Design of Gain Controller of Decoupling Control of Grid-connected Inverter with LCL Filter

Novie Ayub Windarko, Jinmok Lee and Jaeho Choi
School of Electrical and Computer Engineering
Chungbuk National University
410 Sungbong-Ro, Heungduk-Gu, Cheongju, Chungbuk, KOREA

Abstract

Grid Connected inverter is produced current to deliver power to grid. To provide low THD current, LCL filters is effective to filter high frequency component of current output from inverter. To provide sinusoidal waveform, there are many researchers have been proposed several controllers for 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. But SRF based controller is contained cross-coupling components, which generate some difficulties to analyze.

In this paper, SRF based controller is analyzed. By applying decoupling control, cross-coupling component is eliminated and single phase model of the system is obtained. Through this single phase model, gain controller is designed. 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 the near future, microgrid system is expected to be widely implemented. Several reasons have been boosting the research on this area, such as oil prices, environmental issues, reducing losses etc. So far, microgrid sources are based on Wind power [1], PV power, Fuel Cell and so on. These microgrid sources could be categorized into two types, uncontrolled and controlled sources. Uncontrolled microgrid source is based on uncontrolled renewable energy, such as wind, solar etc. Controlled type is based on controlled renewable energy such as Fuel Cell etc.

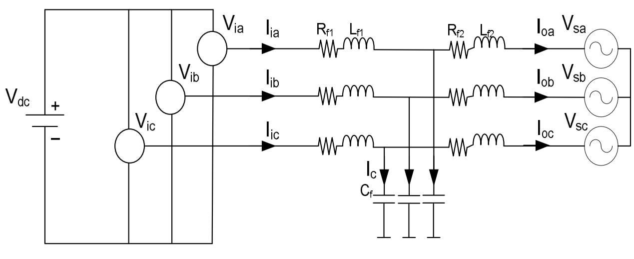

Fig. 1. Grid-Connected Three phase Inverter

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 isolated area.

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, 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. However, to evaluate its performance, it needed the single phase model of system.

In this paper, single phase model of the system is obtained by eliminating cross-coupling component. Cross-coupling is eliminated by decoupling method. Then, the single phase model is analyzed to evaluate its performance in stability and frequency response. 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

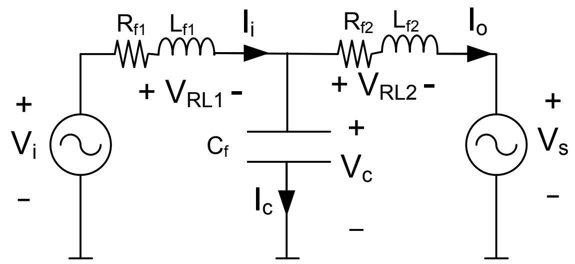

Fig. 2. Grid-Connected Three phase Inverter in single phase equivalent circuit

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 this filter type is strongly influenced the system stability.

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

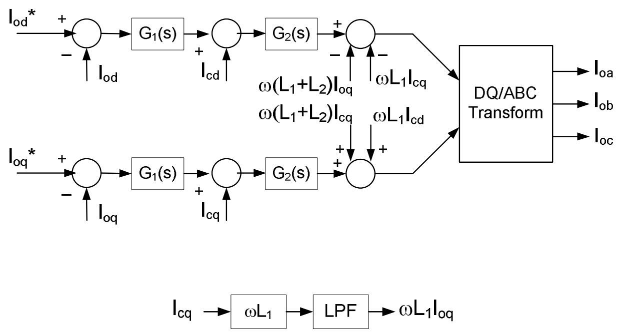

Fig. 3. Block of the decoupling controller

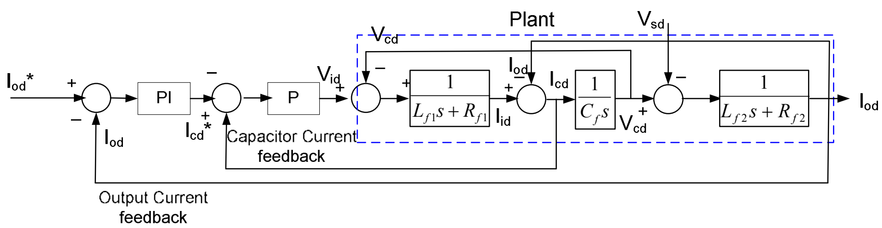

Fig. 4. Model of the system in s-Laplace domain

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
LCL Filter	L_{f1}= L_{f2}=4mh, Rf1=Rf2=0.01 Ω 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]:

