Design and Analysis of Observer-Based Active Damping for LCL Filter Resonance in Grid-Connected Converter

Gaafar, Mahmoud A
Department of Electrical and Electronic Engineering, Graduate School of Information Science and Electrical Engineering, Kyushu University : Graduate Student

Shoyama, Masahito
Department of Electrical Engineering, Faculty of Information Science and Electrical Engineering, Kyushu University : Professor

https://doi.org/10.15017/1669721

出版情報：九州大学大学院システム情報科学紀要. 21 (2), pp.39-44, 2016-07-29. 九州大学大学院システム情報科学研究院

九州大学大学院
システム情報科学紀要
第 21 巻　第 2 号　平成 28 年 7 月

Research Reports on Information Science and
Electrical Engineering of Kyushu University
Vol.21, No.2, July 2016

Design and Analysis of Observer-Based Active Damping for LCL Filter Resonance in Grid-Connected Converter

Mahmoud A. GAAFAR* and Masahito SHOYAMA**

(Received June 23, 2016)

Abstract: Due to its superiority over L and LC filters, LCL filters are widely used to connect PWM converters to the grid. However, the resonance problem produced by these filters requires more effort in the design process to damp it. Active damping techniques which use the sensed capacitor current are widely used in this regard; however this requires an additional current sensor which increases the overall cost. In this paper, an observer is employed in the control system to estimate the capacitor current without the need for additional sensors. A systematic design and analysis for the observer-based active damping system is introduced in this paper. The simulation results and the experimental verification are presented as well.

Keywords: LCL filter, Resonance, Active damping, Grid, Observer

1. Introduction

PWM converters are often used to transfer the harvested energy from the renewable energy sources to the utility grid. To damp the switching harmonics in the injected grid current, grid side filters are used to connect the PWM converters with the grid[1]. Compared with L and LC filters, LCL filters are more interesting for this purpose because of: 1) Its low grid current distortion and reactive power production, 2) Attenuation of -60 dB/decade for frequencies in excess of the resonance frequency can be obtained, 3) Possibility of using a relatively low switching frequency for a given harmonic attenuation[2]. However, LCL filters bring undesirable resonance effect, which caused by zero impedance for some higher order harmonics of grid-connected current. The resonance effect can cause instability of the control system. Also it declines the safety of the converter especially if some harmonic is near the resonant frequency.

Damping techniques have to be adopted to overcome these resonance oscillations. Passive damping methods by using physical damping circuit is usually adopted. This damping circuit can be purely resistive, causing relatively high losses, or more complex solutions consisting of combination of resistors, capacitors and inductors[3), 4)]. This method is simple but it creates additional power losses and decreases the system performance. Thus active damping by modifying the control algorithm is preferred because of no additional power losses and more flexibility can be obtained[1)].

Many active damping methods have been proposed in the literature[5)-15)]. A cascaded first-order or higher-order filter can be tuned to produce anti-resonance peak in the control loop to damp the resonance of the LCL filter[5), 6)]. However, this method is highly sensitive to resonant frequency variations. In addition, it causes a reduction in the system bandwidth.

To cope with these challenges, a feedback loop of one of the filter states has been used for damping purpose. It was proved that the proportional feedback of the filter capacitor current is equivalent to a resistor in parallel with the filter capacitor[7)]. Recently, this method has been further discussed[8)-11)]. This method can be modified to use the capacitor voltage with a differentiator or with a well-tuned lead-lag compensator[12)]. This active damping method is simple, flexible, effective and robust. However, it needs an additional high-precision current sensor to get the capacitor current or voltage, and this increases the overall cost of the system.

Model-based analytical methods have been proposed to estimate the capacitor current or voltage [13)-15)]. However, these algorithms have been applied mainly in the *dq* synchronous reference frame which increases the control effort. Moreover, it have been carried out based on converter side current control. However, one of the main objectives of the whole control system is controlling the power factor at the point of grid connection [16)].

