Analysis of Proportional Control for Grid Connected Inverter With LCL Filter

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Abstract

There are many types of grid-connected inverter controllers; Synchronous Reference Frame (SRF)-based controller is the most popular methods. SRF-based controller is capable for reducing both of zero-steady state error and phase delay. However, SRF-based controller has a complex algorithm to apply in real application such as digital processor. Resonant controller is also reduced zero-steady state error, but its transfer function has a high order.

In this paper, a simple proportional control is applied for grid connected inverter with LCL filter. LCL filter is a third order system. Applying a simple proportional controller is not increased the order of closed loop transfer function. By this technique, the single phase model is easily obtained. To reduce steady state error, proportional gain is set as high as possible, but it may produce instability. To compromise between a minimum steady state error and stability, the single phase model is evaluate through Root Locus and Bode diagram. PSIM simulation is used to verify the analysis.

1. Introduction

In recent years, energy is become more and more expensive caused by oil crisis. In the other hand, energy consumption is increased by the time. To solve this problem, Renewable Energy is a solution: Wind power, PV power, Fuel Cell and so on.

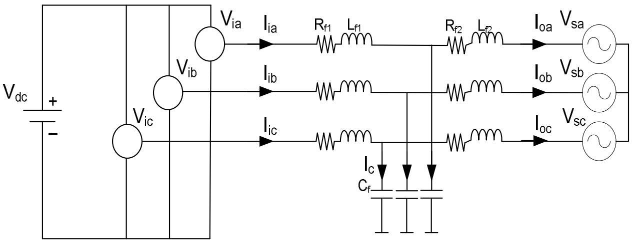

Fig. 1. Grid-Connected Three phase Inverter

Among the renewable energy sources, hydropower and wind power is utilized largely nowadays. In countries with hydropower potential, small hydro turbines are used at the distribution level to sustain the utility network in dispersed or remote locations.

Renewable Energy is also well known as Distributed Generation (DG). This term is used by its characteristic, small rating but distributed in a wide area. Most of the DG power is generated in DC. But recently, mostly low/medium voltage electric power is delivered in AC power.

Inverter is needed to connect DG into Grid. To produce current waveform in sinusoidal form, the inverter is needed a closed loop control. There are many types of inverter controller to produce sinusoidal current waveform, such as deadbeat [1], repetitive control, fuzzy [2] etc. Those types are very complex and difficult to analyze. Resonant controller is suitable for sinusoidal reference, but this controller is increased order of transfer function [3], it may produce difficulties to analyze. SRF-based based controller is also suitable for sinusoidal reference. SRF-based based controller is reduced both of zero-steady state error and phase delay. But SRF-based controller has a complex algorithm to apply in real application such as digital processor.

PI controller based is the most popular method. But, in inverter application the reference is sinusoidal. And common PI control is produced zero-steady state error and phase delay in sinusoidal reference.

In this paper, a simple proportional control is applied for grid connected inverter with LCL filter. LCL filter is a third order system. Applying a simple proportional controller is not increased the closed loop transfer function order. By this technique, the single phase model is easily obtained. To reduce steady state error, proportional gain is set as high as possible, but it may produce instability. To compromise between a minimum steady state error and stability, the single phase model is evaluate through Root Locus and Bode diagram. PSIM simulation is used to verify the analysis.

2. Grid-connected Inverter System and Modeling

2.1 Grid-connected Inverter System

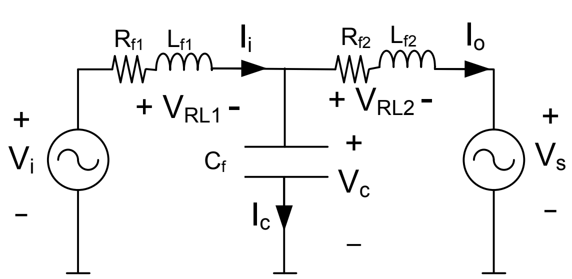

Fig. 2. Grid-Connected Three phase Inverter in single phase equivalent circuit

Grid-Connected Three phase inverter is connected to the grid via any type of filter. In the past, L filter is often used. But in practically, to reduce switching ripple produce by inverter switching modulation, a high value of L filter should be used. For high power application it becomes inefficient. Moreover, the response may become very slow. The alternative LCL filter is an attractive solution, as shown in Fig. 1. It acts as a common low-pass filter but require a deeply study on system stability.

