Optimal Control Design-based Gain Selection of an LCL-filtered Grid-connected Inverter in State-Space under Distorted Grid Environment

Vi-Thuy Tran, Seung-Jin Yoon, Kyeong-Hwa Kim†
Seoul National University of Science and Technology

ABSTRACT

In order to alleviate the negative impacts of harmonically distorted grid condition on grid-connect inverters, an optimal control design-based gain selection scheme of an LCL-filtered grid-connected inverter and its ability to compensate selective harmonics are presented in this paper. By incorporating resonant terms into the control structure in the state-space to provide infinity gain at selected frequencies, the proposed control offers an excellent steady-state response even under distorted grid voltage. The proposed control scheme is achieved by using a state feedback controller for stabilization purpose and by augmenting the resonant terms as well as intergral term into a control structure for reference tracking and harmonic compensation. Furthermore, the optimal linear quadratic control approach is adopted for choosing an optimal feedback gain to ensure an asymptotic stability of the whole system. A discrete-time full state observer is also introduced into the proposed control scheme for the purpose of reducing a total number of sensors used in the inverter system. The simulation results are given to prove the effectiveness and validity of the proposed control scheme.

1. Introduction

The increasing interest in a grid-connected voltage source inverter for renewable energy conversion system poses a challenge not only to ensure high quality of the inverter injected current, but also to alleviate the deleterious impacts of harmonically distorted grid condition on grid-connect inverters. The fundamental requirement in control system is the capability to offer a high-quality injected output current which is immune from harmonic contents presented in the grid.

Conventionally, the PI controller implemented in the synchronous reference frame is generally employed because it can achieve zero steady-state error. However, the PI controller cannot work properly under adverse grid environment. To deal with adverse grid condition, the proportional-resonant (PR) controller implemented in the stationary reference frame is used more commonly for a grid-connected inverter in order to provide a good tracking ability for sinusoidal reference current [1]. Selective harmonics in the current can be eliminated by using additional PR controllers performing at particular frequencies. However, the solution usually increases significant complexity and computational efforts.

This paper presents a design methodology for a grid-connected inverter with an LCL filter in the state-space using an integral state feedback control incorporating resonant terms into control structure. In this proposed scheme, the controller is implemented in the synchronous reference frame in order that the integral control on DC quantities can ensure zero steady-state error. Also, two harmonic components in phase currents at the 5^{th} and 7^{th} order can be effectively compensated at the same time with one resonant term. In order to reduce a total number of sensors required for the control of LCL filtered grid-connected inverter, a full state observer is designed in the discrete-time domain.

On account of the augmentation of the resonant terms as well as intergral term into inverter model, an increasing number of feedback gains should be selected. To choose feedback gains in a systematic way, the optimal linear quadratic control approach is adopted by minimizing the cost function for the purpose of satisfying the stability and robustness requirements of the system. The simulation results under adverse grid condition are provided to demonstrate the effectiveness and validity of the proposed control scheme.

2. Grid-connected Inverter with LCL Filter

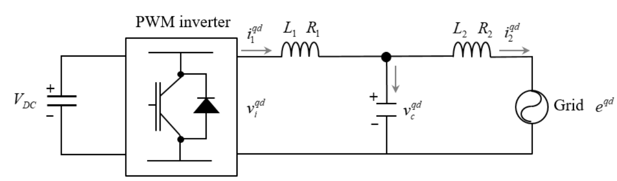

Fig. 1 Grid-connected inverter with LCL filter.

Fig. 1 shows a three-phase inverter connected to the grid through LCL filters. A mathematical model is represented in the synchronous reference frame as follows:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{D}\mathbf{e}(t) \quad (1)$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) \quad (2)$$

where $\mathbf{x} = [i_2^q\ i_2^d\ i_1^q\ i_1^q\ v_c^d\ v_c^q\ v_c^d]^T$ is the system state vector, i_2^q and i_2^d are the grid currents, i_1^q and i_1^d are the inverter currents, and v_c^q and v_c^d are the capacitor voltages, respectively, $\mathbf{u} = [v_i^q\ v_i^d]^T$ is the system input vector with v_i^q and v_i^d being the inverter output voltages, and $\mathbf{e} = [e^q\ e^d]^T$ is grid voltage vector. The continuous-time model can be discretized as

$$\mathbf{x}(k+1) = \mathbf{A_d}\mathbf{x}(k) + \mathbf{B_d}\mathbf{u}(k) + \mathbf{D_d}\mathbf{e}(k) \quad (3)$$

$$\mathbf{y}(k) = \mathbf{C_d}\mathbf{x}(k) \quad (4)$$

where $\mathbf{A_d} = e^{\mathbf{A}T_s} = \mathbf{I} + \frac{\mathbf{A}T_s}{1!} + \frac{\mathbf{A}^2T_s}{2!} + \cdots$

