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Inertia and Damping Analysis of Grid-Tied Photovoltaic Power Generation System With DC Voltage Droop Control

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ABSTRACT Photovoltaic power generation relies on power electronics and therefore does not have natural inertia and damping characteristics. In order to make the capacitance of the medium time scale participate in the grid frequency response without adding additional equipment, this paper takes the grid-connected photovoltaic power generation system based on DC voltage droop control as the research object, and establishes the static synchronous generator (SSG) model of the system. The model is used to analyze the main parameters affecting the inertia, damping and synchronization characteristics of the system and their influence laws. The research results show that the energy storage effect of the capacitor on the medium time scale can also make the system exhibit certain inertia characteristics. From the point of view of control parameters, as the droop coefficient D_p decreases, the inertia characteristic exhibited by the system is stronger. The larger the DC voltage outer loop proportional coefficient K_p is, the stronger the damping effect of the system is. The larger the DC voltage outer loop integral coefficient K_i, the stronger the synchronization capability of the system. In addition, the MATLAB/Simulink simulation platform is used to verify the correctness of the theoretical analysis results.

INDEX TERMS Grid-connected photovoltaic power generation system, DC voltage droop control, inertia characteristic, damping effect, synchronization ability.

I. INTRODUCTION

With the global energy crisis and environmental pollution becoming more and more serious, vigorously developing clean energy has become the development consensus of all countries in the world. The electric vehicles, FACTS equipment and the renewable energy generation have been extensively developed [1]–[3]. Grid-tied photovoltaic power generation, as a representative of renewable energy power generation technology, has shown explosive growth by virtue of its abundant resources and pollution-free advantages [4]–[6].

In the traditional power system, the main body of power generations is the rotational synchronous generator (RSG), and RSG itself has the large inertia and strong damping ability. In the grid-tied photovoltaic power generation system, the physical characteristics of the grid-connected inverter are obviously different from RSG. As a power electronic device, the grid-tied inverter itself does not have physical inertia. It is connected to the grid on a large scale with the characteristics of low inertia and weak damping, resulting in a decrease in the inertia of the power system, and bringing severe challenges to the safe and stable operation of the power grid [6]–[8]. At the same time, photovoltaic power generation has high volatility, strong randomness, and obvious intermittent, which will adversely affect the stable operation of the power grid. Therefore, when photovoltaic power is integrated into the power grid, they generally need to be equipped with a certain amount of energy storage to provide inertia [9].

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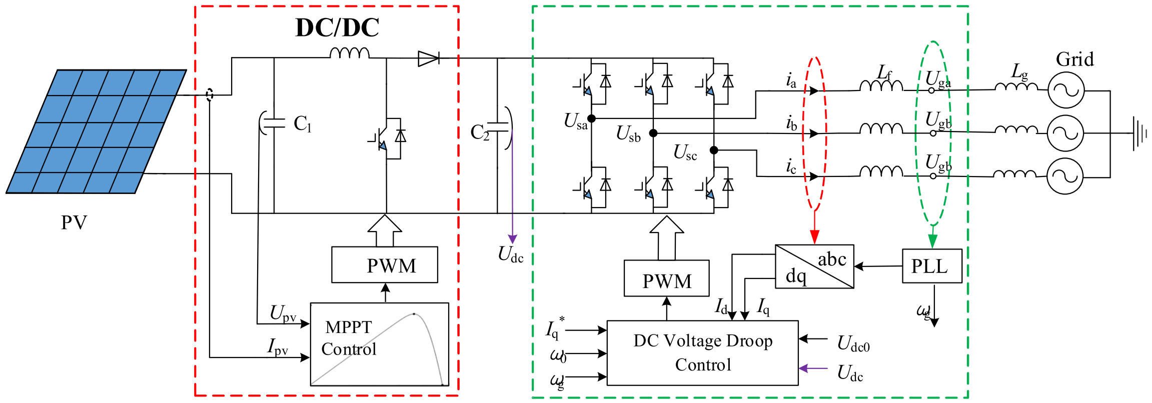

FIGURE 1. Grid-connected photovoltaic power generation system based on DC voltage droop control.

