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A Grid Voltage Feed-forward Control Strategy Based on The Virtual Impedance

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Abstract. This paper initially investigates the conventional LCL filter grid-connected inverts system, which introduces the control strategy with inverter-side current feedback, and analyzes the deficiencies within the strategy. The stability of the controller can be improved by adopting the active damping scheme. However, the output current of the inverter is severely influenced by the external grid voltage distortion and the grid low-order harmonic voltage. In order to reduce this impact and gain high-quality power, a novel control strategy is proposed in this paper, in which the virtual complex impedance is introduced to feed grid voltage forward. By using the proposed control strategy, the total harmonic distortion can be greatly decreased, allowing the grid current to synchronize the reference current well. In addition, the modulation of the virtual complex impedance by controller can also quantificationally regulate the equivalent output impedance, which brings great convenience for inverters system designers to calculating and devising. Simulation results are presented to prove the validity and improvements achieved by the proposed controller.

Ⅰ Introduction

With the acceleration of the industrialization process, the pollution problems caused by the use of fossil fuels and problems of the energy shortage have attracted people’s attention, which also promotes the development of renewable energy technologies, such as photovoltaic power generation technology[1-2], wind power generation technology[3-4]and tidal power generation technology[5-6]. In order to meet the demands of users, the power generated by these renewable energy power generation devices needs to be connected into grid through inverters[7]. Hence, stable operation of the inverter can greatly improve the overall capacity and the stability of the grid.

In the case of grid connection, the total harmonic distortion(THD) of the grid current and the power factor of the generation are two important technical indicators[8]. Under the condition in which inverters are required to work both independently and corporately, the inverter normally adopts an LCL filter to inhibit harmonics and control the THD of the grid current in a reasonable range. The distortion of the inverter can also meet the distortion limits as recommend in IEEE Std[9]. However, the LCL filter increases the order of the grid-connected inverter, thereby reducing the system’s stability. To address this problem, many kinds of strategies are presented, including double-closed loop control strategy with active damping [10-13],closed-loop control in inverter-side current[14],Split capacitance in closed-loop control[15-16]. In active damping control schemes, the closed-loop control in inverter-side current and the split capacitance in closed-loop control are the most widely used, and compared with other control strategies, the power factor of grid is lower. However, these two strategies have both a stable system and only single

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current loop which can make the design of parameters easy to achieve. But all these control methods have a common deficiency that in some areas, the grid current can be affected by the quality of the grid voltage because of the severe distortion of grid voltage in these areas.

The control strategy based on the virtual impedance adopts the virtual impedance feedforward branch, which can regulate the output impedance quantificationally and decouple the active and reactive power, bringing convenience to the design of the control algorithm. This control strategy which balances the active and reactive power is widely applied in the parallel inverters system.

In this paper, the analysis of conventional LCL grid-connected inverter system is presented, and furthermore, the module of the system is built. Nevertheless, while applying the control strategy of the inverter-side current feedback, according to the Routh criterion, the quadratic coefficient of the characteristic equation of the system is zero, which means the system is unstable. To stabilize the system, the active damping is introduced, adding a quadratic coefficient and enhancing the stability of the system. Under this control strategy, however, the grid harmonic current is still influenced by the grid harmonic voltage and the grid voltage distortion. To compensate this impact and improve the quality of the grid current, a novel control strategy with the adoption of the virtual complex impedance is proposed in this paper. Applying this controller, the impact can be greatly reduced, and the controller enables the grid current to synchronize with the reference current signal.

Ⅱ Theoretical Analysis of Conventional Inverter

A. Conventional Inverter Modeling

Full-bridge inverter circuit, consisting of four IGBTs in parallel with the freewheeling diodes, is one of the most widely used circuits in the single phase voltage inverter system [17]. At the same time, the LCL filter needs to be connected to the post-stage circuit because the post-stage circuit contains a great amount of high-order harmonic voltage. The typical structure of the inverter circuit is shown in Fig. 1.

