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Inertial and Damping Characteristics of DC Distributed Power Systems Based on Frequency Droop Control

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Abstract: With high penetration of renewable energy, DC distributed power systems (DDPSs) need to improve the inertia response and damping capacity of the power grid. The effects of main circuit parameters and control factors on the inertia, damping and synchronization of the DDPS were studied in this paper. Firstly, the dynamic model of DDPSs based on frequency droop control is established in the DC voltage control (DVC) timescale. Then, a static synchronous generator (SSG) model is used to analyze the parameters that affect the inertial level, damping effect and synchronization capability of the DDPS. The analysis results show that an optimal design of the frequency droop coefficient and proportional integral (PI) parameters of the DC bus voltage control loop can equivalently change the characteristics of inertia and damping when the frequency droop control strategy is applied to the DC/DC converter and the DC bus voltage control strategy is used in the grid-tied inverter. Simulation results verify the correctness of the conclusions. This paper helps to design an effective control strategy for DDPSs to enhance the inertial level and damping effect of the power grid and to improve the stable operation capability of renewable energy systems.

Keywords: frequency droop control; DC distributed power systems (DDPSs); inertia response; damping effect; DC voltage control (DVC) timescale

1. Introduction

In recent years, with the rapid development of power electronics, the proportion of power electronic equipment in the power grid has increased dramatically, and the effective control of electrical energy has become increasingly inseparable from the converter operation. Meanwhile, the proportion of the traditional rotary synchronous generator (RSG) has reduced in the power system with high renewable energy integration [1–4]. Renewable energy has the characteristics of intermittence and randomness, decreasing the stability margin of the power system. Therefore, the renewable energy generation system needs a friendly interaction between the grid-tied inverter and power grid to improve grid stability [5–8]. Then, DC distributed power systems (DDPSs) were introduced into the power grid to improve the inertial level and the damping effect of the power grid with renewable energy. Nowadays, the main control strategies of DDPSs are direct power control, frequency droop control and virtual synchronous generator (VSG) control.

Direct power control provides desired power based on the needs of the power system, and the desired power instructions are issued by the scheduling system [9]. However, direct power control cannot directly respond to the power grid frequency or improve grid frequency stability. The frequency droop control of DDPSs simulates the primary frequency modulation and quickly responds to the grid frequency variation. Frequency droop control is independent of the communication system and has high reliability and flexibility. At the same time, it is widely used in the grid-tied inverter systems [10–12]. Based on grid-tied inverter control and energy scheduling algorithms, VSG allows the DDPS to simulate the large inertia and strong damping characteristics of RSG [13–15]. Nevertheless, the VSG control also requires the frequency droop control loop for grid frequency response [16].

To investigate the concerned inertia and damping characteristics, this paper focuses on the DVC timescale dynamics [17], which corresponds to the electromechanical timescale dynamics in RSG [18]. In the DVC timescale, the frequency droop control is equal to the VSG control [19]. However, D'Arco et al. [19] did not analyze the influential parameters and the characteristic laws of inertia, damping and synchronization. As a result, engineers still cannot fully utilize the frequency droop control to improve the power grid stability. In [20], the static synchronous generator (SSG) model was proposed to effectively analyze the inertia and damping characteristics of the grid-tied inverter system based the double closed-loop control. Until now, based on the SSG model, the effect of the phase-locked loop on the dynamic characteristics of the inverter system was investigated [21,22]. Meanwhile, a novel inertia control method for the grid-tied inverter system has been put forward [23]. Therefore, the SSG model is a prospective and effective method to analyze the inertia and damping characteristics of DDPSs, while no work in this prospective direction has been done in other papers so far. Therefore, this paper is aimed at analyzing the influencing factors of the DDPS by the SSG model to provide a practical reference for optimal design.

This paper is organized as follows. This paper firstly introduces the DDPS, and the basic control principles of the DC/DC converter and the grid-tied inverter are analyzed and modeled in Section 2. In Section 3, the dynamics model of the DDPS based on the SSG model is established in the DVC timescale, which is simplified as a typical second order swing equation to analyze the inertia, damping and synchronization of the DDPS. Then, the effects of the main circuit parameters and key control factors on the inertia, damping and synchronization of the DDPS are studied. Finally, in Section 4, the simulation results show that DDPSs based on frequency droop control have the typical dynamic characteristics such as inertia, damping and synchronization, which can be well designed and fully utilized to enhance the power grid stability.

