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Research on Control Strategy of Grid-Connected Converter Based on Virtual Inertia

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Abstract. As the DC microgrid has low inertia, this paper draws on the virtual synchronous machine technology to propose and control a new virtual inertial control strategy. This control strategy enables the grid-connected converter to have both AC inertia and DC inertia. By small signal decomposition, the transfer function block diagram of the system is established. The effects of different inertial parameters on the system's AC inertia and DC inertia are studied. The dynamic characteristic analysis and simulation results show that the proposed virtual inertial control can effectively suppress the fluctuation of DC bus voltage and AC power and increase the AC and DC inertia of the converter.

1. Introduction

With the increasing penetration rate of renewable energy such as wind power and photovoltaics in the power grid, the concept of DC microgrid has received more attention [1]. The grid-connected converter is an interface connecting the DC microgrid and the AC grid. The control characteristics of the grid-connected converter play an important role in maintaining the stability of the DC voltage [2]. The DC microgrid with power electronic converter as the main interface is a low-inertia-network. The load or the power supply frequent switching and power fluctuations in the network will cause disturbing voltage fluctuation of DC bus voltage [3]. The fluctuation of the DC bus voltage directly affects the performance of the DC load in the system [4].If we design a virtual DC inertia control in the grid-connected converter, the inertia of the DC system would increase, and the voltage fluctuation of the DC bus would increase[5].

At present, the research on virtual inertia of power electronic converters mainly focuses on the field of virtual synchronous generator (VSG) control. The concept of virtual synchronous generator was proposed in [6]. The inverter exhibits external characteristics similar to the synchronous generator on the AC side. In [7], the power-frequency small-signal model of the VSG power loop is established. It is proved that the active and reactive loops can be decoupled and controlled separately[8]. All the researches above mainly focuses on the inertia of the frequency and power of the AC side of the converter. In [9], the inertial simulation control strategy is proposed by deriving the coupling relationship between the AC side angular frequency and the DC voltage. The DC inertia is gain while the AC inertia is sacrificed. In [10] proposed a DC microgrid coordinated virtual inertia control and the virtual inertia provided by the energy storage device copes with the fluctuation of the system when it is disturbed. However, a high-pass filter composed of a differential link may introduce high-frequency components. In [11], the virtual inertial control of DC microgrid is studied. By dynamically changing the droop curve, the DC voltage change rate is reduced. In [12], the similarity between the

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DC capacitor energy storage equation and the generator rotor energy storage equation is compared. In summary, there are problems exist: (1) Most researches are limited in the idea of virtual synchronous generator control; (2) As increasing the DC inertia, the AC inertia is sacrificed. The DC bus voltage fluctuation is reduced while the AC side power or frequency fluctuation is significantly increased.

In order to solve the problems, this paper proposes a virtual inertial control strategy for grid-connected converters, which makes the converter have both virtual DC inertia and virtual AC inertia. Virtual DC inertia can effectively suppress DC bus voltage fluctuation and the virtual AC inertia can effectively suppress the fluctuation of the AC side power.

2. Grid-connected converter virtual inertia control

2.1. Grid-connected converter structure

The structure of the grid-connected converter is shown in Figure 1. It mainly consists of a three-phase bridge converter circuit composed of IGBTs, a DC-side capacitor C and an AC-side inductor L. The DC bus voltage is u_{dc}. The three-phase output voltage of the converter are e_a, e_b, e_c and the three-phase voltages on the grid side are u_a, u_b, u_c. The current on the AC side are i_a, i_b, i_c. The current flowing into the DC grid by the converter is I_{dc}., and the load current is I_o. The power flow into the converter from the AC side is P_{in}. The power flow out from the converter to DC is P_{out}.