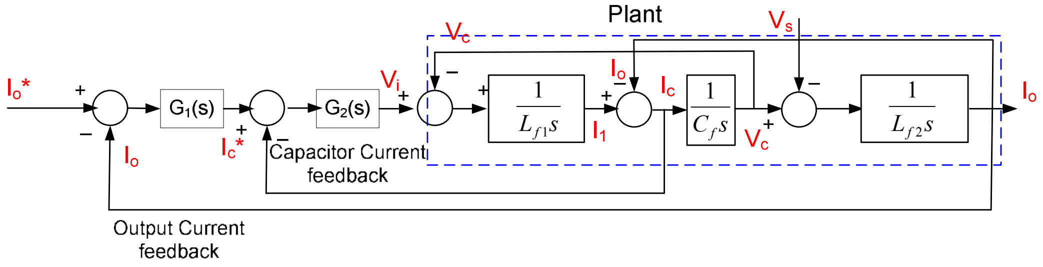

Fig. 3. Model of the system in s-Laplace domain

Generated power, it can be from fuel cell, solar or any type of renewable energy is represented as V_{dc} and grid voltage is represented as V_s. Output current i_o is injected from inverter to the grid. LCL filter is used to filter V_i, the output voltage of PWM inverter which contains high switching frequency component.

In this application, switching frequency is lower than mostly used in inverter application, at 5 kHz It is shown in Fig. 2, single phase equivalent circuit for the system. Inverter is modeled as an ideal voltage source. The system parameters are shown in Table 1. Grid voltage is assuming as an ideal sinusoidal waveform 50Hz. Resistance of inductor is neglected.

Table 1 Values of the system parameter

Parameters	Value
V_{dc}	650V
Inductor Filter	L_{f1}= L_{f2}= 4mh, C_f=20uF
Grid Voltage (Vs)	380 V, 50 Hz
Inverter Switching Freq	5 kHz

In this paper resonant frequency of the filer is set on 750Hz. It is followed a common rules for switching filter which filter resonant frequency is around one tenth of switching frequency. The resonant frequency of LCL is obtained by [4]:

$$f = \frac{1}{2\pi}\sqrt{\frac{L_{f1}+L_{f2}}{L_{f1}L_{f2}C}} \quad (1)$$

2.2 Modeling of the System

DC source generated from renewable energy in Fig. 1 is assumed constant in any condition such as increasing or decreasing power injected to the grid. Switching device is also assumed as an ideal switch without any losses. As shown in Fig. 2, the inverter is connected to the grid via LCL filter. Mathematical model for this circuit can be expressed as these following equations:

$$v_i - R_1 i_o - L_1\frac{d[i_o]}{dt} - R_2 i_o - L_2\frac{d[i_o]}{dt} - v_s = 0 \quad (2)$$

$$i_i - i_c = i_o \quad (3)$$

Which V_i is result of controller calculation which applied double loop controller. Fig. 3 is shown the single phase model for the system. The aim of controller is to maintain output current in phase with grid voltage Vs. So that inverter is injected real power only to the grid. Outer loop controller is used for controlling output current i_o, and inner loop controller is used for controlling capacitor current i_c. Output current feedback loop is provided reference for capacitor current feedback loop. Both of controllers $G_1(s)$ and $G_2(s)$ are proportional. By applying proportional controller, the advantage is no phase delay and not increasing transfer function of the system.

From Fig. 3, the closed loop transfer function of the system can be derived as:

$$i_o = \frac{K_{P1}K_{P2}}{C(s)} i_o * - \frac{C_f K_{P2} s + C_f L_{f1} s^2 + 1}{C(s)} v_s \quad (4)$$

Which:

$$C(s) = L_{f2}C_f L_{f1}.s^3 + L_{f2}C_f K_{P2}s^2 + (L_{f1}+L_{f2})s + K_{P1}.K_{P2} \quad (5)$$

Which i_o* is reference current, it is in sinusoidal form not in dc form. K_{p1} is proportional gain for outer loop controller which control output current i_o and K_{p2} is proportional gain for inner loop controller which control capacitor current i_c. From (4) and (5), output current would be identical to reference if K_{p1} and/or K_{p2} is very high. But it should be also consider that high gain might make the system unstable.

