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Optimized design method for grid-current-feedback active damping to improve dynamic characteristic of LCL-type grid-connected inverter

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ABSTRACT

In LCL-type grid-connected inverter, an optimized design method for grid-current-feedback active damping (AD) is proposed to improve the system dynamic characteristic. By analyzing the equivalent virtual impedance model, the essential relationship between the system dynamic characteristic indicators and damping control parameters is obtained, and the damping control parameters are contradictory that difficult to optimize. Then, a parameters optimization design method combining zero-pole model and Routh stability criterion is proposed to reduce the complexity of the parameters design and improve the system dynamic. Moreover, the influence of the control delay on system stability and parameters design is analyzed in the discrete domain. Simulation and experimental results verified the validity of the proposed method.

1. Introduction

Due to the shortage of fossil energy and environmental pollution, more renewable energy and distributed power generations are rapidly developed. The grid-connected inverter has become an important topology for linking renewable and other clean energy to utility grids [1,2]. However, the high harmonics generated by inverter pulse width modulation will affect the safety and stability of the grid-connected system, which should be suppressed or eliminated. It is well known that using an LCL-filter instead of a simple inductor could improve the ability of high frequency harmonic suppression, and reduce inductance values to make the device smaller and lighter. But, as a three-order model, the resonance problems exist in the LCL-type grid-connected inverter, which could bring oscillation and instability. Therefore, damping methods should be considered to avoid these problems [3–7].

Both passive damping and active damping (AD) are effective methods to suppress the LCL-filter resonance [8,9]. Compared to passive damping, the active one, using extra feedback control loop, could get the same suppression effect without additional power loss. Therefore, active damping is more efficient and flexible, which becomes a hot issue recently. In [10,11], the capacitive current is sampled and fed back to suppress the resonance, but the amplitude of capacitive current is so small that increases the difficulty of precisely processing on control variables. In [12–15], a feedback control method, which is based on the differential of inductance voltage in grid side or capacitive voltage, is used to add the system damping. However, it is hard to realize differentiation element without noise signals in practice. All these methods are need extra current or voltage sensors besides grid current sensor, which increase the cost and unreliability of system. In [16], a creative method using twice differentials of grid current is proposed to realize the resonance damping control without extra sensors. However, the derivative will amplify the noises, and the feedback parameter will be hard to select. In [17], capacitive current is estimated and fed back to eliminate the resonance peak without extra sensors, but the estimating method is complicated, time-consuming and easy to lead errors. In [18–22], an effective grid-current-feedback AD method based on HPF is proposed. It could improve the system reliability and reduce the cost without extra sensor. However, there are two inter-constraint parameters for system dynamic characteristic which mainly affects the system response speed and damping factor, so that the parameters of this method are hard to be selected in a suitable way.

In this paper, an optimized design method for grid-current-feedback AD is proposed to improve system dynamic characteristic. Firstly, it presents a virtual impedance model to analyze the mechanism of grid-current-feedback AD based on HPF. Secondly, based on the virtual impedance mode and the Routh stability criterion, the difficulties in the parameters design of this AD method is presented in the Section 3. Then the essential relationship between the system dynamic characteristic indicators and damping control parameters is obtained. In the Section 4, the parameters optimized design method is derived, which not only

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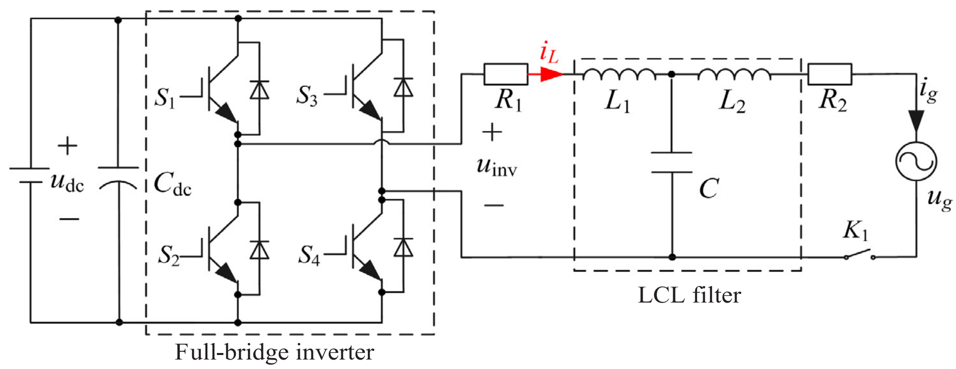

Fig. 1. Structure of single-phase grid-connected inverter with LCL-filter.

improves the system dynamic performance, but also reduces the complexity of parameters design significantly. In Section 5, a discrete control model is established to analyze the delay effect imposing on parameters optimization and system stability. In the Section 6, experimental results are presented to validate the theoretical analysis. Finally, Section 7 concludes this paper.