This paper adopts the PWM control mode to get the equivalent SPWM wave. In fact, the on-off action of the IGBTs may have an adverse impact on the system, but this impact is limited. In order to establish the mathematical model of the PWM inverter and the LCL filter, for convenience, this part of impact can be ignored and the PWM inverter bridge can be regarded as a gain K_{pwm}[18]:

$$K_{pwm} = \frac{V_{dc}}{V_{tri}} \tag{1}$$

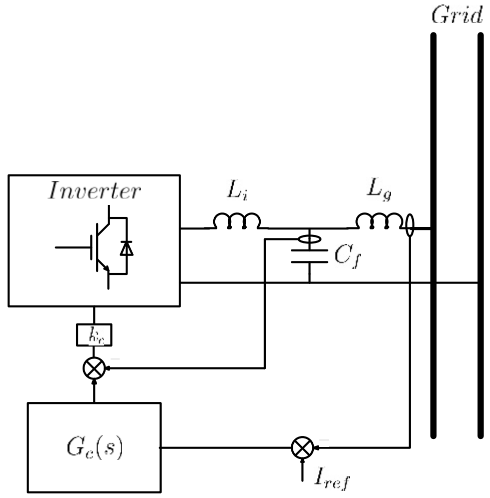

Fig. 1. Power stage of grid-connected inverter using LCL filter

where V_{tri} is the triangular carrier peak; $V_{dc}$is the input voltage of inverter.

At the same time, the complex equations of the LCL filter voltage and current in the output stage can be got, ignoring the filter inductance and stray capacitance. The complex equations are derived as follows:

$$\begin{cases} sL_iI_i(s) = V_i(s) - V_{cf}(s) \\ sL_gI_g(s) = V_{cf}(s) - V_g(s) \\ I_c(s) = I_i(s) - I_g(s) \\ sC_fV_{cf}(s) = I_c(s) \end{cases} \tag{2}$$

where $L_i$is the inductance in inverter side ; I_i is the inverter output current ; V_i is the inverter output voltage ; V_{cf} is the filter-capacitor voltage ; I_C is the filter-capacitor current;C_f is the filter capacitor ; L_g is the inductance in the grid side ; I_g is the grid current ; V_g is the grid voltage.

According to the voltage and current equations, we can draw the block diagram of LCL filters. The block diagram is shown in Fig.2:

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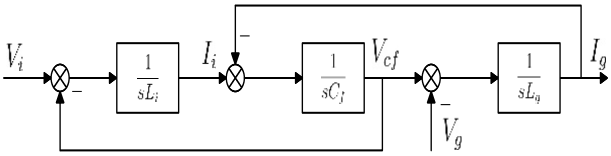

Fig. 2. Block diagram of LCL filter

From the block diagram, we can get the transfer function from the inverter output voltage to the grid current:

$$G_{gi}(s) = \frac{1}{s^3 L_i L_g C_f + s(L_i + L_g)} \qquad (3)$$

B. Active Damping

According to the transfer function (3), when the control scheme of the current loop is proportion, the system is a third order system and the system's characteristic equation is $D(s) = a_0 s^3 + a_1 s^2 + a_2 s + a_3$. This equation indicates the instability of the system for the second-order term is 0. To stabilize this system, an active damping control scheme was adopted [17]. The system chart of damped system is depicted in Fig.3.

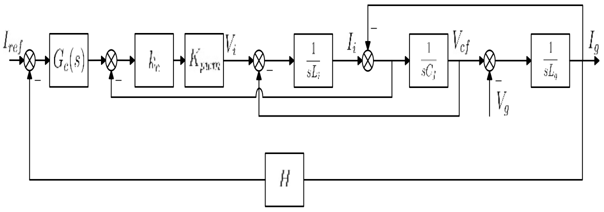

Fig. 3. Block diagram of an inverter with the active damping

Where $G_c$is the transform function of the controller, k_c is the coefficient of active damp , H is the gain of current feedback stage, I_{ref} is the reference current.
The mathematical model of the system can be established and the transform function of this system is as follow:

$$G_{gi}(s) = \frac{G_c K}{s^3 L_i L_g C_f + s^2 K L_g C_f + s(L_g + L_i) + K G_c H} \qquad (4)$$

where the$K = K_c K_{pwm}$. According to this function, with the active damp adopted, a second order term is added to the characteristic equation, thereby stabilizing the system.

C. The Impact of Grid Voltage on The Output Current

The output stage of the inverter is connected to the grid through a LCL filter and the output current is influenced by the grid voltage. Whereas the voltage can be affected by a lot of factors such as power-generation quality, nonlinearity of loads, etc. and there are much high order harmonics in the grid voltage. The transform function of grid voltage to output current is derived as follows:

$$I_{\mathrm{gv}} = -\frac{s^2 L_i C_f + sKC_f + 1}{s^3 L_i L_g C_f + s^2 K L_g C_f + s\left(L_g + L_i\right) + KG_{\mathrm{c}} H} V_g \qquad (5)$$

III Virtual Impedance Controller

The grid connected inverter can be modeled as a current source and the equivalent circuit is shown in Fig.4.

