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Published in:

Proceedings of the 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)

DOI (link to publication from Publisher):

[10.1109/ICPE.2015.7167816](https://doi.org/10.1109/ICPE.2015.7167816)

Publication date:

2015

Document Version

Early version, also known as pre-print

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Han, Y., Li, Z., & Guerrero, J. M. (2015). Dynamic Evaluation of LCL-type Grid-Connected Inverters with Different Current Feedback Control Schemes. In *Proceedings of the 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)* (pp. 391 - 396). Article 7167816 IEEE Press. <https://doi.org/10.1109/ICPE.2015.7167816>

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Dynamic Evaluation of LCL-type Grid-Connected Inverters with Different Current Feedback Control Schemes

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Abstract-- Proportional-resonant (PR) compensator and LCL filter becomes a better choice in grid-connected inverter system with high performance and low costs. However, the resonance phenomenon caused by LCL filter affect the system stability significantly. In this paper, the stability problem of three typical current feedback control schemes in LCL grid-connected system are analyzed and compared systematically. Analysis in s-domain take the effect of the digital computation and modulation delay into account. The stability analysis is presented by root locus in the discrete domain, the optimal values of the controller and filter with different feedback configurations are provided. The impacts of digital delay, PR parameters and LCL parameters on different control strategies are also investigated. Finally, the theoretical analysis are validated by simulation results.

Index Terms-- grid-connected converter, active damping, dual-loop, current control.

I. INTRODUCTION

Grid-connected inverter plays an important role in interconnecting renewable energy and the utility grid. High order LCL filter can attenuate harmonics produced by PWM inverter effectively with low cost and size [1]. However, the resonance peak produced by LCL filter can affect the stability of the system seriously. In order to stabilize the system, damping resistors can be added in series with capacitors or inductors to attenuate the resonance peak. But it brings power loss and decreases system efficiency [2]. The active damping methods are effective and flexible in stabilizing the system and has been widely used [3]. However, it's more complex and costly than passive damping methods.

The proportional resonant (PR) controller have been proved to be a good choice and applied to the single-phase grid-connected inverter system [4], [5]. The ideal PR controller can provide infinite gain at the resonate frequency. Therefore, the static error at the fundamental

frequency can be totally eliminated. In recent literatures, the control and stability issues of the LCL-type grid-connected inverter have been extensively discussed [6], [7]. In [7], a pole placements method is proposed to assure system stability and dynamic response considering the impacts of PR, LCL parameters and digital delay by analyzing the root locus. But in [7], only one current feedback control scheme is analyzed, and the conclusion is drawn without considering the delay effect, thus it's not accurate when the digital controller is employed.

The single-loop current control applied in LCL-type grid-connected inverter can operate with good performance by utilizing the inherent damping effect introduced by the LCL inverter side current [8], [9]. This kind of control scheme is simple and effective, but the quality of the output current is not satisfactory [10]. Besides, the resonance can be suppressed by employing the multiloop control strategies [11]. The typical dual-loop control strategies includes converter current plus grid current (i_L plus i_g) feedback control scheme and capacitor current plus grid current (i_c plus i_g) feedback control scheme, these two kinds of control schemes provide similar dynamic performance [12]. However, the stability and dynamic performance between them has not been investigated yet.

In this paper, the discrete root locus of different delay time, PR controller and LCL-filter parameters with three different current feedback configurations are presented. The conclusion can be drawn that the i_L plus i_g and i_c plus i_g feedback control have the similar dynamic performance. When the system delay time increases, the stability of the i_L plus i_g and i_c plus i_g feedback system increases until the delay time is greater than the critical value ($2.5 T_s$), and the system stability decrease dramatically. Whereas, the system stability margin under the i_L feedback control decrease monotonically when T_d increases. From the stability analysis based on the root locus in discrete domain, the stability region of the delay time, PR and LCL-filter parameters can be obtained. The effect of delay time, PR and LCL filter parameters on the system stability has been obtained, and the optimal value for different control strategies are presented and compared. The conclusion contributes optimizing the design of LCL filter and PR controller parameters.

This work is supported by National Natural Science Foundation of China (NSFC) under grant No.51307015 and by Visiting Scholarship of State Key Laboratory of Power Transmission Equipment & System Security and New Technology (Chongqing University) (2007DA10512713405), and by Visiting Scholarship of China Scholarship Council (CSC), and the Oversea Academic Training Funds (OATF), UESTC.