In this paper, an observer in the control system is employed to estimate the capacitor current without the

* Department of Electrical and Electronics Engineering, Graduate Student
** Department of Electrical Engineering

need for additional sensors. A systematic design of the observer loop is presented. The grid current is adopted as the main controlled state with taking into account the transport delay du to digital implementation. The control algorithm is implemented in stationary reference frame.

Following this introduction, the capacitor-current-based active damping method is presented. The third part introduces the design procedures of the proposed observer algorithm. The design steps of the fundamental current regulator along with the active damping coefficient are presented in the fourth part. The fifth part introduces the simulation results and the experimental verification. Finally, some conclusion is presented.

2. Capacitor-Current-Based Active Damping Method

Figure 1 shows the power circuit of a single phase inverter connected to the grid through an LCL filter. **Figure 2** shows the block diagram of the complete control system where a proportional feedback (H_d) of the capacitor current is used for active damping purpose. The un-damped filter transfer function, which relates the inverter output voltage (v_i) to the injected grid current (i_g), is expressed in (1) as $G_f(s)$ where ω_{res}, expressed in (2), is the filter resonant frequency in rad/sec.

$$G_f(s) = \frac{I_g(s)}{v_i(s)} = \frac{1}{L_i L_g C s(s^2+\omega_{res}^2)} \tag{1}$$

$$\omega_{res} = \sqrt{(L_i + L_g)/(C L_i L_g)} \tag{2}$$

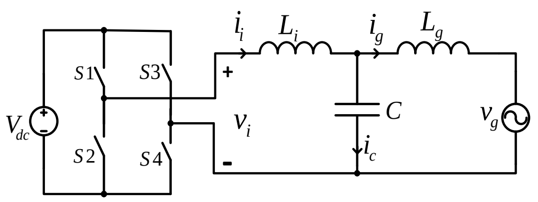

Fig. 1. Single phase inverter connected to the grid through an LCL filter.

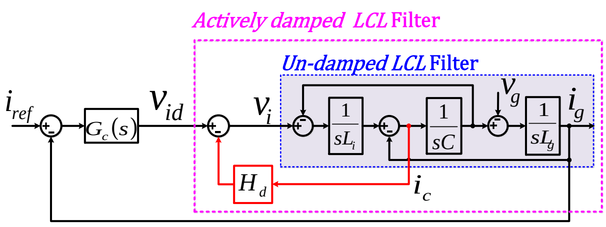

Fig. 2. Capacitor-current-based active damping system.

On the other hand, the actively damped filter transfer function is expressed in (3) as $G_{f\text{-}d}(s)$ where ζ is the damping ratio expressed in (4) in terms of H_d. It is shown from (3) that the damping effect can be achieved by a proper tuning for H_d without the need for any passive elements.

$$G_{f-d}(s) = \frac{I_g(s)}{V_{id}(s)} = \frac{1}{C_f L_g L_i S(S^2+2\zeta\omega_{res}S+\omega_{res}^2)} \tag{3}$$

$$\zeta = \frac{H_d}{2L_i\omega_{res}} \tag{4}$$

In **Fig. 2**, $G_c(s)$ is a current controller to regulate the fundamental current component. A Proportional resonant (PR) controller, with a transfer function expressed in (5), is employed here.

$$G_c(s) = K_p + \frac{K_r s}{s^2+\omega_o^2} \tag{5}$$

where ω_o is the fundamental grid frequency in rad/sec.

3. Proposed Observer System

To reduce the number of sensors, an observer is employed to estimate the capacitor current using the available measurements of the grid voltage and grid current along with the inverter modulation index. The observer-based system is shown in **Fig. 3**. For design purpose, a state space model for the LCL filter is derived firstly, as introduced in the next section.