2. DC Distributed Power Systems Based on Frequency Droop Control

The schematic view of DDPSs based on frequency droop control is shown in Figure 1, including the DC distributed energy sources, the DC/DC converter based on the frequency droop control and the grid-tied inverter based on the DC bus voltage control. The DC/DC converter is equivalent to the prime mover in the conventional generator, and the grid-tied inverter plays the role of RSG in the conventional generation system.

In Figure 1, U_{gk} ($k = a, b, c$) is the grid line-to-line voltage. U_{sk} and i_k are the voltage and current of the grid-tied inverter. U_b is the voltage of the DC distributed energy sources. R and L are the equivalent resistance and inductance, respectively. SPWM is a method of sinusoidal pulse width modulation. PLL indicates the phase-locked loop. In the following subsections, the basic control principles of the DC/DC converter and the grid-tied inverter are analyzed and modeled, serving as the bases for dynamic behavior inspection.

Figure 1. DC distributed power systems (DDPSs) based on frequency droop control.

2.1. DC/DC Converter Control

From the perspective of the SSG model in [20], the DC distributed energy sources, the DC/DC converter and the grid-tied inverter correspond to the primary energy sources, the prime mover and the RSG, respectively. Moreover, the DC-side capacitor corresponds to the rotor of RSG. Therefore, the DDPS can be simplified (see Figure 2).

Figure 2. Simplified circuit diagram.

δ is the phase angle difference between the output voltage of the DDPS and the grid voltage. The equivalent impedance of the DDPS and the line is X . PCC is the point of common coupling. This paper uses the grid voltage vector orientation for the d-axis reference, and the phasor diagram is shown in Figure 3.

Figure 3. Phasor diagram.

The voltage and current are transformed into the d-q frame, and the transformation matrix is adopted as:

$$T_{abc/dq} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ \sin \theta & \sin(\theta - 120^\circ) & \sin(\theta + 120^\circ) \end{bmatrix} \quad (1)$$

The electromagnetic power and reactive power of the DDPS are expressed as:

$$P_e = \frac{3}{2}(U_d I_d + U_q I_q) \quad (2)$$

$$Q = \frac{3}{2}(U_q I_d - U_d I_q) \quad (3)$$

According to Figure 2, Equations (2) and (3), we have:

$$P_e = \frac{3}{2} \frac{U_s U_g}{X} \sin \delta \approx \frac{3}{2} \frac{U_s U_g}{X} \delta \quad (4)$$

$$Q = \frac{3}{2} \frac{U_s U_g \cos \delta - U_g^2}{X} \approx \frac{3}{2} \frac{U_g (U_s - U_g)}{X} \quad (5)$$

According to Equations (4) and (5), the electromagnetic power P_e can be changed by adjusting δ , U_s , U_g and X . The reactive power Q is mainly determined by U_s . The power grid voltage U_g is generally a constant value. X is the structural parameter of the system and is not convenient to change. Thus, changing the electromagnetic power P_e mainly adjusts δ . P_e and P_{in} are approximately equal at steady state. Therefore, the frequency droop curve can be obtained as shown in Figure 4.

Figure 4. The frequency droop curve.

According to Figure 4, it is indicated that:

$$\omega = \omega_0 - D_p (P_{in} - P_0) \quad (6)$$

where D_p is the frequency droop coefficient. P_0 is the rated power of the DC/DC converter, and P_{in} is the actual power of the DC/DC converter.

Then, Equation (6) can be rewritten as:

$$P_{in} = \frac{1}{D_p} (\omega_0 - \omega) + P_0 \quad (7)$$

If the energy of the DC distributed energy sources is stable and sufficient, the DC/DC converter can achieve a fast response of the grid frequency, referring to the primary frequency modulation process of the power system. Obviously, the frequency droop control of DDPSs essentially corresponds to the droop characteristics of the traditional power generation system (see Figure 5).