2. System modeling and characteristics

The structure of single-phase grid-connected inverter with LCL-filter is shown in Fig. 1, which mainly includes the dc regulated voltage U_{dc}, the single-phase full-bridge inverter, and LCL filter. The single-phase full-bridge inverter is formed by power switches S_1-S_4 and their anti-parallel-diodes. The inverter output current is smoothened by the LCL filter. In Fig. 1, L1 and L2 are the inverter side inductance and grid side inductance of LCL filter separately, and their equivalent series resistors (ESR) are R_1 and R_2; C is the capacitance of the LCL filter. C_{dc} is the energy-storage capacitors. u_{inv} is the output voltage of inverter and u_g is grid voltage. i_g is the grid current of inverter and i_L is the inverter current. u_c is the capacitive voltage of LCL filter, and K_1 is grid-connected switch.

Selecting i_L, i_g and u_c as state variables, the inverter system state space equation is derived as:

$$\begin{cases} \frac{di_L}{dt} = -\frac{R_1}{L_1}i_L - \frac{1}{L_1}u_c + \frac{1}{L_1}u_{inv} \\ \frac{di_g}{dt} = -\frac{R_2}{L_2}i_L + \frac{1}{L_2}u_c - \frac{1}{L_2}u_g \\ \frac{du_c}{dt} = \frac{1}{C}i_L - \frac{1}{C}i_g \end{cases} \quad (1)$$

From (1), the Block diagram of the LCL-type inverter system is showed in Fig. 2.

Taking u_g as the disturbance signal, the transfer function between u_{inv} and i_g is given as:

$$G_d = \frac{1}{s^3L_1L_2C + s^2C(R_1L_2 + L_1R_2) + s(L_1 + L_2 + R_1R_2C) + R_1 + R_2} \quad (2)$$

where R_1、R_2 is so small that can be ignored. From (2), the grid current is easily resonated at the natural resonance angular frequency:

$$\omega_{res} = \sqrt{\frac{(L_1 + L_2)}{L_1L_2C}} \quad (3)$$

Therefore, an efficient damping method is needed to suppress the inherent resonance of the LCL-filter, otherwise the overall system might oscillate and even be unstable.

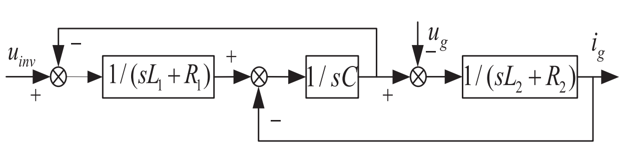

Fig. 2. Block diagram of the LCL-type inverter system.

3. System control method and design difficulty

Fig. 3 presents the control block diagram of LCL-type grid connected inverter, which includes the outer current controller and inner AD controller. The outer controller regulates the grid current i_g to control the injected power into the grid. The inner AD controller damps LCL-resonance and improves both transient and steady-state performances. Since only one high-precision sensor is required to facilitate both the grid current tracking and the LCL-resonance restraining, the proposed control strategy decreases the hardware cost and improves the system stability. $G_i(s)$ is the transfer function of output grid current controller. i_{ref} is the commanded grid current. K_{inv} is the equivalent gain of inverter, and i_d is PWM modulation signal.

Here, the transfer function of this AD method is expressed as,

$$H(s) = \frac{K_d}{s + \omega_d}s \quad (4)$$

where K_d and ω_d are the gain and cutoff angular frequency of the HPF respectively.

3.1. Virtual impedance model of the grid-current-feedback AD

To illustrate the feasibility and effectiveness of this strategy, a virtual impedance equivalent model is established in Fig. 4. Referring to Fig. 3, if replacing the feedback variable of the grid current i_g with the capacitor voltage u_c, and moving the feedback node backward to the output of $1/s_{L1}$, the grid-current-feedback AD is equivalent to virtual impedance Z_{eq1} in parallel with the filter capacitor C, as shown in Fig. 4(a).

The impedance is expressed as:

$$Z_{eq1} = -\frac{s^2L_1L_2(s + \omega_d)}{K_dK_{inv}s} \quad (5)$$

Z_{eq1} is presented in the form of parallel connection between a resistor R_0 and a capacitor C_0, as shown in Fig. 4(b). Bringing $s = j\omega$ into (5), then the expressions of R_0 and C_0 are:

$$\begin{cases} R_0 = \frac{L_1L_2(\omega^2 + \omega_d^2)}{K_dK_{inv}} \\ C_0 = \frac{K_dK_{inv}\omega_d}{L_1L_2(\omega^4 + \omega^2\omega_d^2)} \end{cases} \quad (6)$$

From (6), after combining the filter capacitor C and virtual capacitor C_0, the damping factor ξ_0 and the actual resonance angular frequency ω_n can be derived as: