Robust Feedback Control Design for a Three-phase Grid-connected Inverter in Distributed Generation System

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ABSTRACT

This paper presents a robust feedback control design to mitigate the effect of grid voltage disturbances for three-phase grid-connected inverters in distributed generation systems. The proposed strategy consists of two major design steps. First, the controller is synthesized using the internal model principle to achieve a good reference tracking and disturbance rejection performance. Then, the feedback gain is systematically obtained by solving the linear matrix inequality conditions which are directly derived from the stability criteria. The main contribution of this paper is that the complexity of control structure can be substantially reduced and transient response is improved as compared with the existing robust control design methods. The simulation results are given to prove the validity of the proposed control scheme.

1. Introduction

Current controller is known as the essential element in the control system of power electronic-based converters. For grid-connected inverter system, current controller is not only responsible for controlling injected current but also partly in charge of the power quality which is delivered from renewable sources to the utility grid[1].

The most frequently used controller to control the injected current is proportional-integral controller because of its simplicity and effectiveness in terms of design and implementation. However, this controller is unable to cope with the sinusoidal disturbances presented in abnormal grid voltage[2]. To deal with this challenge, a systematic method has been proposed in [3]. Despite the fact that the system stability is guaranteed using the design approach suggested in [3], the resulting controller exhibits a considerable oscillation during the transient periods. Moreover, this controller is designed in natural frame which is not suitable for three-phase grid-connected inverters.

To enhance the transient response of the current controller, and reduce the complexity of control structure, a robust feedback control for three-phase grid-connected inverter which is implemented in synchronous reference frame is proposed in this paper. The effectiveness of the proposed approach is confirmed through numerical results.

2. Modeling of Three-phase Inverter

The continuous-time description of a three-phase inverter connected to the grid through L filters is given in synchronous reference frame as

$$\begin{aligned}\dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) - \mathbf{B}\mathbf{w}(t)\\ \mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t)\end{aligned} \tag{1}$$

where $\mathbf{x} = \begin{bmatrix} i_q & i_d \end{bmatrix}^T$ is inverter current vector, $\mathbf{u} = \begin{bmatrix} v_q & v_d \end{bmatrix}^T$ is inverter output voltage vector, $\mathbf{w} = \begin{bmatrix} e_q & e_d \end{bmatrix}^T$ is grid voltage vector, and

$$\mathbf{A} = \begin{bmatrix} -R/L & -\omega \\ \omega & -R/L \end{bmatrix},\ \mathbf{B} = \begin{bmatrix} 1/L & 0 \\ 0 & 1/L \end{bmatrix},\ \mathbf{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

3. Proposed Current Controller

To improve the robustness of current controller, an internal model-based controller is used. This controller can be expressed as

$$\dot{\mathbf{z}}(t) = \mathbf{H}\mathbf{z}(t) + \mathbf{\Gamma}\mathbf{e}(t) \tag{2}$$

$$\boldsymbol{u}(t) = [\boldsymbol{K_x} \quad \boldsymbol{K}_i]^T \cdot [\boldsymbol{x}(t) \quad \boldsymbol{z}(t)]\,. \tag{3}$$

Equation (2) is the exosystem which describes the grid voltage including harmonics, $\mathbf{z} \in \Re^{(4n+4)\times 1}$ is the state vector, $\mathbf{e} = \mathbf{r} - \mathbf{C}\mathbf{x} \in \Re^{(4n+4)\times 1}$ is the tracking error vector, n is the number of harmonic terms, and

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}_1 & \\ & \mathbf{H}_i \end{bmatrix} = \begin{bmatrix} 0 & 0 & & & & \\ 0 & 0 & & & & \\ & & 0 & 1 & 0 & 0 \\ & & -\omega_i^2 & 0 & 0 & 0 \\ & & 0 & 0 & 0 & 1 \\ & & 0 & 0 & -\omega_i^2 & 0 \end{bmatrix},\ \mathbf{\Gamma} = \begin{bmatrix} \mathbf{\Gamma}_1 \\ \mathbf{\Gamma}_i \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix}$$

where i denotes the i^{th} harmonic component.