Figure 5. Control block diagram of the DC/DC converter.

As shown in Figure 5, the bandwidth of the current loop is generally much larger than the bandwidth of the frequency droop loop. At the same time, the dynamic time of the inner loop is also much shorter than the outer loop. Therefore, the dynamic process of the inner loop is negligible in the DVC timescale. According to Figure 5 and the DVC timescale, we have:

$$I_b = I_b^* = \frac{1}{D_p}(\omega_0 - \omega) + \frac{P_0}{U_b} \quad (8)$$

2.2. Grid-Tied Inverter Control

The DC bus voltage closed-loop control is used in the DC/AC circuit of the DDPS to stabilize DC-side capacitor voltage (see Figure 6).

Figure 6. Control block diagram of the grid-tied inverter.

As shown in Figure 6, the DC bus voltage control of the grid-tied inverter adopts proportional integral (PI) control, and a negative voltage feedback is added to the control strategy to achieve no-difference control. The DDPS mainly provides active power in this paper, so the q-axis current command can be set to zero. Hence, according to Figure 6, we have:

$$I_d^* = I_d = -\left(K_p + \frac{K_i}{s}\right)(U_{dc} - u_{dc}) \quad (9)$$

where K_p and K_i are the proportional gain and the integral gain of the DC bus voltage control, respectively.

3. Dynamic Analysis of the DC Distributed Power Systems

In this section, the dynamic characteristics of the DDPS will be analyzed, and the influential factors and laws will be summarized. The results are then utilized to analyze the inertia, damping and synchronous dynamic performance of the DDPS.

From Figure 1, we have:

$$I_c = C \frac{du_{dc}}{dt} = I_{in} - I_{dc} \quad (10)$$

The current of the DC-side capacitor is:

$$I_c = C \frac{du_{dc}}{dt} = \frac{\frac{1}{2}CU_{dc}^2}{\frac{1}{2}CU_{dc}^2} \cdot C \cdot \frac{du_{dc}}{dt} = \frac{2E_K}{U_{dc}^2} \frac{du_{dc}}{dt} \quad (11)$$

By substituting Equation (11) into Equation (10) and then dividing the equation by the base value of DC-side current I_B , we have:

$$\frac{I_c}{I_B} = \frac{Cdu_{dc}}{I_B dt} = \frac{2E_K}{I_B U_{dc}} \frac{d\left(\frac{u_{dc}}{U_{dc}}\right)}{dt} = \frac{2E_K}{P_B} \frac{du_{dc}^*}{dt} = \frac{I_{in}}{I_B} - \frac{I_{dc}}{I_B} = I_{in}^* - I_{dc}^* \quad (12)$$

In Equation (12), the base value of current can be related to the base values of power and DC bus value as:

$$I_B = \frac{S_B}{U_{dcB}} = \frac{P_B}{U_{dc}} \quad (13)$$

Hence, Equation (12) can be rewritten as:

$$\frac{2E_K}{P_B} \frac{du_{dc}^*}{dt} = T_J \frac{du_{dc}^*}{dt} = I_{in}^* - I_{dc}^* \quad (14)$$

where T_J is the equivalent inertia coefficient of SSG.

Furthermore, Equation (14) can be expressed as:

$$T_J \frac{du_{dc}^*}{dt} = \frac{P_{in}^*}{u_{dc}^*} - \frac{P_e^*}{u_{dc}^*} \quad (15)$$

Because the change of u_{dc} in DC bus voltage control is small, it is assumed that u_{dc}^* is one. Moreover, in the case of stability analysis, the conclusion will not be affected by this assumption. Therefore, linearizing Equation (15), the standard dynamic equation of DDPSs can be obtained as:

$$\begin{cases} \frac{d\Delta\delta}{dt} = \Delta\omega \\ 2H \frac{d\Delta\omega}{dt} = \Delta P_{in} - \Delta P_e \end{cases} \quad (16)$$

In Equation (16),

$$H = \frac{CU_{dc}^2}{S_B} \quad (17)$$

Based on the classical electric torque analysis in the power system, the dynamic model shown in Equation (16) can be rewritten as:

$$\begin{cases} \frac{d\Delta\delta}{dt} = \Delta\omega \\ T_J \frac{d\Delta\omega}{dt} = -T_D \Delta\omega - T_S \Delta\delta \end{cases} \quad (18)$$

where T_D and T_S are the damping coefficient and the equivalent synchronization coefficient of SSG, respectively.