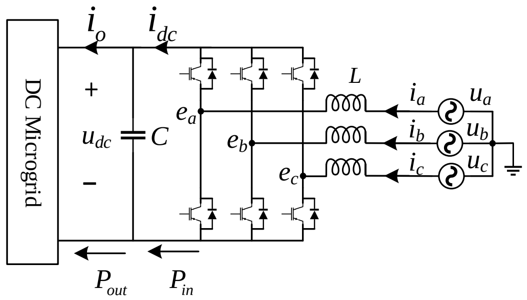

Figure 1. Grid-connected converter structure

2.2. Virtual DC inertial control strategy

The mechanical inertia of the synchronous generator has been refered in the design of the virtual synchronous generator. The active power-frequency control equation of the VSG control is [13]

$$P^* - P = J\omega \frac{d\omega}{dt} \quad (1)$$

Where P^*, P is the reference value and the actual value of the active power of the converter, J is the virtual inertia of the frequency, ω is the angular velocity of the converter. In fact $J\omega$ can be approximated as an inertia constant J_ω. If the damping characteristic of the frequency is considered, equation (1) can be expressed as

$$P^* - P = J_\omega \frac{d\omega}{dt} + D_\omega(\omega - \omega^*) \quad (2)$$

Where D_ω is the frequency damping coefficient, ω^* is the reference angular frequency or the grid angular frequency. The damping coefficient acts as a drooping factor.

According to Figure 1, the power-voltage relationship of the DC side of the converter can be derived as

$$P_{in} - P_{out} = Cu_{dc} \frac{du_{dc}}{dt} \quad (3)$$

If the DC voltage drooping characteristic is considered, then

$$P_{in} - P_{out} = Cu_{dc} \frac{du_{dc}}{dt} + K(u_{dc} - U_{dc}) \quad (4)$$

Where U_{dc} is the nominal DC voltage and K is the DC voltage droop factor. In fact, the DC bus voltage fluctuation is small. Cu_{dc} can be regarded as an inertia constant J_u . Therefore, this paper refers to the active-frequency control of the AC system VSG and constructs virtual DC inertia in the DC system. The virtual DC inertia control equation can be shown as

$$P^* - P = J_u \frac{du_{dc}^*}{dt} + K(u_{dc} - U_{dc}) \tag{5}$$

Where J_u is the inertia coefficients of the voltages. From the equation (5), the reference DC voltage can be given as

$$u_{dc}^* = \frac{1}{J_u s}[P^* + K(U_{dc} - u_{dc}) - P] \tag{6}$$

2.3. Virtual AC inertial control strategy

In the traditional DC inertia control algorithm, the fluctuation response of the AC side power and frequency increases while the inertia enhancing. A virtual AC inertia control with double-loop structure is designed to solve this problem. The voltage-current vector of the converter can be shown in Figure 2. $\vec{E}$ is the vector of e_a, e_b, e_c. $\vec{U}$ is the vector of u_a, u_b, u_c of the grid. $\vec{I}$ is the vector of i_a, i_b, i_c. The voltage vector $\vec{E}$ rotates at an ω and the voltage vector $\vec{U}$ rotates at ω^* .

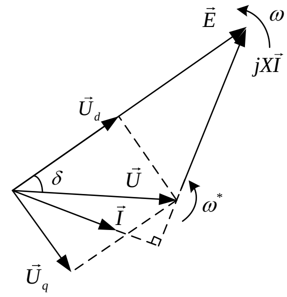

Figure 2. Voltage-current vector of AC side

According to Figure 2, the relationship of the voltage vector can be obtained as

$$\vec{E} = \vec{U} + jX\vec{I} \tag{7}$$

Under the normal circumstances, the voltage on the inductor L is small. Then

$$I_d = \frac{U}{\omega L}\delta \tag{8}$$

Then

$$I_d = \frac{U}{\omega L}\int(\omega - \omega^*)dt \tag{9}$$

In order to improve the stability, a PI regulator G_{v1} is used instead of the integral regulator. The active power-frequency control equation of VSG control in equation (2) can be shown as

$$I_d^* = \frac{G_{v1}}{J_\omega s}[P^* + D_\omega(\omega^* - \omega) - P] \tag{10}$$

2.4. Virtual inertial control strategy

According to the equations (6) and (10), the relationship between the control amount of the active current and the power voltage can be obtained separately. The control block diagram of the virtual inertia of the grid-connected converter can be obtained based on above. Figure 3 shows the control block diagram.