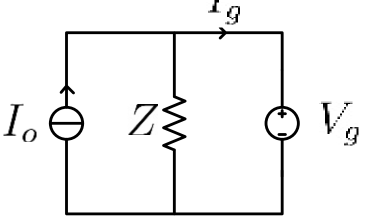

Fig. 4. Equivalent circuit of the grid connected inverter

The output current is expressed as:

$$I_g = I_o - \frac{V_g}{Z} \qquad (6)$$

Assuming that the output impedance $Z = Z_0 \angle \theta$, output current$I_o = I_0 \angle \gamma$, grid voltage $V_g = V_0 \angle 0°$, the vector diagram that illustrates the relationship between the output current and the grid voltage can be depicted in Fig.5.

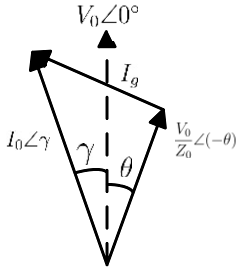

Fig. 5. Vector diagram of equivalent circuit

The impact of grid voltage on the output current depends on two factors: (1) Value of inverter output impedance; (2) The output impedance angle. The impact of grid voltage on the output current is reduced with the increase of the output impedance.

Fig.6 shows a series of bode plots of output impedance for four values of K, varying from 10 to 40, and other parameters are listed in Tab.1. The coefficient of the PI controller are$k_p = 1, k_i = 200$.
With the decrease of K, the output impedance decreases, which enhances the impact of grid voltage. In addition, the impedance in medium frequency is tiny, making this situation even worse.

By implementing a fast control loop, the virtual

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impedance was adopted to change the output impedance of the inverter. Virtual impedance can be implemented by drooping the reference current proportional to the grid voltage and virtual capacitor can be implemented by subtracting the reference current proportional to the time derivative of the grid voltage. Virtual impedance was adopted in UPS design, which provides the following advantages: 1)System damping;2)automatic harmonic current sharing; and 3) active sharing that is barely affected by phase errors[18]. In this paper, a new virtual impedance module was proposed to eliminate the impact of grid voltage on the output current of inverter connected to grid.

Tab 1. Parameters Used for Drawing Bode Plot

L_i/mH	1
L_g/mH	1
C_f/mF	1
k_c	0.1

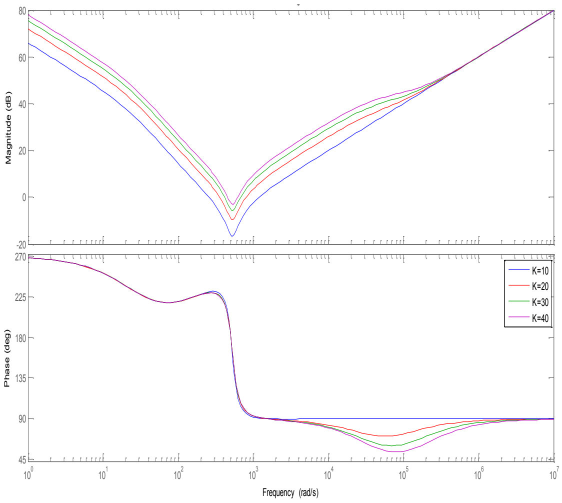

Fig. 6. Bode plot of output impedance

The system chart with a virtual impedance module is depicted in Fig.6

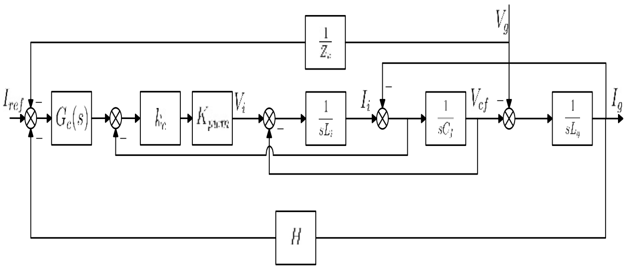

Fig. 7. Block diagram of an inverter with the virtual impedance

where Z_v is virtual impedance. With this module, the transform function from output current to the reference current can be described as follows:

$$G_{gi}(s)=\frac{G_cK}{s^3L_iL_gC_f+s^2KL_gC_f+s(L_g+L_i)+KG_cH} \tag{7}$$

The transform function from output current to the grid voltage is:

$$G_{gv}(s)=-\frac{\frac{G_cK}{Z_v}+(s^2L_iC_f+sKC_f+1)}{s^3L_iL_gC_f+s^2KL_gC_f+s(L_g+L_i)+KG_cH} \tag{8}$$