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

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:

$$v_i - R_{f1}i_o - L_{f1}\frac{d[i_o]}{dt} - R_{f2}i_o - L_{f2}\frac{d[i_o]}{dt} - v_s = 0 \tag{2}$$

$$i_i - i_c = i_o \tag{3}$$

$$(L_1+L_2)\frac{di_{od}}{dt} = -L_1\frac{di_{cd}}{dt} - V_{sd} + V_{id} + \underline{\omega(L_1+L_2)i_{oq}} + \underline{\omega L_1 i_{cq}} \tag{4}$$

$$(L_1+L_2)\frac{di_{oq}}{dt} = -L_1\frac{di_{cq}}{dt} - V_{sq} + V_{iq} - \underline{\omega(L_1+L_2)i_{od}} - \underline{\omega L_1 i_{cd}} \tag{5}$$

Which V_i is result of controller calculation which applied double loop controller. Underline in equation (4) and (5) is indicated the crosscoupling component. Fig. 3 is shown the decoupling controller which eliminated the crosscoupling component. By applying the decoupling controller, the system block is become simple as a single phase model. Decoupling feedback for eliminating crosscoupling is obtained by LPF and constant $\omega(L_1+L_2)$ for ouput current i_o or L_1 for capacitor current i_c. LPF is maintained ouput current or capacitor current to be in dc form. In this single phase model, 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.

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

$$i_{od} = \frac{(K_{pic}K_{pio}s + K_{pic}K_{iio})}{C(s)}.i_{od}^{*} - \frac{(C_f.L_{f1}.s^3 + C_f.R_{f1}.s^2 + C_f.K_{pic}.s^2 + s)}{C(s)}v_{sd} \tag{5}$$

Which:

$$C(s) = L_{f2}.C_f.L_{f1}.s^4 + (R_{f2}.C_f.L_{f1} + L_{f2}.C_f.R_{f1} + L_{f2}.C_f.K_{pic}).s^3 + (R_{f2}.C_f.R_{f1} + L_{f1} + R_{f2}.C_f.K_{pic} + L_{f2})s^2 + (R_{f1} + K_{pic}.K_{pio} + R_{f2}).s + K_{pic}K_{iio} \tag{6}$$

Which i_o* is reference current, it is in dc form. K_{pio} is proportional gain and K_{iio} is integral gain for outer loop controller which control output current i_o and K_{pic} 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_{pio} and/or K_{pic} is very high. But it should be also considered that high gain may be introducing instability to the system.

3. Simulation Results and Discussion

To verify the performance of the designed gain parameter, Root Locus and Bode plot are provided. Fig. 5 is shown Root Locus plot with constant K_{pic}=50 and $0.5 \le K_{pio} \le 3$ In Fig. 5, left half plane is the dark area. It is shown from Root Locus; some value of K_{pio} is lie on left-half plane. Consider to Fig. 5, it is not guaranteed that the system is stable for any value. The system is stable for K_{pio} less than 2.