3.1. Filter State Space Model

The continuous state space model for the LCL filter is expressed as in (6)

$$\frac{dx}{dt} = Fx + GU \tag{6}$$

where

$$x(t) = \begin{bmatrix} i_g \\ i_i \\ v_c \end{bmatrix}, F = \begin{bmatrix} 0 & 0 & {}^{1}/_{L_g} \\ 0 & 0 & {}^{-1}/_{L_i} \\ {}^{-1}/_{C} & {}^{1}/_{C} & 0 \end{bmatrix}, G = \begin{bmatrix} 0 & {}^{-1}/_{L_g} \\ {}^{V_{dc}}/_{L_i} & 0 \\ 0 & 0 \end{bmatrix},$$

$$U = \begin{bmatrix} m(t) \\ V_g(t) \end{bmatrix}$$

The filter discrete model can be expressed as in (7)

$$x(k+1) = \varphi x(k) + \Gamma U(k) \tag{7}$$

where $\varphi = e^{FT}$, $\Gamma = \sum_{k=0}^{\infty} \frac{F^k T_s^{k+1}}{(k+1)!}$

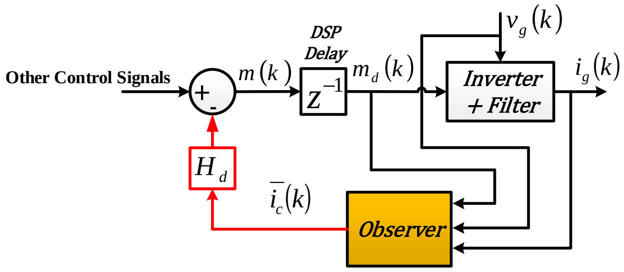

Fig. 3. Observer-based active damping system.

Considering the DSP delay due to computation and digital PWM operation, the modulation index input will be $m_d(k)$ instead of $m(k)$ where:

$$m_d(k) = m(k-1) \tag{8}$$

Then, the discrete state model is re-written in (9) as follow.

$$x(k+1) = \varphi x(k) + \Gamma U_d(k) \tag{9}$$

where $U_d(k) = \begin{bmatrix} m_d(k) \\ V_g(k) \end{bmatrix}$

3.2. Observer Design

Using Luenberger observer technique[17], the observer state space model is expressed in (10).

$$\bar{x}(k+1) = (\varphi - L_p H)\bar{x}(k) + [\Gamma \quad L_p]\begin{bmatrix} U_d(k) \\ i_g(k) \end{bmatrix}$$
$$\bar{y}(k) = H\bar{x}(k) \tag{10}$$

with $H = [-1 \quad 1 \quad 0]$.

In (10), L_p is the weighting matrix for the correction part between the measured output (the grid current i_g) and its estimated value. The value of L_p depends on the Eigen values of the observer which should be at least two times faster than the poles of the plant (actively damped filter) to do not make any deterioration for the dynamic characteristics[17]. In our case, the value of L_p is tuned to obtain observer poles equal to three times the plant poles.

4. Control parameters design

Since the observer poles are chosen to be faster than the plant poles, the fundamental current regulator can be designed separately from the observer based on the original system shown in **Fig. 2**.

4.1 Fundamental current regulator design

For the PR regulator coefficients, they are tuned to achieve a pre-specified value of crossover frequency (ω_c) as follow.

- ***K_p* tuning**: For frequencies greater than the fundamental frequency (ω_o), the PR controller function can be reduced to K_p since the resonant gain has negligible effect above ω_o[7]. Since the crossover frequency (ω_c) should be adequately higher than the fundamental frequency, K_p can be determined as follow[9]:

$$K_P = \omega_C(L_i + L_g) \tag{11}$$

- ***K_r* tuning**: This parameter is tuned to ensure that its phase contribution is small at the crossover frequency (ω_c)[18].

$$K_r = \frac{K_P\omega_C}{10} \tag{12}$$

4.2 Active Damping Coefficient (H_d)

This value is tuned to achieve the best possible damping for the actively damped filter. **Figure 4(a)** shows the block diagram for the discrete system of the observer-based actively damped filter. The grid voltage is considered as a disturbance input. $G_{gc}(z)$ and $G_{mc}(z)$ are the discrete transfer functions from the inputs of the observer, measured grid current and inverter modulation index respectively, to the estimated capacitor current.