So the output current can be described as follows:

$$\begin{aligned} i_g &= G_{gi}(s)I_{ref}+G_{gv}(s)V_g \\ &= \frac{G_cK}{s^3L_iL_gC_f+s^2KL_gC_f+s(L_g+L_i)+KG_cH}I_{ref} \\ &- \frac{\frac{G_cK}{Z_v}+(s^2L_iC_f+sKC_f+1)}{s^3L_iL_gC_f+s^2KL_gC_f+s(L_g+L_i)+KG_cH}V_g \end{aligned} \tag{9}$$

The PI controller was adopted to track the reference current. Assume that the transform function of controller is

$$G_c(s)=k_p+\frac{k_i}{s} \tag{10}$$

The characteristic equation of the proposed system is

$$\begin{aligned} D(s) &= s^4L_iL_gC_f+s^3k_cK_{pwm}L_gC_f+s^2(L_g+L_i)+ \\ & sk_cK_{pwm}K_pH+k_cK_{pwm}K_iH \end{aligned} \tag{11}$$

According to the Routh criterion, the Routh table can be described as in Tab.2.

To stabilize the system, each term in the first column of Routh table must be greater than 0, which indicates that:

$$\begin{cases} L_i+L_g-k_pHL_i>0 \\ (L_i+L_g-k_pHL_i)Kk_pH-k_c^2k_{pwm}^2L_gC_fk_iH>0 \end{cases} \tag{12}$$

In order to eliminate the effects of grid voltage harmonics, the controller should be designed to make $G_{gv}(s)=0$. So, the expression of virtual impedance controller can be derived as follows:

$$H_{zv}(s)=\frac{1}{Z_v}=-\frac{s^2L_iC_f+sKC_f+1}{G_cK} \tag{13}$$

where $G_c(s)$ is the PI controller mentioned above:

$$G_c(s)=k_p+\frac{k_i}{s} \tag{14}$$

Therefore:

$$H_{zv0}(s)=-\frac{s^3L_iC_f+s^2KC_f+s}{K(k_ps+k_i)} \tag{15}$$

Since the order of the numerator is higher than denominator, this controller cannot be realized. A second order low pass filter should be adopted and the transform function of the low pass filter is:

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$$H_{LP}(s) = \frac{1}{(1+\frac{s}{\omega_0})^2} \tag{16}$$

Where the $\omega_0$is the cut-off frequency. Then, the controller function can be derived as follows:

$$H_{zv}(s) = -\frac{s^3 L_i C_f + s^2 K C_f + s}{K(k_p s + k_i)} \frac{1}{(1+\frac{s}{\omega_0})^2} \tag{17}$$

With the ω_0 set high enough, $H_{zv}(s)$ will be equivalent to $H_{zv0}(s)$. In this way, the effect of grid voltage harmonics can be eliminated.

Tab 2. Routh Table for Active Damping Closed Loop System

s^4	$L_i L_g C_f$
s^3	$k_c K_{pwm} L_g C_f$
s^2	$L_i + L_g - k_p H L_i$
s^1	$\frac{(L_i+L_g-k_pHL_i)k_cK_{pwm}k_pH-k_c^2k_{pwm}^2L_gC_fk_iH}{L_i+L_g-k_pHL_i}$
s^0	$k_c K_{pwm} k_i H$