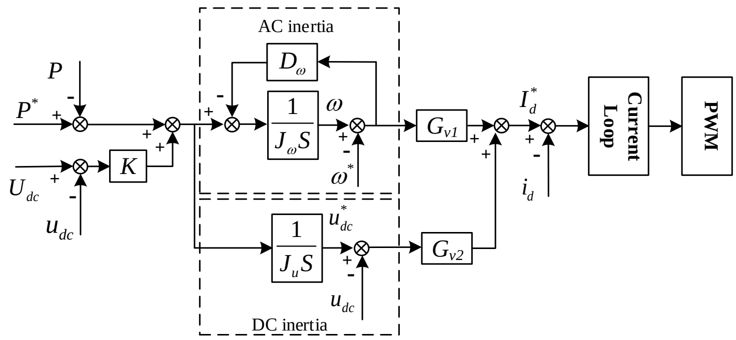

Figure 3. Control block diagram of the virtual inertia

3. Virtual inertial control modelling

3.1. Grid-connected converter small signal modeling

According to Figure 1, The small signal equation of the system as

$$\begin{aligned}\hat{u}_d &= Ls\hat{i}_d - \omega L\hat{i}_q + \hat{e}_d \\ \hat{u}_q &= Ls\hat{i}_q + \omega L\hat{i}_d + \hat{e}_q\end{aligned} \tag{11}$$

Where u_d , u_q is the component of u_a, u_b, u_c in dq coordinate of the grid side. i_d , i_q are the component i_a, i_b, i_c in dq coordinate. And e_d , e_q are the component of e_a, e_b, e_c in dq coordinates.

The small signal decomposition of DC-side voltage-current equation is

$$Cs\hat{u}_{dc} = \hat{d}_d I_d + D_d\hat{i}_d - \hat{i}_o \tag{12}$$

In this paper, the influence of load current is eliminated by current feedforward. The current feedforward transfer function is

$$\hat{i}_o G_f G_c G_k = \hat{i}_o \tag{13}$$

The instantaneous power is controlled by the active power P_{ac} on the AC side, $\hat{P}_{ac} \cong u_d\hat{i}_d$. According to Figure 2, the small signal decomposition of equations (2) and (6) is

$$-u_d\hat{i}_d = J_\omega s\hat{\omega} + D_\omega\hat{\omega} \tag{14}$$

$$-u_d\hat{i}_d = J_u s\hat{u}_{dc}^* + K\hat{u}_{dc} \tag{15}$$

The virtual inertia transfer function block diagram of the grid-connected converter can be obtained as shown in Figure 4.

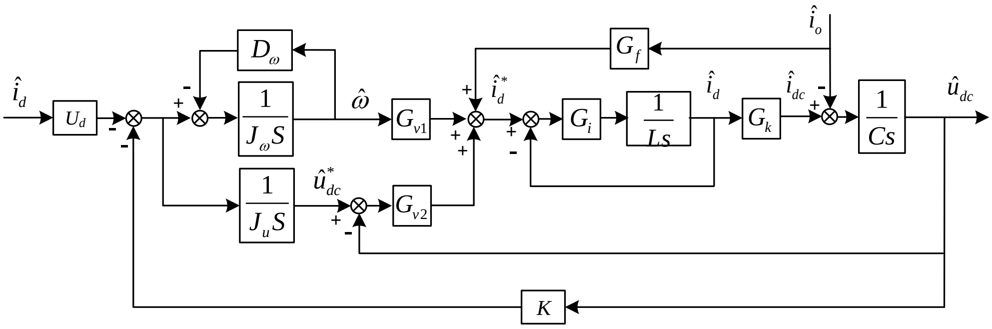

Figure 4. Closed-loop transfer function block diagram

4. Virtual inertial dynamic characteristics and simulation analysis

4.1. Grid converter basic parameters

The basic parameters of the grid-connected converter designed in this paper are shown in Table 1.