To derive an epression for the actively damped filter, this system is manipulated as shown in **Figs. 4(b)** till **4(d)** where,

$$G_1(z) = \frac{1}{1+z^{-1}H_d G_{mc}(z)} \tag{13}$$

From **Fig. 4(d)**, the transfer function of the observer-based actively damped filter can be expressed in (14) as $G_{f\text{-}d\text{-}obs}$.

$$G_{f-d-obs}(z) = \frac{z^{-1}G_1(z)G_f(z)}{1+z^{-1}H_d G_1(z)G_f(z)G_{gc}(z)} \tag{14}$$

5. Results

To verify the behavior of the proposed algorithm, simulation and experimental work are carried out for the system shown in **Fig. 1** in two cases; using capacitor current sensor and using the proposed observer loop. To verify the dynamic response, the reference current is stepped up during these tests. Table 1 lists the system parameters used in the simulation and experimental work.

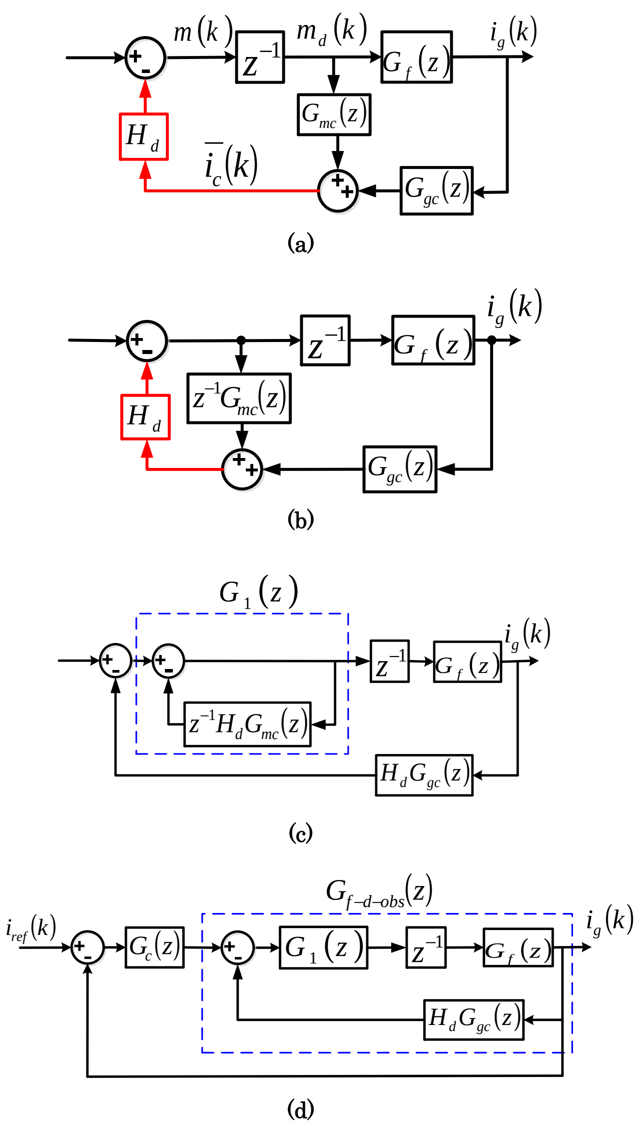

Fig. 4(a)-(d) Block diagram manupulation for the observer-based actively damped filter.

Firstly, the fundamental current regulator (PR regulator in our case) is designed for certain crossover frequency (ω_c). To achieve an adequate phase margin, the crossover frequency should be adequately higher than the fundamental frequency and below the resonant frequency value. For this purpose, a value of ω_c of $0.33\omega_{res}$ is adopted here. Then, using (11) and (12), K_p and K_r are determined as 15.94 and 6436, respectively.

Using (14), the pole-map of the actively damped filter is plotted in **Fig. 5** with sweeping the active damping coefficient (H_d). Using this plot, a value of H_d = 6, corresponding to the farthest resonant poles inside the unit circle, is selected to achieve the best possible damping. Using these tuned parameter, the bode plot of the loop transfer function is shown in **Fig. 6**.