T_J , T_D and T_S are important physical concepts, which respectively represent the inertial level, damping effect and synchronization capability. In order to unify the analysis methods of the DDPS and SSG model, the relationship between Δu and $\Delta\omega$ will be found in the following.

From Figures 2 and 3, we have:

$$I_d = \frac{U_s}{X} \sin \delta \quad (19)$$

According to Equations (9) and (19), we can deduce that:

$$\frac{U_s}{X} \sin \delta = -\left(K_p + \frac{K_i}{s}\right)(U_{dc} - u_{dc}) \quad (20)$$

The incremental relationship of variables is usually only considered for stability analysis. Therefore, Equation (20) is linearized as:

$$sK\Delta\delta = (sK_p + K_i)\Delta u_{dc} \quad (21)$$

In Equation (21),

$$K = \frac{U_s}{X} \cos \delta_0 \quad (22)$$

By manipulating Equation (21) and substituting $\Delta\omega$ for $s\Delta\delta$, we have:

$$\frac{K}{\Delta u_{dc}} = \frac{K_p}{\Delta\delta} + \frac{K_i}{\Delta\omega} \quad (23)$$

According to Figure 1, the incremental power of the DC/DC converter is:

$$\Delta P_{in} = U_b \Delta I_b \quad (24)$$

Substituting Equations (4), (23) and (24) into Equation (16), we give:

$$\begin{cases} \frac{d\Delta\delta}{dt} = \Delta\omega \\ \frac{2KHs^2\Delta\delta}{(sK_p + K_i)} = -\frac{U_b}{D_p}\Delta\omega - 1.5KU_g\Delta\delta \end{cases} \quad (25)$$

Simplifying Equation (25), the SSG equation of the DDPS can be obtained as:

$$\begin{cases} \frac{d\Delta\delta}{dt} = \Delta\omega \\ \left(2KH + \frac{K_p}{D_p}U_b\right)\frac{d\Delta\omega}{dt} = -\left(\frac{K_i}{D_p}U_b + 1.5K_pKU_g\right)\Delta\omega - 1.5K_iKU_g\Delta\delta \end{cases} \quad (26)$$

According to Equation (26), the Phillips–Heffron model of DDPSs with frequency droop control can be obtained, and its structure is completely consistent with RSG (see Figure 7).

Figure 7. The Phillips–Heffron model of the DC distributed power system (DDPS).

It can be seen that the operating mechanism of the DDPS in the DVC timescale is very similar to the traditional power generation systems on the electromechanical time scale. At the same time, all of them have the inertia, damping and synchronization characteristics. The T_J , T_D and T_S of the DDPS are:

$$\begin{cases} T_J = 2KH + \frac{K_p}{D_p} U_b = \frac{2U_s C U_{dc}^2}{S_B X} \cos \delta_0 + \frac{K_p}{D_p} U_b \\ T_D = \frac{K_i}{D_p} U_b + 1.5K_p K U_g = \frac{K_i}{D_p} U_b + \frac{1.5K_p U_s U_g}{X} \cos \delta_0 \\ T_S = 1.5K_i K U_g = \frac{1.5K_i U_g U_s}{X} \cos \delta_0 \end{cases} \quad (27)$$

It can be seen from Equation (27) that the inertial level, damping effect and synchronization capability of the DDPS are determined simultaneously by the structural parameters, control parameters and steady-state operating points. The structural parameters include the capacitance of the DC-side capacitor C and the equivalent impedance X ; The frequency droop coefficient of the DC/DC converter and the PI parameters of the DC bus voltage control loop of the DC/AC converter are the control parameters; The operating points of steady state are comprised of the steady state power angle δ_0 , the capacitor rated voltage U_{dc} , the inverter output voltage U_s , the voltage of the DC distributed energy sources U_b and the grid voltage U_g .