Table 1. Parameters of the grid-connected converter

Parameter	Value	Parameter	Value
Nominal power *P*/kW	10	Three-phase line voltage RMS *u*/V	380
DC bus voltage U_{dc}/V	800	DC capacitor *C*/mF	1
AC inductance *L*/mH	1	Switching frequency *f*/kHz	10

The he regulators in the control loop are $G_i = 5\times\frac{0.01s+1}{0.01s}$, $G_{v1} = 5\times\frac{0.5s+1}{0.5s}$, $G_{v2} = \frac{0.5s+1}{0.5s}$.

4.2. Virtual inertia simulation analysis

In order to verify the effectiveness of the proposed virtual inertial control, the simulation of grid-connected converter is built in Psim. In the simulation, the grid-connected converter is first operated at rated power. At 0.05 s, the load on the DC side is suddenly increased by 5 kW.

When $D_\omega = 300$, $J_\omega = 1$, DC bus voltage variation under different J_u is shown in Figure 5. The DC bus voltage changes slowly, indicating that the virtual inertial control proposed in this paper can effectively suppress the DC bus voltage fluctuation. Comparing the changes of the DC bus voltage under different virtual DC inertia parameters, it can be found that the larger of J_u, the more inertia the DC voltage have.

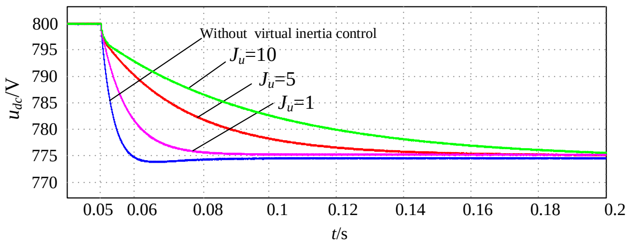

Figure 5. DC bus voltage variation under different J_u

Then this paper analyzes the influence of different virtual AC inertia parameters on DC bus voltage and AC power. Supposing $J_u = 5$, $J_\omega = 0.1$, When the load is abrupt, the simulated waveforms of AC power under different virtual AC inertia parameters D_ω and J_ω are shown in Figure 6 and Figure 7.

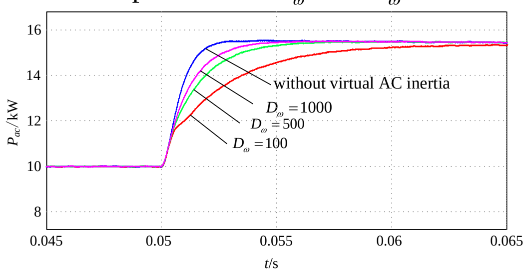

Figure 6. Waveforms under different D_ω

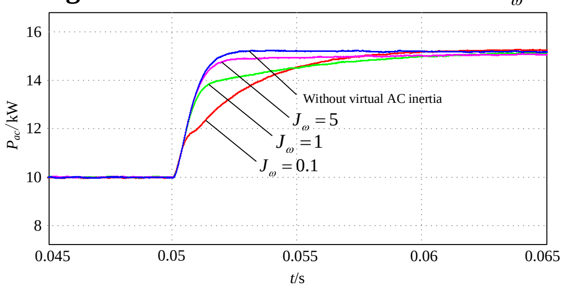

Figure 7. Waveforms under different J_ω

It can be seen from Figure 6 that the fluctuation of the AC power is large without the virtual AC inertia. With the virtual inertia control, the change of AC power is relatively gradual. The smaller of D_ω , the more gradual change of AC power. It can be seen from Figure 7 that the smaller J_ω , the more gradual the AC inertia. The virtual AC inertia provided by the virtual inertial control strategy can effectively suppress the fluctuation of the AC power.

5. Conclusion

This paper designs a virtual inertial control algorithm that can make the grid-connected converter have both DC inertia and AC inertia. The main conclusions are as follows:

(1) The virtual DC inertia control equation and virtual AC inertia equation is established. This paper proposes a virtual inertial control strategy for converters with both AC inertia and DC inertia, which could be widely used in the control of various types of grid-connected converters.

(2) The virtual inertial control strategy can effectively suppress the DC bus voltage fluctuation and AC power fluctuation caused by load fluctuation and power load switching. The converter has certain inertia characteristics from the perspective of the AC system or the DC system.

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