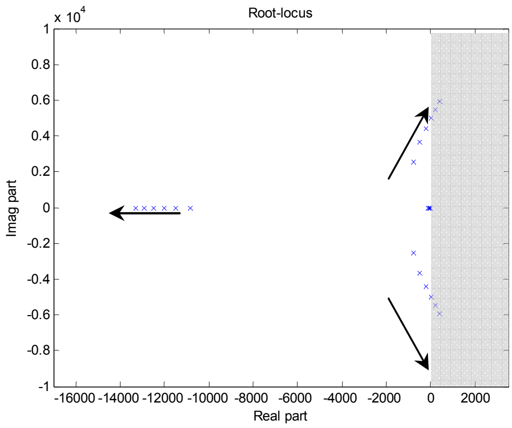

Fig. 5. Root locus of system with K_{pic}=50 and $0.5 \le K_{pio} \le 3$, K_{iio}=50

In Fig. 6, is shown Root Locus plot with constant K_{pio}=1.5, K_{iio}=50 and $1 \le K_{pic} \le 7$. It is shown that the Root Locus is entered to left half plane for very high K_{pic}. Consider to Fig. 5, K_{pic} value is not critical. It is possible to increase K_{pic} with very high value while the system is maintained in stable condition.

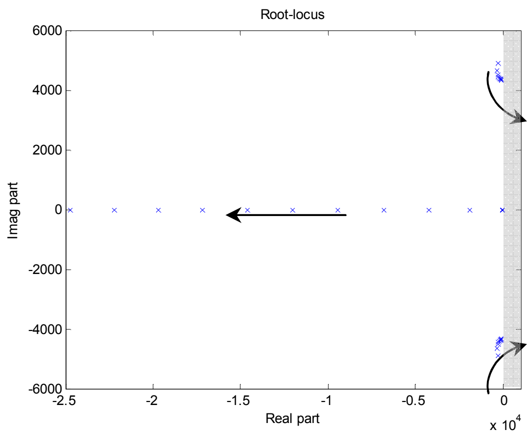

Fig. 6. Root locus of system with K_{pio}=1.5, K_{iio}=50 and $10 \le K_{pic} \le 100$

In Fig. 7 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 no phase delay between reference current and output current, and the magnitude is almost same.

In Fig. 8 is shown PSIM simulation result with K_{pio}=1.5. This is verified the result of frequency response. There is no small phase delay between reference current and output current. Oscillation in output current is resulted from a pole which very close to left half plane, it is shown both of ini Fig 5 and Fig 6.

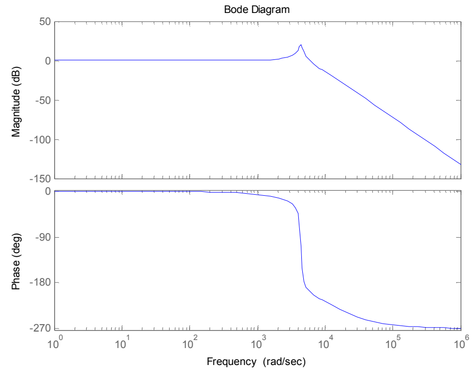

Fig. 7. Bode plot of K_{pio}=1.5, K_{iio}=50 and K_{pic}=50

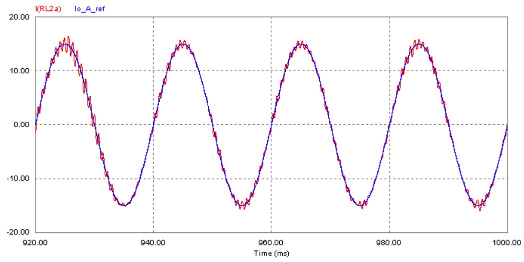

Fig. 8. PSIM simulation result for K_{pio}= 1.5,K_{iio}=50 and K_{pic}=50

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. Oscillation in output current is resulted from a pole which very close to left half plane.

4. Acknowledgement

This work was supported by New & Renewable Energy RD&D Program from National RD&D Organization for Hydrogen and Fuel Cell, Korea Energy Management Corporation, and MOCIE (Ministry of Commerce, Industry and Energy).

References

[1]. Jaeho Choi, Eel-Hwan Kim, Gil-Soo Jang, Seung-Ho Song, Se-Ho Kim, Seong-Bo Oh, “Power Quality Analysis of Jeju Island Power System Connected with Wind Farm and HVDC System,” EPE-PEMC 2008

[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.