In [10]–[12], the combination of the solar generation and energy storage system has been taken as the research object, and the design and control strategy research are conducted to improve the system stability of the photovoltaic power generation integrated into the grid. However, in the case of small disturbances, the energy storage system is less economical, and the primary energy and its converter's huge potential in inertia and damping characteristics simulation are not fully utilized. In [13], it is pointed out that the DC side capacitor of the grid-tied inverter has similar dynamic behavior characteristics to the RSG rotor, and the capacitor voltage on the DC side of the grid-tied inverter can fluctuate within a certain range, providing a certain inertia support, but it did not analyze the inertia, damping and synchronization characteristics of the whole system including the capacitor dynamic. In [14], it is shown that the grid-tied new energy power generation system has correspondence with the traditional power generation system, and from the perspective of electromechanical transient process modeling, it proves the grid-tied inverter in the new energy grid-tied power generation system and the RSG in the traditional power generation system has a similar physical mechanism and equivalent dynamic model. An SSG model that is suitable for the analysis of the DC voltage time scale dynamic characteristics of the grid-tied converter system is proposed, and the inertia, damping and synchronization characteristics of the grid-tied converter system under voltage and current double closed-loop control is analyzed. In [15], by establishing the SSG model, the mechanism of a static synchronous compensator for suppressing the power oscillation of power grid is analyzed. In [16], the rapid power compensation (RPC) based frequency control strategy is developed to optimize the converter ability to compensate the grid imbalance power, by fully exploiting the converter idle capacity. The mathematical proof demonstrated the improved performance of the RPC strategy in terms of frequency deviation suppression versus droop control, and in terms of RoCoF suppression versus inertia control, with identical converter capacity limit. In [17], [18], the SSG model based analysis method is utilized to analyze the inertia and damping characteristics of the grid-tied energy storage system under two different control strategies.

This paper takes the grid-tied photovoltaic power generation system that is controlled by the DC voltage droop control as the research object, establishes the SSG mathematical model, and uses the electrical torque analysis method to study the inertia, damping and synchronization characteristics of the photovoltaic grid-tied inverter side DC voltage droop control system, and derives the system equivalent parameter expression, and expound the function law of the parameter from the level of mathematical analysis and physical mechanism. The study proved that some changes to the conventional control methods can also change the system inertia and damping characteristics, and provide a theoretical basis for the design of relevant parameters of the grid-tied photovoltaic power generation system.

II. THE STRUCTURE OF GRID-TIED PHOTOVOLTAIC POWER GENERATION SYSTEM

The structure of the grid-tied photovoltaic power generation system with the DC voltage droop control is shown in Figure 1. The system mainly includes the photovoltaic module, the DC/DC converter, and the grid-tied inverter. The DC/DC converter adopts the maximum power point tracking (MPPT) control, and the inverter side introduces frequency deviation based on the voltage outer loop and inner current loop to form the DC voltage droop control [14].

In Figure 1, U_{pv} and I_{pv} are the voltage and current output by the photovoltaic module, respectively; C_1 and C_2 represent the low and high-voltage side capacitance of the DC/DC converter, respectively; U_{sk} ($k = $ a, b, c) represents the three-phase output voltage of the inverter; i_k ($k = $ a, b, c) represents the three-phase output current by the inverter; U_{dc} represents the measured voltage of the DC capacitor; L_f represents the filter inductance; U_{gk} ($k = $ a, b, c) represents the three-phase voltage on the grid side; L_g represents the equivalent inductance on the grid side; PLL represents a phase-locked loop [18], which is used to collect the real-time grid frequency; ω_0 and ω_g represent the rated angular velocity of the grid and the actual angular velocity of the grid, respectively;

I_d and I_q represent the current in the d axis and the q-axis current component in the dq coordinate system; I_q* represents the q-axis current reference value; U_{dc0} represents the DC capacitor voltage reference.

A. DC/DC CONVERTER CONTROL STRATEGY

Since the output voltage of photovoltaic modules cannot meet the requirements of the grid voltage class, a boost DC/DC converter is required to increase the output voltage of photovoltaic modules, and then the grid-tied inverter is integrated into the grid.

When the grid frequency fluctuates, the grid-tied photovoltaic inverter needs to provide reasonable inertia support to the power system to quickly restore the power balance of the system. In fact, in the context of the application of photovoltaic power grids, the maximum output power of photovoltaic system is far less than the demand of the power grid, so the photovoltaic power generation system often outputs the maximum power, and the DC/DC converter adopts the MPPT control. The control block diagram of the DC/DC converter is shown in Figure 2 as below.

