LCL-LC 필터를 포함하는 컨버터의 공진현상 분석 및 능동댐핑 제어

스티븐, 정재정
경북대학교

Resonance Analysis and Active Damping Control of Converters with LCL-LC Filters

Obi Stephen Arinze and Jae-Jung Jung
Kyungpook National University

ABSTRACT

This article discusses a method for actively damping interconnected current and voltage-controlled converters that employ $LCL-LC$ filters. Such interconnected converters are commonly encountered in power electronic systems, such as test benches and microgrid systems. Instability due to resonance and the coupling of the $LCL-LC$ filters can arise. The active damping solution discussed involves the addition of damping signals to either converter's control loops through a high pass filter with a gain k_{ad} and cutoff frequency w_{ad} greater than the resonance frequency to be damped but limited to the Nyquist frequency, which can effectively suppress the resonance and stabilize the system. The paper reviews the stability of the interconnected converters with and without active damping solution and this is confirmed via simulation result.

1. INTRODUCTION

With the global drive for clean energy generation, more and more power electronics-based power converters are being introduced into the power system. Aside from the interaction with the grid, the output impedance of these converters also interacts with each other, thus reshaping the output impedance of the system. Similarly, in a test workbench where several power converters are interconnected as depicted in Figure 1(a): some converters play the role of voltage regulation and others, the role of power flow control through current control.

In the design of the control system of the converters, the interconnected system is usually ignored, and linearity is assumed. However, as disclosed by the authors in [1], not only is there control coupling, there exist also the impedance coupling problem between the voltage-controlled converter's LC output filter impedance and the current controlled converter's LCL filter impedance. This can be missed when the system is considered individually. Coupled with the digital control delay, the internal stability based on impedance-based analysis of the open-loop transfer function is insufficient for stability analysis. This is because it fails to identify the resonance instability due to the impedance coupling. Hence external stability analysis of the closed loop pole is needed. The focus of this article is to employ the active damping solution described in [2] to solve the resonance due to external instability and enhance the system stability.

(a)

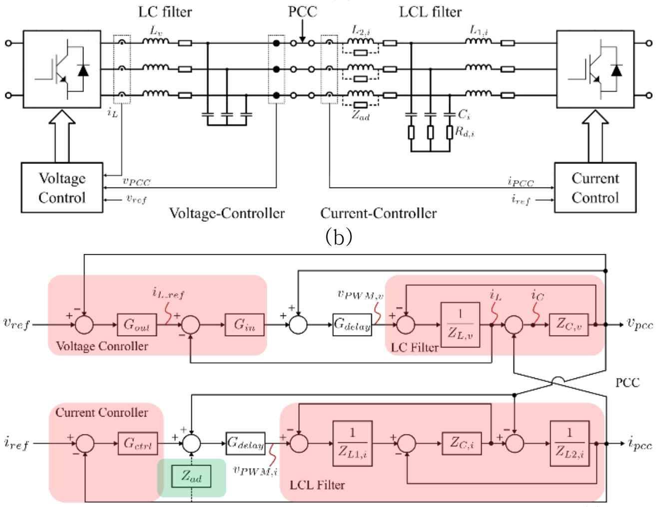

Fig. 1: A generalized representation of the interconnected system (a) and the control block diagram (b).

2. CIRCUIT CONFIGURATION

The interconnected system and its relevant equivalent circuit and control block diagram is as depicted in Figure 1. The authors of [1] derived the open and closed loop transfer functions and equivalent relationships without the active damping loop (green) as:

$$v_{PCC}(s) = \frac{Z_{C,v}}{Z_{L,v}+Z_{C,v}} \cdot v_{PWM,v}(s) + \frac{Z_{L,v}Z_{C,v}}{Z_{L,v}+Z_{C,v}} \cdot i_{PCC}(s)$$
$$= G_1(s) \cdot v_{PWM,v}(s) + G_2(s) \cdot i_{PCC}(s) \quad (1)$$

$$i_{PCC}(s) = \frac{Z_{C,i}}{Z_{L1,i}Z_{L2,i}+Z_{L1,i}Z_{C,i}+Z_{L2,i}Z_{C,i}} \cdot v_{PWM,i}(s) - \frac{Z_{L,i}+Z_{C,i}}{Z_{L1,i}Z_{L2,i}+Z_{L1,i}Z_{C,i}+Z_{L2,i}Z_{C,i}} \cdot v_{PCC}(s)$$
$$= G_3(s) \cdot v_{PWM,i}(s) + G_4(s) \cdot v_{PCC}(s) \quad (2)$$