† Corresponding author

$$\mathbf{B_d} = \mathbf{A}^{-1}(\mathbf{A_d} - \mathbf{I})\mathbf{B},\ \mathbf{C_d} = \mathbf{C},\ \mathbf{D_d} = \mathbf{A}^{-1}(\mathbf{A_d} - \mathbf{I})\mathbf{D}$$

and T_s is the sample time.

3. Proposed Current Control Scheme

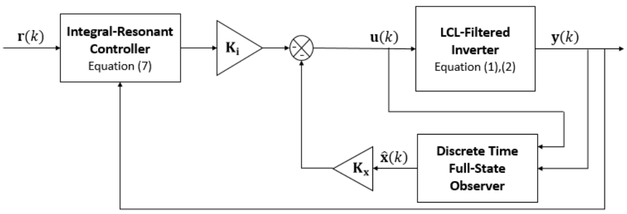

Fig. 2 Block diagram of the proposed current controller.

To ensure an asymptotic reference tracking as well as disturbance rejection for the harmonics in the orders of 6th and 12th in the synchronous reference frame, a current controller is constructed by augmenting integral control and resonant terms in the state−space. An integral term in the state−space is expressed as [2]

$$\begin{bmatrix} \dot{x}_i^q(t) \\ \dot{x}_i^d(t) \end{bmatrix} = \mathbf{A_i} \begin{bmatrix} x_i^q(t) \\ x_i^d(t) \end{bmatrix} + \mathbf{B_i} \begin{bmatrix} x_e^q(t) \\ x_e^d(t) \end{bmatrix} \quad (5)$$

where $\mathbf{A_i} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$, $\mathbf{B_i} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

$$\mathbf{x_e} = \begin{bmatrix} x_e^q & x_e^d \end{bmatrix}^T = \mathbf{r} - \mathbf{C_d}\mathbf{x},\ \mathbf{r} = \begin{bmatrix} i_2^{q*} & i_2^{d*} \end{bmatrix}^T.$$

Resonant terms for the q−axis and d−axis are expressed in the state−space as

$$\begin{bmatrix} \dot{\delta}_1^q(t) \\ \dot{\delta}_2^q(t) \\ \dot{\delta}_1^d(t) \\ \dot{\delta}_2^d(t) \end{bmatrix} = \mathbf{A_{rj}} \begin{bmatrix} \delta_1^q(t) \\ \delta_2^q(t) \\ \delta_1^d(t) \\ \delta_2^d(t) \end{bmatrix} + \mathbf{B_{rj}} \begin{bmatrix} x_e^q(t) \\ x_e^d(t) \end{bmatrix} \text{ for } j = 6,\ 12 \quad (6)$$

$$\mathbf{A_{rj}} = \begin{bmatrix} 0 & 1 & & \\ -(j\omega)^2 & -2\xi(j\omega) & & \\ & & 0 & 1 \\ & & -(j\omega)^2 & -2\xi(j\omega) \end{bmatrix},\ \mathbf{B_{rj}} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}$$

The system states in (5) and (6) are augmented as

$$\dot{\mathbf{z}}_\mathbf{c}(t) = \mathbf{A_c}\mathbf{z_c}(t) + \mathbf{B_c}\mathbf{x_e}(t) \quad (7)$$

where $\mathbf{z_c} = \begin{bmatrix} x_i^q & x_i^d & \delta_{16}^q & \delta_{26}^q & \delta_{16}^d & \delta_{26}^d & \delta_{112}^q & \delta_{212}^q & \delta_{112}^d & \delta_{212}^d \end{bmatrix}^T$

$$\mathbf{A_c} = \begin{bmatrix} \mathbf{A_i} & & \\ & \mathbf{A_{r6}} & \\ & & \mathbf{A_{r12}} \end{bmatrix},\ \mathbf{B_c} = \begin{bmatrix} \mathbf{B_i} \\ \mathbf{B_{r6}} \\ \mathbf{B_{r12}} \end{bmatrix}.$$