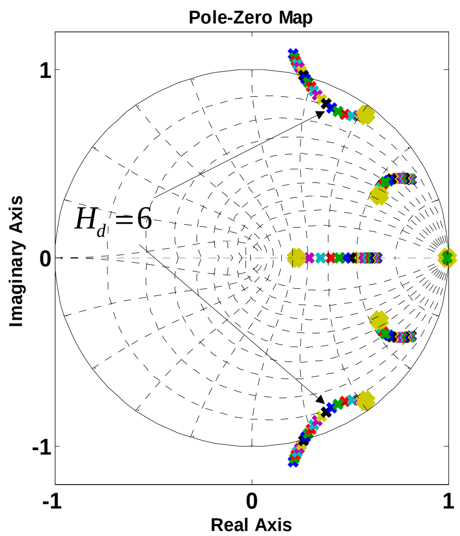

Fig. 5. Pole-map of the closed loop system.

Table 1 System parameters for simulation and experimental work.

Symbol	Quantity	Value
P	Rated power	400 W
V_g	Grid voltage	100 V
F_o	Grid Frequency	50 Hz
V_{dc}	DC Voltage	180 V
L_i	Inverter side inductance	2.75 mH
L_g	Grid side inductance	1.2 mH
C	Capacitance	8 μF
F_{sw}	Switching Frequency	10 kHz
F_s	Sampling Frequency	10 kHz

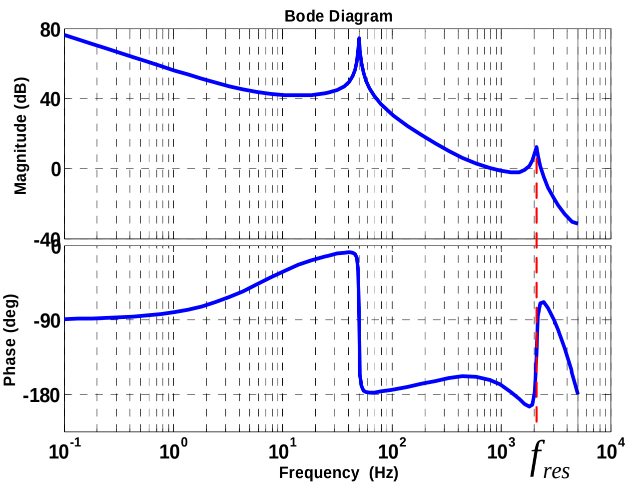

Fig. 6. Bode plot for the loop transfer function.

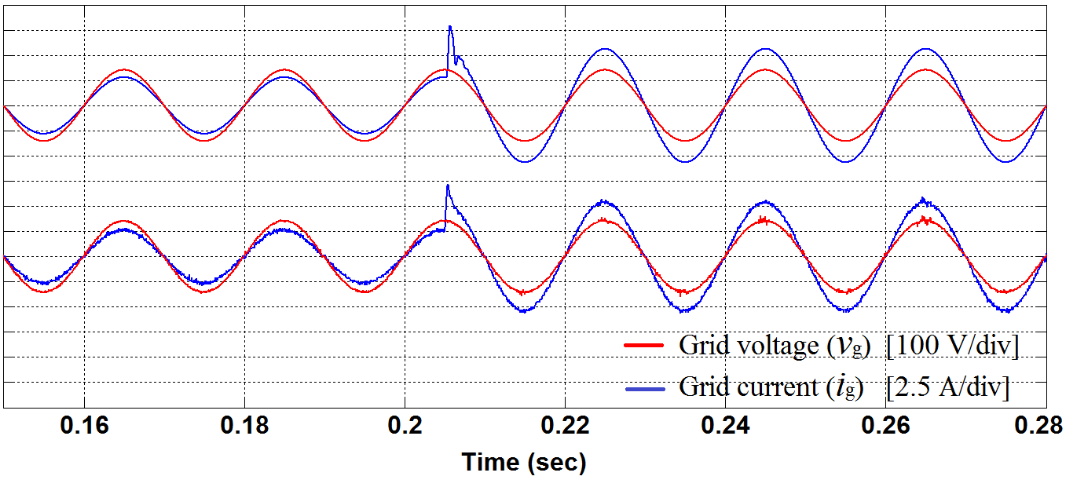

Fig. 7. Results with using current sensor, upper waveforms (simulation), lower waveforms (experimental).