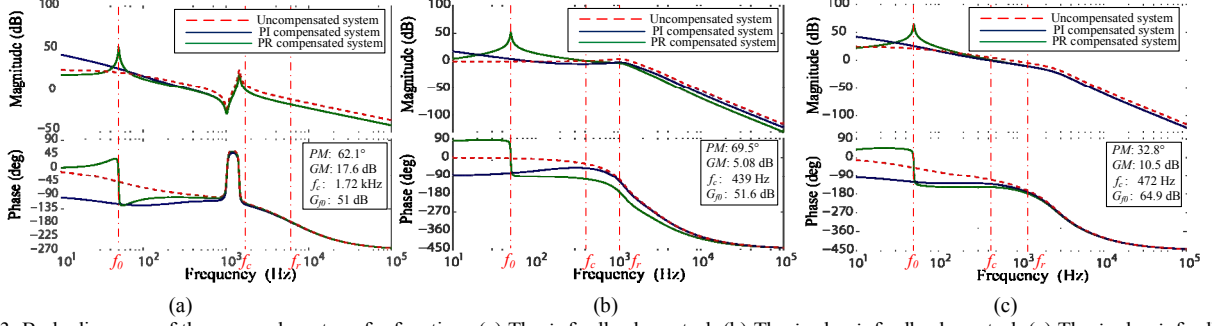


Fig.3. Bode diagrams of three open loop transfer functions (a) The i_L feedback control. (b) The i_L plus i_g feedback control. (c) The i_c plus i_g feedback control

C. The i_c plus i_g feedback control scheme.

The open loop transfer function is

$$G_c(s)_{open} = \frac{i_g(s)}{i_{ref}(s)} = \frac{G_{PR}(s)k_L G_d(s)V_{dc} G_{i_g/v_s}(s)}{1 + k_L G_d(s)V_{dc} G_{i_c/v_s}(s)G_{i_g}(s)} \quad (8)$$

The Bode diagrams of $G_c(s)_{open}$ is shown in Fig. 3 (c). It can be seen that the i_c plus i_g and i_L plus i_g feedback control provide better resonance damping effects over single i_L feedback control, while the PM of i_c plus i_g feedback system is relatively low.

To conclude, by employing the abovementioned current control schemes, the good dynamic performance and enough stability margin (with $GM \geq 5$ dB and $PM \geq 45^\circ$) can be obtained. So they are all practical solution and can be analyzed through aforementioned s-domain models. When applying the single current feedback control scheme, the cost and the complexity is low, the system stability can be guaranteed if the system parameters are fixed or the passive method is used. Adding an extra current feedback can actively damp the resonance but the cost is also increased.

In the next section, the models are established in z-domain, the root locus of the discrete model are presented to analyze the system performance and the stability margin with different system parameters.

III. DISCRETE-DOMAIN MODELING AND ANALYSIS

With the development of the digital controllers, the price/performance ratio of digital signal processor (DSP) is decreasing dramatically. Many control strategies for digitally controlled grid-connected inverter have been proposed [1], [15] without considering the inherent discrete sampling and the effect of control delay [16]. Therefore, the modeling for those novel digitally controlled system in s-domain is not accurate in all frequency range.

Fig. 4 shows the z-domain modeling of the digital control schemes. By using the Tustin bilinear transform [17], the discrete equivalent of $G_{PR}(s)$ in z-domain can be written as

$$G_{PR}(z) = k_p \frac{a_z z^2 + b_z z + c_z}{A_z z^2 + B_z z + C_z} \quad (9)$$

where

$$a_z = 4 + T_s^2 w_0^2 + 4T_s \xi w_0 + 4T_s \xi k_r w_0, \quad b_z = 2T_s^2 w_0^2 - 8,$$

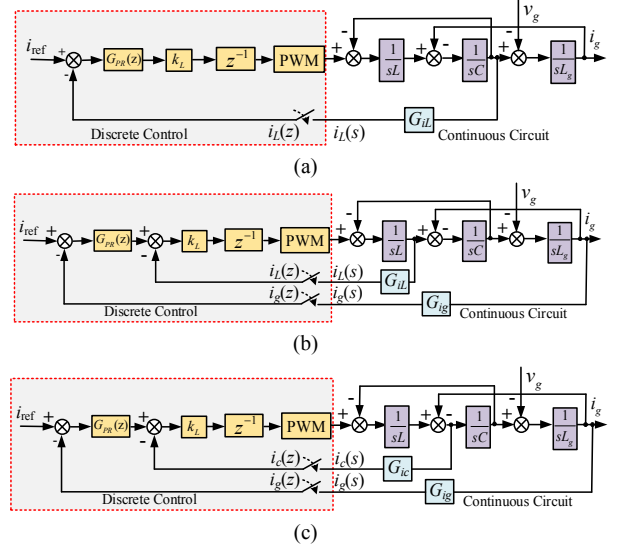


Fig. 4. The z-domain block diagrams of the inverters. (a) The i_L feedback control. (b) The i_L plus i_g feedback control. (c) The i_c plus i_g feedback control

$$c_z = 4 + T_s^2 w_0^2 - 4T_s \xi w_0 - 4T_s \xi k_r w_0, \quad A_z = T_s^2 w_0^2 + 4\xi T_s w_0 + 4$$

$$B_z = 2T_s^2 w_0^2 - 8, \quad C_z = T_s^2 w_0^2 - 4\xi T_s w_0 + 4.$$

The sample and hold circuit in control system lead to one sample delay z^{-1} . The transfer function (2), (3) and (4) describing LCL can be discretized includes the effect of the PWM with zero-order hold (ZOH) method [18].