Therefore, the simplest way to control the inertia and damping characteristics of the system is obviously adjusting the control parameters of the DDPS. On the grounds of Equation (27) and its related analysis, the following main conclusions are obtained:

- (1) The inertial level can be adjusted by the proportional controller gain K_p and the frequency droop coefficient D_p . Meanwhile, adjusting the capacitance of the DC-side capacitor C , the voltage of the DC distributed energy sources U_b , the inverter output voltage U_s and the capacitor rated voltage U_{dc} can also equivalently adjust the inertial level of the system. When C increases, the system increases the buffering effect against external disturbances and improves the inertia level of the system, which are consistent with the actual situation.
- (2) Changing the frequency droop coefficient D_p and the PI controllers of the DC bus voltage control loop can be equivalent to adjusting the damping effect of the system.
- (3) The synchronization capability can be changed by adjusting the integral controller gain K_i .

In summary, optimizing the frequency droop control loop and the DC bus voltage control loop can equivalently change the inertial and damping characteristics of the system. Besides, according to Equation (27), it is shown that the inertia factor of the DDPS also includes the components that are completely unrelated to the control parameters, and that part is only determined by the structural parameters and the steady-state operating points. The results show that the DDPS naturally has an inertial effect, which is opposed to the traditional idea of DDPSs having no inertia effect.

4. Simulation Verification

The simulation model was established in MATLAB/Simulink to demonstrate the effects of the DDPS parameters on the inertial level, damping effect and synchronization capability. The simulation circuit is shown in Figure 1, and the circuit parameters of the DDPS are shown in Table 1. A frequency disturbance occurs at the time of 0.03 s.

Table 1. Main parameters of the DC distributed power systems (DDPSs).

Symbol	Meaning	Value	Symbol	Meaning	Value
U_g	Grid line-to-line voltage (V)	380	U_{dc}	Voltage of the DC-side capacitor (V)	750
C	Capacitance of the DC-side capacitor (mF)	5	U_b	Voltage of the DC distributed energy sources (V)	350
L	Filter inductance (mH)	4	f_0	Grid frequency (Hz)	60
K_i	I gain of current loop	100	f_s	Switching frequency (kHz)	10
K_p	P gain of current loop	0.1			

4.1. Damping Characteristics Verification

On the basis of Equation (27), the damping characteristics are influenced by the frequency droop coefficient and the PI parameters of the DC bus voltage control loop. D_p demonstrates the dynamic behavior of u_{dc} (see Figure 8).

Figure 8. Influence of D_p on the dynamic performance of the DDPS.

The simulation results show that with the increase of D_p , the oscillation amplitude of the capacitor voltage u_{dc} increases, and the oscillation attenuation becomes slower. At the same time, the inertia level of the system is inversely proportional to D_p . In summary, with the decrease of D_p , the inertial level and damping effect of the DDPS are enhanced, which is consistent with Equation (27). Adjusting D_p , K_p and K_i allows adjusting the damping characteristic equivalently.

Figure 9 shows that the damping effect of the DDPS is changed by K_p . The oscillation amplitude becomes smaller with the increase of K_p , obtaining a stronger damping effect. When K_p is one, the DDPS operates in a critical damping state and is characterized by small overshooting and fast dynamics. It is obvious that larger K_p has a better damping effect. However, a large K_p can cause DDPS instability, when the DDPS stability margin is small.

Figure 9. Influence of K_p on the dynamic performance of the DDPS.

4.2. Inertial Characteristics' Verification

According to Equation (27), the inertial coefficient of the DDPS is affected by the proportional controller gain K_p , the frequency droop coefficient D_p , the capacitance of the DC-side capacitor C and

the capacitor rated voltage U_{dc} . The ability of the DDPS to resist external interference is affected by the capacitance of the DC-side capacitor (see Figure 10).

Figure 10. Influence of C on dynamic performance of the DDPS.

With the increase of C , the oscillation amplitude of u_{dc} decreases, obtaining better resistance of the DDPS against external disturbances. The higher inertia level is conducive to maintaining the stability of the system, avoiding big fluctuation or, even worse, a fault in the external disturbances. This result is consistent with Equation (27). Besides, a larger C makes the DC-side capacitor voltage smoother.