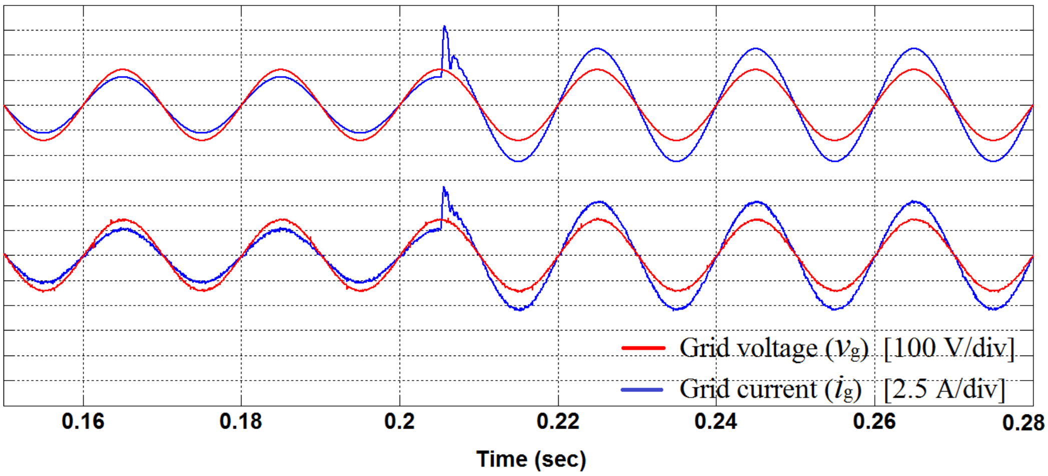

Fig. 8. Results with using the proposed observer loop, upper waveforms (simulation), lower waveforms (experimental).

5.1 Simulation & experimental results

The simulation work is carried out in PSIM environment. Discrete models for the observer loop and the PR controller are constructed using PSIM digital control modules. For experimental verification, a single phase inverter prototype has been constructed and connected through an LCL filter to an AC source to emulate the utility grid. The controller was implemented on a Texas Instruments TMS320C6713 DSP.

Figures 7 and 8 show the simulation and experimental waveforms of the grid voltage and the grid current for the two considered cases; using capacitor current sensor and observer loop, respectively.

Both the simulation and experimental waveforms indicate that the proposed active damping algorithm can damp the resonance oscillations without the need for additional current sensors. For the experimental waveforms, it is shown that the steady state grid current contains some ripples in the sensor-based case. On the other hand, such high frequency switching ripples are largely attenuated with the observer-based case. This is due to the limited bandwidth of the observer. This represents another practical merit for replacing the current sensor by the observer.

6. Conclusion

An active damping algorithm based on the capacitor current estimation is proposed in this work. The proposed algorithm uses an observer in the control loop to estimate the capacitor current value without the need for additional current sensor. The observer poles are selected to be faster than the plant poles. This in turn, facilitates a separate design for the fundamental current regulator along with the active damping coefficient to meet pre-specified values of cross over frequency and damping behavior. The simulation and the experimental results are introduced to verify the performance of the proposed active damping algorithm. These results show that the observer-based system offer a good damping behavior without the need for additional sensors. Moreover, compared to sensor-based system, it offers lower switching ripples.