The state equation in (7) is similarly discretized by means of the procedure used to obtain (3) and (4). Then, the entire control system can be augmented as follows:

$$\begin{bmatrix} \mathbf{x}(k+1) \\ \mathbf{z_c}(k+1) \end{bmatrix} = \begin{bmatrix} \mathbf{A_d} & \mathbf{0} \\ -\mathbf{B_{cd}}\mathbf{C_d} & \mathbf{A_{cd}} \end{bmatrix} \begin{bmatrix} \mathbf{x}(k) \\ \mathbf{z_c}(k) \end{bmatrix} + \begin{bmatrix} \mathbf{B_d} \\ \mathbf{0} \end{bmatrix} \mathbf{u}(k) + \begin{bmatrix} \mathbf{D_d} \\ \mathbf{0} \end{bmatrix} \mathbf{e}(k) + \begin{bmatrix} \mathbf{0} \\ \mathbf{B_{cd}} \end{bmatrix} \mathbf{r}(k) \quad (8)$$

$$\mathbf{y}(k) = \begin{bmatrix} \mathbf{C_d} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{x}(k) \\ \mathbf{z_c}(k) \end{bmatrix} \quad (9)$$

$$\mathbf{u}(k) = -\begin{bmatrix} \mathbf{K_x} & \mathbf{K_i} \end{bmatrix} \begin{bmatrix} \mathbf{x}(k) \\ \mathbf{z_c}(k) \end{bmatrix}. \quad (10)$$

where $\mathbf{A_{cd}}$ and $\mathbf{B_{cd}}$ are the discrete−time counterparts of $\mathbf{A_c}$ and $\mathbf{B_c}$, $\mathbf{K} = [\mathbf{K_x} \quad \mathbf{K_i}]$ is a set of feedback gains.

To ensure the control performance and system stability, the two gain vectors in system (8) are evaluated systematically by minimizing the quadratic cost function as follows:

$$\mathbf{J} = \int_0^\infty (\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{u}^T\mathbf{R}\mathbf{u})dt \quad (11)$$

where $\mathbf{Q}$ and $\mathbf{R}$ denote the weighting matrices. In addition, a full−state observer is constructed in the discrete−time domain by using (3) and (4), and the estimated states are used in the state feedback control in (10) to avoid the necessity of additional sensors. The block diagram of the proposed current control is described in Fig. 2.

4. Simulation Results

To demonstrate the performance of the proposed scheme, the simulation results are presented. Fig. 3 shows three−phase distorted grid voltages used in the simulation and Fig. 4 shows the current responses of the proposed scheme. It is clearly confirmed that the proposed scheme can provide good injected inverter output currents even under distorted grid environment.

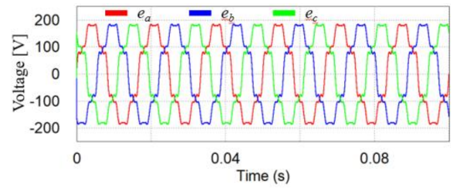

Fig. 3 Distorted grid voltages.

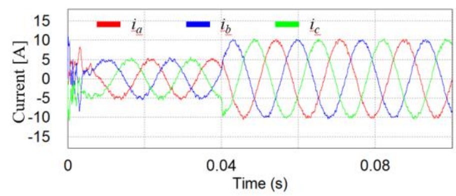

Fig. 4 Current waveforms of the proposed controller.

5. Conclusion

This paper has presented an optimal control design−based gain selection scheme for LCL−filtered grid−connected inverters. The proposed scheme is achieved by the augmentation of an integral control and resonant terms into a state feedback control for the purpose of reference tracking and harmonic compensating. The simulation has confirmed the validity of the proposed scheme.

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[1] C. Lascu, L. Asiminoaei, I. Boldea, and F. Blaabjerg, "High performance current controller for selective harmonic compensation in active power filters," IEEE Trans. on Power Electron., vol. 22, no. 5, pp. 1826− 1835, 2007.

[2] S. J. Yoon, N. B. Lai, and K. H. Kim, "A systematic controller design for a grid−connected inverter with LCL filter using a discrete−time integral state feedback control and observer," Energies, vol. 11, no. 437, pp. 1−20, Feb. 2018.