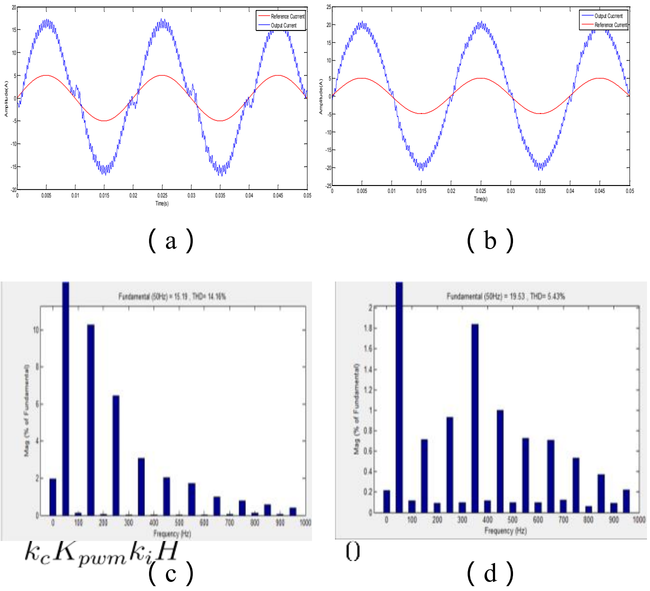
IV Simulation and Data Analysis

After using the control strategy according to the control block diagram shown in Fig. 6,the grid-connected inverter model of the LCL filter can be established. Here, the PI control coefficient are $k_p = 5, k_i = 100$,.The grid voltage contains a serial of harmonic voltage, including the fundamental wave 220V(50HZ),the 3rd harmonic voltage 73.7V, the 5th harmonic voltage 44V , and the 7th,9th,11th harmonic voltage 5V.

Figure 8 (a) and (b) depict the reference current and grid current waveform under the corresponding control schemes and the spectrum analysis of   is shown in(c), (d).

It can be concluded from the simulation results of Fig. 8 (a) and (c) that when the virtual complex impedance is not added, the grid current contains a large amount of low-order harmonics (mainly 3 and 5 harmonic waves).Besides, the phase position is lagged behind the reference phase and the current distortion rate THD is 14.16%.The waveform has obvious distortion and this issue has not been properly treated in the conventional techniques.

In contrast, from the simulation results in Fig. 8 (b) and (d), it can be seen that after adding the virtual complex impedance, the low-order harmonics contained in the grid current have been obviously inhibited and the phenomenon of phase lagging is improved. In addition, the distortion is not very obvious, with the THD turning into 5.43%, and the 3rd, 5th harmonics amplitudes have reduced significantly.



$k_c K_{pwm} k_i H$

(a) (b)

(c) (d)

Fig. 8. LCL grid-connected inverter simulation waveform and spectrum analysis(a) the current waveform without virtual complex impedance; (b) the current waveform with the virtual complex impedance; (c) the current spectrum without virtual complex impedance; (d) the current spectrum with the virtual complex impedance;

It is clear that the current quality has been improved significantly after adding the feedforward branch. However, due to the impact of the low-pass filter, the high-order signal is not sent into the feedforward branch, this part of the high-order signal may result in waveform distortion. As a consequence, the improvements in the impacts of the 7th,9th,11th harmonics are not very obvious. Moreover, the LCL capacitor inductance value selection, the controller temperature drift and the inverter DC power supply voltageU_d can increase the voltage distortion rate. Nonetheless, compared with the distortion caused by the high-order harmonics of the grid voltage, these factors only have few impacts. In the real power grid, there are only few harmonics, whose orders are higher than 5. So the differences between the real situation and the simulation results are not huge. Therefore, it is also proven that the virtual complex impedance can minimize the harmonic components of the output current and the output current can track the reference signal well. The feedforward loop has effectively inhibited the output current distortion.

V Conclusion

This paper is based on the analysis of the conventional grid-connected inverter system with a LCL filter, using the inverter-side current feedback control strategy, and points out its inherent deficiencies. To fix those deficiencies, a novel control strategy for grid-connected inverter was presented. Applying the proposed controller, grid-connected inverters can deliver high-quality power, even when there is voltage distortion in the grid. In the paper, the active damping module was adopted to improve the deficiency of the conventional LCL inverters' control strategy and the module increases the stability of the system. Besides, the relationship among the grid voltage, the grid current and the reference current are presented and well investigated as well. With the introduction of the virtual complex impedance module, the impact of the grid voltage distortion and harmonic grid voltage on the grid current can be substantially reduced.

A series of simulations was carried out to test the performance of the proposed controller. According to the results, by adopting the control scheme, the impact of the grid harmonic voltage on grid current has been effectively minimized, and the grid current could be synchronized with the reference current. Simulation results substantiated the validity and improvement of the proposed control scheme.

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