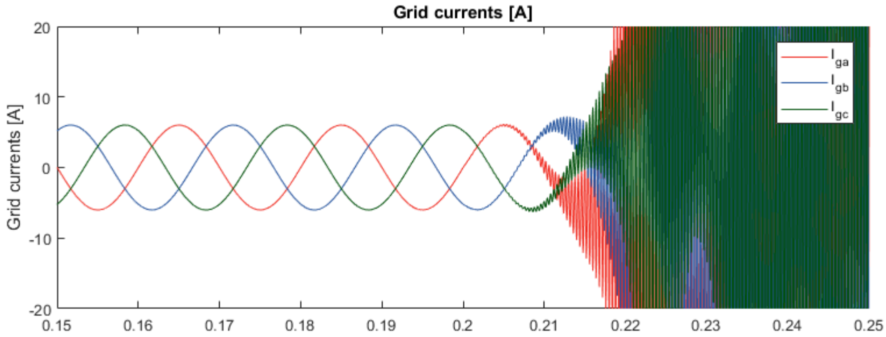
The system and the control presented in this note were simulated using Matlab Simulink and PLECS. The system parameters are summarized in the next table. They correspond to the inductors and capacitors of the passives rack. The latter indeed contains inductors and a three-phase LC filter, which can be easily connected together to form a full LCL filter.

The existing LC filter is preconfigured with 1Ω damping resistors, but these are generally insufficient to provide satisfying damping in a broad range of conditions.

Parameters	**Value**	**Parameters**	**Value**
Grid voltage (line-to-line)	400 V_{RMS}	Grid frequency	50Hz
Grid inductor L_g	0.5mH	Grid side inductor L_2	2mH
Capacitor C_f	3μF	Serie resistor R_f	1Ω
Inverter side inductance L_1	2.5mH	DC bus voltage	750V
Inverter PWM frequency	20kHz	Sample time T_s	50μs
Proportional gain (PR controller) *kp*	5V/A	Resonant gain (PR controller) *kr*	523Vs/A
Active damping gain k_{AD}	40Ω	Active damping pulsation ω_{AD}	16493 rad/s

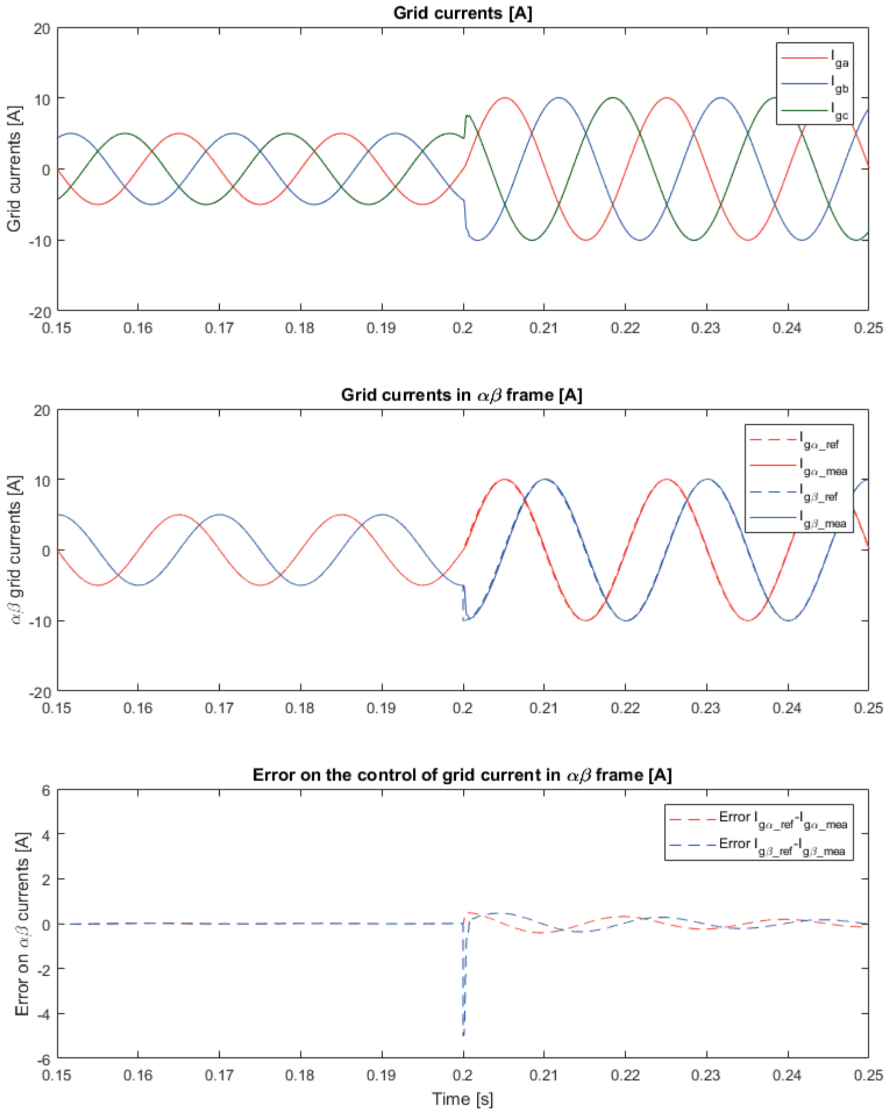
System parameters

The following figures show the result of the deactivation of the active damping at 0.2s. As it can be seen, the system becomes rapidly unstable. In practice, if such a phenomenon would occur, the over-current protection thresholds on the controller (e.g. BBox RCP) would block the generation of inverter PWM signals, hence almost instantly blocking the grid currents and damaging consequences.



LCL filter becomes unstable after deactivation of the active damping at 0.2s

The following figures show the system response to a step of reference current, with the active damping properly configured. During the transition, an oscillation of 0.2A peak-peak appears which is damped in 2ms with a damping frequency at 2.5kHz (8 times lower than the switching frequency).



Experimental results of active damping

Experimental results related to this active damping method are available in the application note AN005.

References

[1] A. K. Balasubramanian, V. John "Analysis and design of split capacitor resistive inductive passive damping for LCL filters in grid-connected inverters," *IET Power Electronics*, vol. 6, November. 2013

[2] J. Dannehl, F. W. Fuchs, S. Hansen, P. B. Thogersen, "Investigation of Active Damping Approaches for PI-Based Current Control of Grid-Connected Pulse Width Modulation Converters With LCL Filters", *IEEE Trans. on Industry Applications*, vol. 46, August 2010

[3] J. Wang, J. Yan, L. Jiang, J. Zou, "Delay-dependent stability of single-loop controlled grid-connected inverters with LCL filters," *IEEE Trans. on Power Electronics*, vol. 31, pp. 743–757, January 2016

[4] X. Wang, F. Blaabjerg, P. C. Loh, "Grid-Current-Feedback Active Damping for LCL Resonance in Grid-Connected Voltage-Source Converters", *IEEE Trans. on Power Electr.*, vol. 31, January 2010