The per-unit value is used in the case of different capacitor rated voltages U_{dc} to better express the dynamic characteristics of the system (see Figure 11). The simulation results show that with the increase of U_{dc} , the oscillation amplitude of u_{dc} decreases. At the same time, the ability of the DDPS to resist external disturbances becomes stronger. In summary, with the increase of U_{dc} , the inertial level of the DDPS is enhanced, which is coherent with Equation (27).

Figure 11. Influence of U_{dc} on the dynamic performance of the DDPS.

4.3. Synchronization Characteristics' Verification

From Equation (27), it can be seen that adjusting the integral controller gain K_i and the grid voltage U_g allows equivalently adjusting the synchronization coefficient. When adjusting the integral controller gain K_i , the influence of the synchronization characteristics of the DDPS is as shown in Figure 12.

Figure 12. Influence of K_i on dynamic performance of the DDPS.

As K_i increases, u_{dc} returns to a steady state faster. When the DDPS has a larger K_i , u_{dc} has a stronger adjustment ability and a stronger synchronization ability. The results are consistent with Equation (27) and Figure 11. Meanwhile, adjusting U_g and K_i allows adjusting the synchronization characteristic equivalently.

Figure 13 shows that with the increase of U_g , the time of the oscillation regression becomes shorter, and the synchronization ability is enhanced. It can be observed that as U_g increases, the synchronization capability becomes stronger, and the u_{dc} can quickly return to the steady-state value. Therefore, the results are consistent with Equation (27). The simulation results show that the inertial capability of u_{dc} is not affected by U_g . Therefore, U_g hardly affects the inertial effect of the DDPS, which is consistent with Equation (27).

Figure 13. Influence of U_g on the dynamic performance of the DDPS.

In the above cases, when the controller parameters are different, u_{dc} remains close to its rated value (750 V), although the dynamic characteristics are not the same. The deviations are less than 0.3%. The main reason is that the frequency droop loop and the DC bus voltage control loop provide a positive damping effect, inertial level and synchronization capability, and hence, the DDPS is small signal stable.

4.4. Stability Verification

The system stability of the DDPS is verified by an experimental platform for real-time simulation. The circuit parameters of the experimental platform for real-time simulation is shown in Table 2. The DDPS runs stably for a while, and then, a frequency disturbance occurs during stable operation.

Table 2. Main parameters of real-time simulation.

Symbol	Meaning	Value	Symbol	Meaning	Value
U_g	Grid line-to-line voltage (V)	380	U_b	Voltage of the DC distributed energy sources (V)	350
C	Capacitance of the DC-side capacitor (mF)	5	U_{dc}	Voltage of the DC-side capacitor (V)	750
K_p	The proportional controller gain of the DC bus voltage control	1	K_i	The integral controller gain of the DC bus voltage control	100
f_0	Grid frequency (Hz)	60	L	Filter inductance (mH)	4
f_s	Switching frequency (kHz)	12	D_p	The frequency droop coefficient	1.5

Figure 14 shows the parameter variations of the DDPS when the frequency has a disturbance. The results show that u_{dc} can quickly stabilize at the set value after disturbance, and the active power output of the DDPS can also quickly reach a new steady state.

Figure 14. The verification results: (a) the DC-side capacitor voltage; and (b) active and reactive power output from the DDPS.

5. Conclusions

Enhancing the inertial level, damping effect and synchronization capability of the DDPS are conducive to improving the frequency stability of the power grid. In this paper, the dynamic model of the DDPS based on the SSG model was established in the DVC timescale, analyzing the intrinsic mechanism, mainly affecting the parameters and influential laws of the inertial level and damping effect of the DDPS. The results show that the inertia, damping and synchronization characteristics of DDPSs with frequency droop control are determined by the structural parameters, control parameters

and steady-state operating points. The main sources of the inertial level and damping effect of the DDPS are the frequency droop coefficient and PI parameters of the DC bus voltage control loop. Furthermore, the DC/DC converter using the frequency droop control intrinsically corresponds to the droop control characteristics of the prime mover. The simulation results show that the DDPS has the typical dynamic characteristics such as the inertia, damping and synchronization, which can be well designed and utilized to enhance the power grid stability.

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