From (1) and (2), the augmented system can be rewritten as

$$\begin{bmatrix} \dot{\mathbf{x}}(t) \\ \dot{\mathbf{z}}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{\Gamma}\mathbf{C} & \mathbf{H} \end{bmatrix} \begin{bmatrix} \mathbf{x}(t) \\ \mathbf{z}(t) \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ \mathbf{0} \end{bmatrix} \mathbf{u}(t) - \begin{bmatrix} \mathbf{B} \\ \mathbf{0} \end{bmatrix} \mathbf{w}(t)$$

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$$\mathbf{y}(t) = \begin{bmatrix}\mathbf{C} & \mathbf{0}\end{bmatrix}\mathbf{x}(t) \qquad (4)$$

From (3) and (4), one can easily obtain the feedback gains by using any gain evaluation methods such as the pole placement or linear matrix inequality. In this paper, feedback gains are evaluated by solving the matrix inequality conditions which are derived from the Lyapunov stability criteria. The block diagram of the proposed controller is illustrated in Fig. 1.

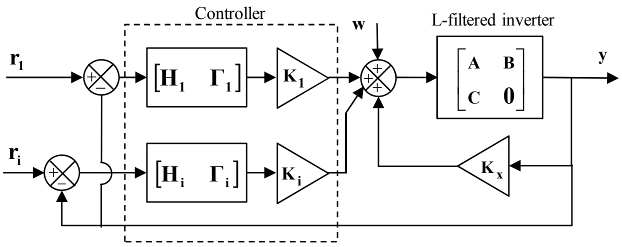


Fig. 1 Block diagram of the proposed current controller.

3. Simulation Results

To highlight the effectiveness of the proposed controller, the simulations have been carried out. The system includes three-phase inverter connected to utility grid through L filters. The unbalanced and distorted gird voltage is formed by superimposing 10% of 5th and 7th, and 5% of 11th and 13th harmonics into sinusoidal unbalanced grid voltages whose amplitudes have 20% voltage sag in c-phase, as depicted in Fig. 2.

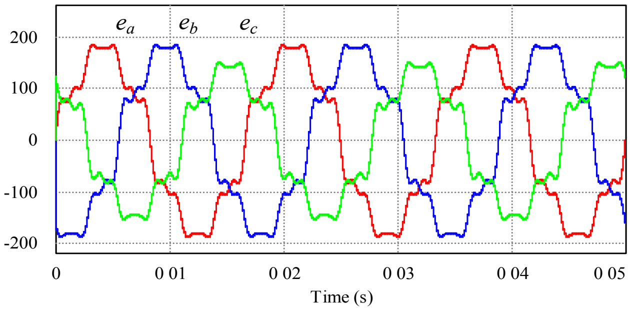


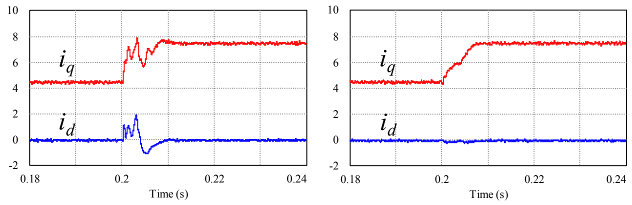
Fig. 2 The unbalanced and distorted gird voltage.

Fig. 3 compares the step responses of inverter currents using the controller in [3] and that using the proposed controller. As clearly shown in Fig. 3b, there is no oscillation in the step response of the proposed controller as compared with the noticeable fluctuation in Fig. 3a by the controller suggested in [3].

To demonstrate the steady-state performance of the proposed controller under adverse grid voltage, Fig. 4 shows the waveforms of inverter phase currents under unbalanced and distorted grid voltage. As can be observed, the phase currents still remain sinusoidal in spite of highly distorted grid voltage.

4. Conclusion

This paper has presented a robust feedback current controller to enhance the power quality of distributed generation system by alleviating the harmful effect of adverse grid voltage on inverter current. The proposed controller is based on the internal model principle and implemented in the synchronous reference frame, which results in a significant reduction of the controller dimension. The simulation has confirmed the better transient response in comparison with the conventional feedback controller.



(a) (b)

Fig. 3 Step response of inverter currents under unbalanced and distorted grid voltage. a) using the current controller suggested in [3]. b) using the proposed current controller.

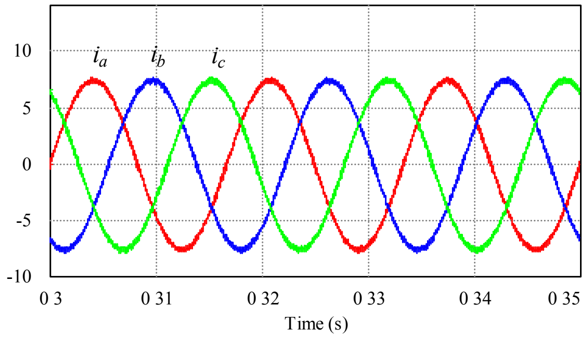


Fig. 4 Steady-state response of the proposed controller.

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4. References

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