3. Simulation Results and Discussion

To verify the performance of the designed gain parameter, Root Locus and Bode plot are provided. Fig. 4 is shown Root Locus plot with constant K_{p2}=5 and 1≤K_{p1}≤7. It is shown that the Root Locus is reached left-half plane for high Kp1. In Fig. 4, left half plane is the dark area. Consider to Fig. 4, it is not guaranteed that the system is stable for any value. The system is stable for K_{p1} less than 2.4.

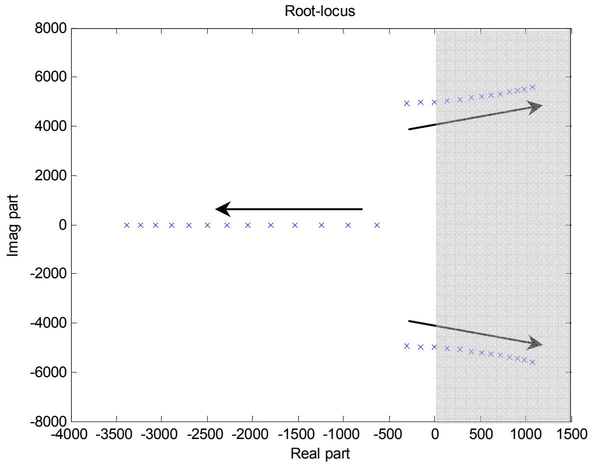

Fig. 4. Root locus of system with Kp2=5 and 1≤Kp1≤7

In Fig. 5, is shown Root Locus plot with constant K_{p1}=1 and 1≤K_{p2}≤7. It is shown that the Root Locus is entered to left half plane for high very high K_{p2}. Consider to Fig. 5, K_{p2} value is not critical. It is possible to increase K_p2 with very high value while the system is stable.

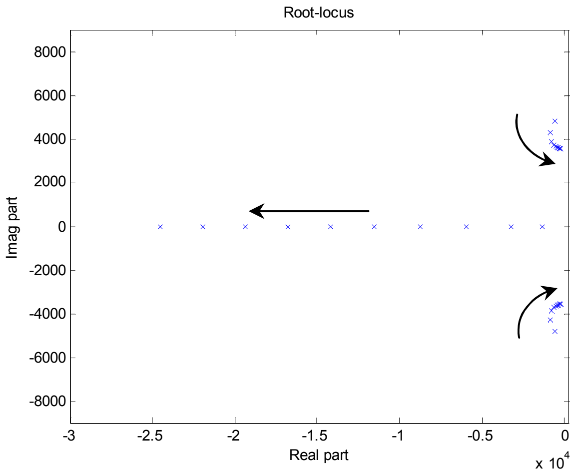

Fig. 5. Root locus of system with Kp1=1 and 1≤Kp2≤7

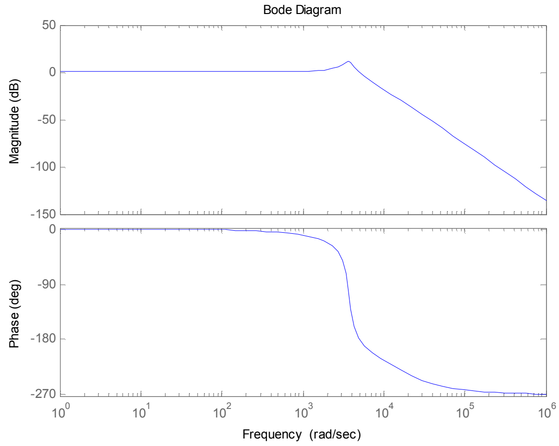

Fig. 6. Bode plot of Kp1=1 and Kp2=50

In Fig. 6 is shown the Bode Plot of closed loop system. It is shown that the characteristic is similar to low-pass filter. The cut off frequency of low-pass filter is similar to LCL frequency resonance. Consider to Bode plot, at operating frequency, 50Hz, it is shown that there is a small phase delay between reference current and output current. But the magnitude is almost same.