A. Influence of Digital Control Delay

Fig. 5 shows the root locus of the three current feedback control schemes in z-plane with the delay time varies from the minimum delay time ($0.5T_s$) to maximum the delay time ($3T_s$), and $T_s = 50 \mu s$. There are ten poles and nine zeros introduced by the whole system, Z1 is introduced by LCL , and P1~P5 are introduced by the delay, P3 is cancelled by Z2.

In Fig.5 (a), with the increasing of T_d , the first cluster of root locus are changing slowly inside the circle, the second cluster of root locus that moving outside the unit circle change a lot. Therefore, when the delay time increases, the system gradually becomes unstable. Besides, comparing with i_L plus i_g and i_c plus i_g feedback system, i_L feedback system is more sensitive to the change of the delay time.

In Fig.5 (b), with the increasing of T_d , P1 (P2) are moving away from the real axis and moving closer to the

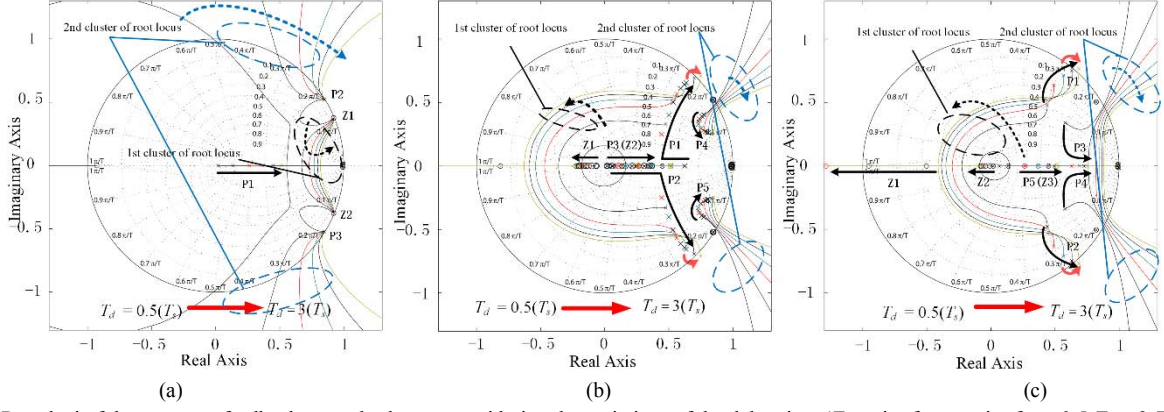


Fig. 5 . Root loci of three current feedback control schemes considering the variations of the delay time (T_d varies from varies from $0.5 T_s$ to $3 T_s$) in z -plane. (a) The i_L feedback control. (b) The i_L plus i_g feedback control. (c) The i_c plus i_g feedback control

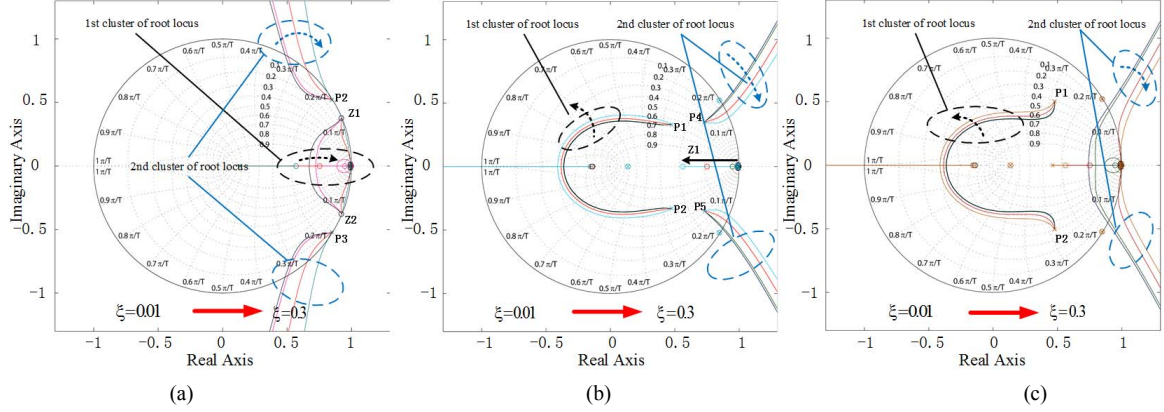


Fig. 6 . Root loci of three current feedback control schemes considering the variations of the damping factor (ζ varies from 0.01 to 0.3) in z -plane. (a) The i_L feedback control. (b) The i_L plus i_g feedback control. (c) The i_c plus i_g feedback control