References

1) C. Wessels, J. Dannehl, F. W. Fuchs “Active Damping of LCL-Filter Resonance based on Virtual Resistor for PWM Rectifiers – Stability Analysis with Different Filter Parameters” in IEEE Power Electronics Specialists (PESC) Conf., pp. 3532-3538, 2008.
2) K. H. Ahmed, S. J. Finney and B. W. Williams, “Passive Filter Design for Three-Phase Inverter Interfacing in Distributed Generation,” Electrical Power Quality and Utilisation, Journal Vol. XIII, No. 2, pp. 49-58, 2007.
3) R. N. Beres, X. Wang, M. Liserre, F. Blaabjerg and C. L. Bak, "A Review of Passive Filters for Three-phase Grid-Connected Voltage-Source Converters," IEEE Trans. Emerg. Sel. Topics Power Electron., vol. 4, no. 1, pp. 54-69, Mar. 2016.
4) R. N. 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, pp. 2083-2098, Mar. 2016.
5) J. Dannehl, M. Liserre, and F. W. Fuchs, "Filter-Based Active Damping of Voltage Source Converters With LCL Filter," IEEE Trans. Ind. Electron., vol. 58, no. 8, pp. 3623-3633, Aug. 2011.
6) W. Yao, Y. Yang, X. Zhang, and F. Blaabjerg, "Digital notch filter based active damping for LCL filters," in Proc. of IEEE APEC, pp. 2399 - 2406, 2015.
7) P. A. Dahono, Y. R. Bahar, Y. Sato, and T. Kataoka, “Damping of transient oscillations on the output LC filter of PWM inverters by using a virtual resistor,” in Proc. IEEE Int. Conf. Power Electron. Drive Syst., vol. 1, pp. 403–407, 2001.
8) C. Bao, X. Ruan, X. Wang, W. Li, D. Pan, and K. Weng, "Step-by-step controller design for LCL-type grid-connected inverter with capacitor–current-feedback active-damping," IEEE Trans. on Power Electron., vol. 29, no. 3, pp. 1239-1253, Mar. 2014.
9) S. G. Parker, B. P. McGrath, and D. G. Holmes, "Regions of active damping control for LCL filters," IEEE Trans. Ind. Appl., vol. 50, no. 1, pp. 424-432, Jan./Feb. 2014.
10) D. Pan, X. Ruan, C. Bao, W. Li, and X. Wang, "Capacitor-Current-Feedback active damping with reduced computation delay for improving robustness of LCL-type grid-connected inverter," IEEE Trans. on Power Electron., vol. 29, no. 7, pp. 3414-3427, July 2014.
11) Z. Xin, X. Wang, P. C. Loh, F. Blaabjerg, "Enhanced Stability of Capacitor-Current Feedback Active Damping for LCL-Filtered Grid Converters," in Energy Conversion Congress and Exposition (ECCE), pp. 4729 - 4736, 2015.
12) R. P-Alzola, M. Liserre, F. Blaabjerg, R. Sebastián, J. Dannehl, and F. W. Fuchs, "Systematic Design of the Lead-Lag Network Method for Active Damping in LCL-Filter Based Three Phase Converters," IEEE Trans. on Ind. Informatics, vol. 10, no. 1, pp. 43-52, Feb. 2014.
13) M. Malinowski and S. Bernet, “A simple voltage sensorless active damping scheme for three-phase PWM converters with an LCL filter,” IEEE Trans. Ind. Electron., vol. 55, no. 4, pp. 1876–1880, April 2008.
14) W. Gullvik, L. Norum, and R. Nilsen, "Active damping of resonance oscillationsin LCL-filters based on virtual flux and virtual resistor," in Eur. Conf. Power Electron. Appl., pp 1-10, Sep.2–5, 2007.
15) V. Miskovic, V. Blasko, T. Jahns, A. Smith, C. Romenesko, “Observer Based Active Damping of LCL Resonance in Grid Connected Voltage Source Converters” in proc. IEEE Energy Conversion Congress and Exposition (ECCE) conf., 2013 , pp. 4850 – 4856.
16) J. Dannehl, C. Wessels, and F. Fuchs, “Limitations of voltage-oriented pi current control of grid-connected PWM rectifiers with LCL filters,” IEEE Trans. Ind. Electron., vol. 56, no. 2, pp. 380–388, Feb. 2009.
17) G. F. Franklin, J. D. Powell and M. L Workman, Digital Control of Dynamic Systems, 2nd ed., California: Addison Wesley Longman, Inc., 1998
18) D. G. Holmes, T. A. Lipo, B. P. McGrath, and W. Y. Kong, “Optimized design of stationary frame three phase AC current regulators,” IEEE Trans. Power Electron., vol. 24, no. 11, pp. 2417–2426, Nov. 2009.