$$v_{PCC}(s) = \frac{G_{out}(s)G_{in}(s)G_{delay}(s)Z_{C,v} \cdot v_{ref}(s)}{Z_{L,v}+G_{out}(s)G_{in}(s)G_{delay}(s)Z_{C,v}+G_{in}(s)G_{delay}(s)+Z_{C,v}-Z_{C,v}G_{delay}(s)} + \frac{Z_{C,v} \cdot \left(Z_{L,v}+G_{in}(s)G_{delay}(s)\right) \cdot i_{PCC}(s)}{Z_{L,v}+G_{out}(s)G_{in}(s)G_{delay}(s)Z_{C,v}+G_{in}(s)G_{delay}(s)+Z_{C,v}-Z_{C,v}G_{delay}(s)}.$$
$$= G_A(s) \cdot v_{ref}(s) + G_B(s) \cdot i_{PCC}(s) \quad (3)$$

$$i_{PCC}(s) = \frac{G_{ctrl}(s)G_{delay}(s)Z_{C,i} \cdot i_{ref}(s)}{Z_{L1,i}Z_{L2,i}+Z_{L1,i}Z_{C,i}+Z_{L2,i}Z_{C,i}+G_{ctrl}(s)G_{delay}(s)Z_{C,i}}$$

$$-\frac{Z_{L1,i}+Z_{C,i}-G_{delay}\cdot Z_{C,i}\cdot v_{PCC}(s)}{Z_{L1,i}Z_{L2,i}+Z_{L1,i}Z_{C,i}+Z_{L2,i}Z_{C,i}+G_{ctrl}(s)G_{delay}(s)Z_{C,i}}$$
$$= G_C(s)\cdot i_{ref}(s) - G_D(s)\cdot v_{PCC}(s) \quad (4)$$

where $Z_C = \frac{1}{sC}$, $Z_L = sL$, $G_{ctrl} = G_{out} = G_{in}$ = PI controller, and G_{delayl} is a second order *pade* approximation of the combined PWM and sampling delay. It is clear from (3) and (4) that i_{PCC} is coupled to v_{PCC} through G_B. Similarly, v_{PCC} is coupled to i_{PCC} through G_D.

$$\begin{bmatrix} v_{PCC}(s) \\ i_{PCC}(s) \end{bmatrix} = \begin{bmatrix} \frac{G_A(s)}{1+G_B(s)G_D(s)} & \frac{G_B(s)G_C(s)}{1+G_B(s)G_D(s)} \\ \frac{-G_A(s)G_D(s)}{1+G_B(s)G_D(s)} & \frac{G_C(s)}{1+G_B(s)G_D(s)} \end{bmatrix} \cdot \begin{bmatrix} v_{ref}(s) \\ i_{ref}(s) \end{bmatrix} \quad (5)$$

Rearranging (3) and (4) gives (5) which is used to describe the control coupling as well as stability analysis.

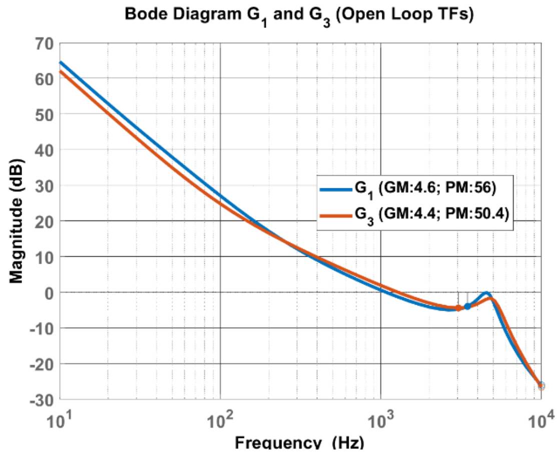

Figure 2: Bode plot of open-loop transfer function (G_1 and G_3) of converters with parameters in Table 1.

From the result of the above bode diagram, one can assume both converters are stable.

3. SIMULATION

Table 1: Parameter values of simulation

Parameter	Value	Parameter	Value
V_{dc}	200 V	$k_{p,in}$	1.5
V_{PCC}	110 V	$k_{i,in}$	2000
$L_{1,i}$, $L_{2,i}$ & L_V	0.2 mH	$k_{p,out}$	0.4
C_v	15 μF	$k_{i,out}$	100
C_i	10 μF	k_p	3
$R_{d,i}$ & $R_{d,v}$	5 mΩ	k_i	2000
f_{SW}	20 kHz	f_{Samp}	20 kHz

The system was verified through a 6kW PLECS simulation. The interconnected system was first operated without the active damping term Z_{ad}. As in Figure 3(a), the system exhibits lasting oscillation and resonance instability on power injection. On the other hand, the active damping solution exhibits better dynamics and steady-state stability.