unit circle which makes the system inclined to unstable. The second cluster of root locus that start from P4 (P5) and have intersection with the unit circle decide the critical gain of the system. When T_d is less than $2.6 T_s$, the critical gain, GM and PM remain almost unchanged. However, when T_d is bigger than $2.6 T_s$, the first cluster of root locus begin to have intersection with the unit circle which makes the critical gain, GM and PM reduce dramatically. Thus the stability of the system is affected if T_d is too large.

Fig.5 (c) shows the root locus of i_c plus i_g feedback system when T_d varies. P1~P4 and Z1 are introduced by the delay time, Z2 is introduced by LCL. With the increasing of T_d , the first and the second cluster of the root locus are all moving towards outside of the unit circle. The system stability decrease slowly until T_d grows to $2.6 T_s$ and the similar result can be obtained from i_L plus i_g feedback control analysis mentioned above.

B. Influence of the damping factor of PR Compensator

The PR compensator can be designed to have a high bandwidth which provides high gain at resonant peaks. System dynamic response can be improved while the stability is also affected. Damping factor ζ is defined as the coefficient of W_0 ($W_c = \zeta W_0 = 2\pi f_0 \zeta$) in (1), the influence of ζ varies from 0.01 to 0.3 (W_c changes from 3 to 100 accordingly) on the system root locus is shown in Fig.6.

From Fig.6 (a), with the increasing of ζ , the first and second cluster of root locus are all moving outside the

unit circle. The first cluster of root locus begin to across the unit circle when ζ increase to 0.3, thus the system cannot operate in stable state when ζ is too large. In Fig.6 (b), Z1 is introduced by PR and moves towards the circle center when ζ increases. The first cluster of root locus moves towards the unit circle when ζ changes from 0.01 to 0.3, the corresponding critical gain changes from 0.93 to 0.45. When K_p is set to 0.5 and ζ varies from 0.01 to 0.3, the corresponding GM changes from 5.45 dB to 0 dB, PM changes from 115 deg to -17.4 deg. Therefore, when the ζ increases, the system gradually becomes unstable.

In Fig.6 (c), when ζ changes from 0.01 to 0.3, the second cluster of root locus are moving towards the circle. The corresponding critical gain changes from 1.78 to 0.09, and the GM and PM decrease dramatically which indicates that i_c plus i_g feedback system is more sensitive to the change of ζ .

C. Influence of the LCL grid side inductor

The LCL filter plays an important role in the grid connected system which achieves higher harmonic attenuation with same (or lower) inductance than L filter. The parameters of the inductor, the capacitor and the resistor may change with the variation of the temperate and operation conditions. Therefore, the variation of LCL parameters should be taken into account to analyze the system performance. In weak grid case, the wide variation of the grid impedance (L_g) affects the system

Then, Fig.9 shows the simulated waveforms of i_c plus i_g feedback control system when the damping factor ζ varies. From Fig.6 (c), it can be inferred that the stability of the system decreases when ζ increases. In Fig.9, when $\zeta=0.01$, the system bandwidth is suitable, the corresponding GM=5 dB and PM=40.6 deg, so the grid current waveform is sinusoidal. When $\zeta=0.12$, the system is critically stable, and the large-scale oscillations appear on the i_g . When ζ is higher than 0.15, the system becomes unstable.

The simulation results when i_L are used for feedback is shown in Fig. 10. With the increasing of the grid side conductor L_2 , the system becomes more stable. When L_2 decreases from 1600 mH to 800 mH, the GM decreases while the PM stay almost unchanged. When L_2 reduces to 700 mH, the corresponding GM drop dramatically below 0 dB so the system becomes unstable.

V. CONCLUSION

In this paper, the digitally controlled grid-connected inverters with the inverter current, the inverter current plus grid current and the capacitor current plus grid current feedback control system have been studied. The impact of the delay time, parameters of the PR compensator and LCL-filter on the system stability of three feedback control system are analyzed and compared systematically. The discrete z-domain models are derived which allows direct design of the digital controllers in z-domain model. The results shows that the single-loop converter current feedback control scheme has good dynamic performance when the damping resistor is needed. Dual-loop current feedback control scheme shows better system stability but the dynamic response is also affected. The simulation results are in good agreement with the stability analysis in the z-domain models.

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