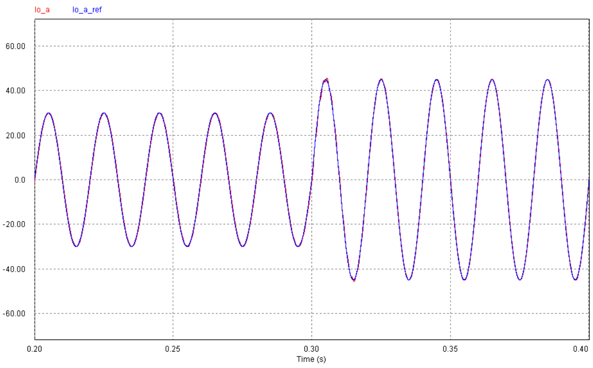

Fig. 8. PSIM simulation result for Kp1= 1 and Kp2=50 with decoupled control

In Fig. 8 is shown PSIM simulation result with K_{p1}=1. This is verified the result of frequency response. There is a small phase delay between reference current and output current. For 32Arms reference current, steady state error is 1.47Arms. Fig. 9 is shown for K_{p1}=2, the time response is very similar to Fig. 8, with less steady state error, 0.7Arms. Steady state error wave form is indicated with arrow. This simulation result is verified transfer function for the closed loop system, equation (4), which showing higher gain of K_{p1} would reduce steady state error. The current THD for figure 8 is around 1.5%.

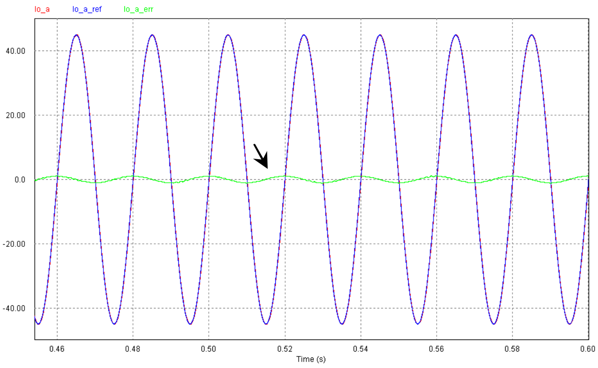

Fig. 9. PSIM simulation result for Kp1= 2 and Kp2=50 with decoupled control

3. Conclusion

In this paper, a simple proportional control is applied for grid connected inverter with LCL filter. LCL filter is a third order system. Applying a simple proportional controller is not increased the closed loop transfer function order. By this technique, the single phase model is easily obtained. To reduce steady state error, proportional gain is set as high as possible, but it may produce instability. To compromise between a minimum steady state error and stability, the single phase model is evaluate through Root Locus and Bode diagram. PSIM simulation result is verified the bode plot for system. There is a small phase delay between reference and output current. The current THD for output current is 1.5%. It is fulfilled IEEE standard. For future work, controller gain is design by CRA method.

4. Acknowledgement

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References

[1]. Sayaka Takamatsu, Eigo Shimada, and Tomoki Yokoyama, “ Digital Control Method for Single Phase Utility Interactive Inverter Using Deadbeat Control with FPGA Based Hardware Controller,” IEEE EPE-PEMC 2006 Conf. Proc., pp. 1436-1441.

[2]. Francisco Jurado, ”Novel Fuzzy Flux Control for Fuel-Cell Inverters,” IEEE Trans Ind. Electr., Vol. 52, No. 6, pp. 1707-1710, Dec. 2005.

[3]. Novie Ayub Windarko, Jinmok Lee, Kyoungmin Son, and Jaeho Choi, ”Pole-Assignment-based Gain Parameter Design of Resonant Current Control of Grid-Connected Single Phase Inverter,” KIPE 2008 Annual Power Electronics Conf. Proc., pp. 18-20

[4]. Marco Liserre, Frede Blaabjerg, and Steffan Hansen,”Design and Control of an LCL-Filter-Based Three-Phase Active Rectifier,” IEEE Trans. On Ind. Appl. Vol. 41, no.5. pp.1281-1291, Sept/Oct 2005.