4. CONCLUSION

In this article, we have reviewed the resonance problem inherent in an *LC-LCL* interconnected converter system. We have also shown that the resonance problem can be mitigated through active damping solution.

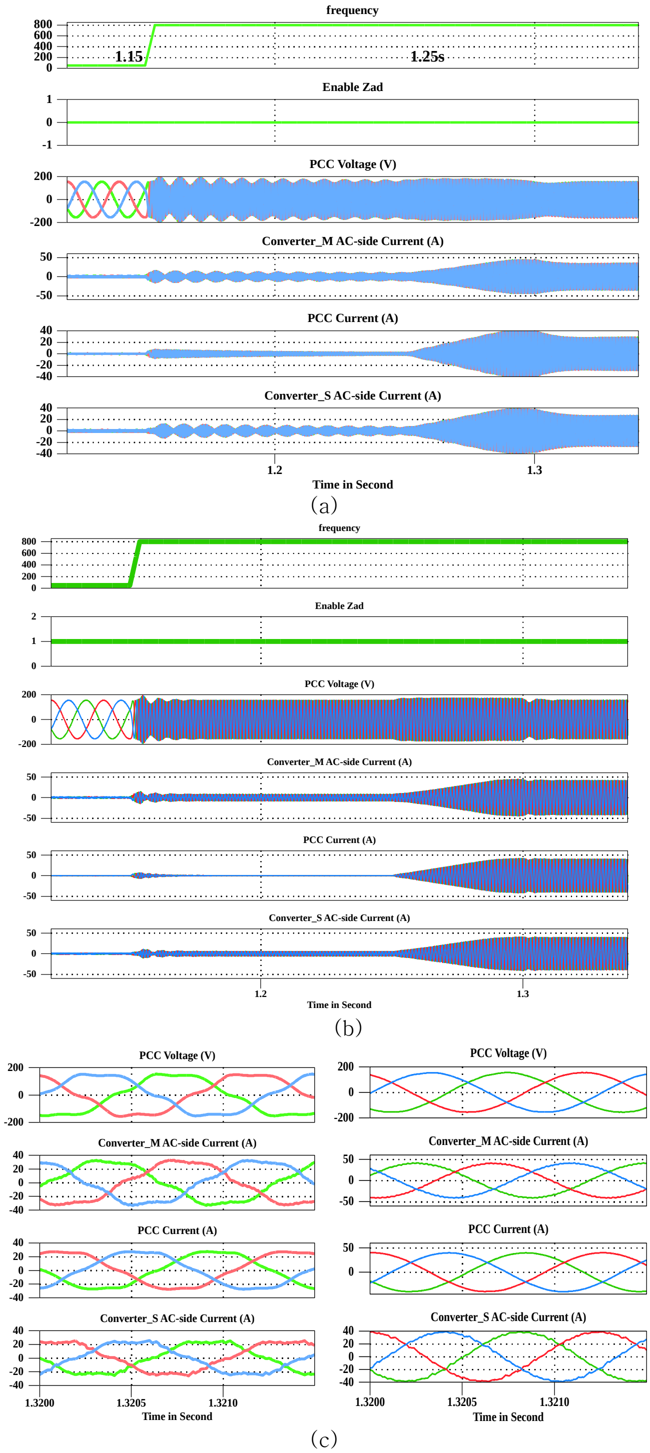

Fig. 3: Operation without active damping (a) with active damping (b) and zoomed version of Fig. (a) and (b)

This work was conducted under the framework of the research and development program of the Korea Institute of Energy Research (C3-2471).

REFERENCES

[1] K. Ma, W. Tang, R. Cheng and Y. Song, "Modeling of Interconnected Voltage and Current Controlled Converters With Coupled LC–LCL Filters," in IEEE Transactions on Power Electronics, vol. 36, no. 4, pp. 3995-4005, April 2021,

doi: 10.1109/TPEL.2020.3023911.
[2] X. Wang, F. Blaabjerg and P. C. Loh, "Grid-Current-Feedback Active Damping for LCL Resonance in Grid-Connected Voltage-Source Converters," in IEEE Transactions on Power Electronics, vol. 31, no. 1, pp. 213-223, Jan. 2016, doi: 10.1109/TPEL.2015.2411851.