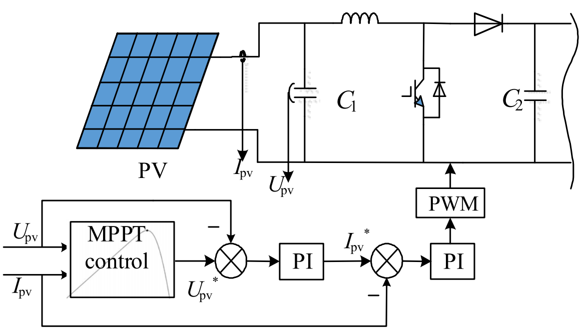

FIGURE 2. DC/DC converter control strategy.

In this figure, $U_{pv}*$ and $I_{pv}*$ are the DC voltage and current reference signals output by the photovoltaic module, respectively; PI represents the proportional integral regulator. As shown in Figure 2, the boost DC/DC converter adopts the double closed-loop control with outer DC voltage loop and inner current loop. Under the DC voltage time scale, the dynamic process of the inner current loop can be ignored [14], so the output current of the photovoltaic module can be expressed as:

$$I_{pv}^* = I_{pv} = \left(K_p' + \frac{K_i'}{s}\right)\left(U_{pv}^* - U_{pv}\right) \tag{1}$$

where K_p' and K_i' represent the proportional and integral coefficients of the outer voltage loop, respectively.

Photovoltaic module outputs the maximum power. Under the condition of constant temperature and constant light intensity, the output power of photovoltaic modules and DC/DC converters does not change, so we can get:

$$\Delta P_{in} = 0 \tag{2}$$

where ΔP_{in} represents the amount of input power change.

B. THE INVERTER CONTROL STRATEGY

The grid-tied inverter adopts the double closed-loop control with the outer DC voltage loop and the inner current loop to realize the capacitor voltage stability. But when the small disturbance occurs, because the DC/DC converter outputs the maximum power, it is compatible with the grid-connected inverter. The decoupling relationship cannot respond to the changes of the grid frequency, so the frequency deviation is introduced in the typical double closed loops to form the DC voltage droop control. The control block is shown in Figure 3 as below.

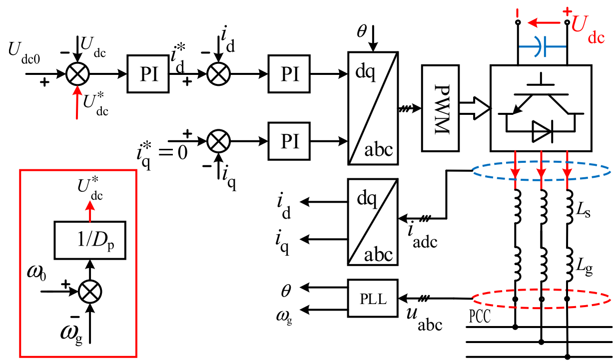

FIGURE 3. Grid-connected inverter control strategy.

In the DC voltage control time scale, ignoring the dynamic process of the inner current control loop, the control process shown in Figure 3 can be described as:

$$I_d^* = I_d = -\left(U_{dc}^* + U_{dc0} - U_{dc}\right)\left(K_p + \frac{K_i}{s}\right) \tag{3}$$

where K_p and K_i represent the proportional and integral coefficients of the outer DC voltage loop, respectively; $U_{dc}*$ represents the deviation of the DC voltage.

The deviation of the DC voltage can be described as:

$$U_{dc}^* = \frac{1}{D_p}(\omega_g - \omega_0) \tag{4}$$

where D_p represents the DC voltage droop coefficient.

III. DYNAMIC CHARACTERISTICS ANALYSIS OF GRID-TIED PHOTOVOLTAIC POWER GENERATION SYSTEM

A. THE ORETICAL BASIS OF SYSTEM DYNAMIC CHARACTERISTIC ANALYSIS

In [14], following the method of analyzing the static stability and instability mechanism of the RSG system, the dynamic process of the grid-tied inverter under the DC voltage control time scale is expressed as:

$$\begin{cases} \dfrac{d\Delta\delta}{dt} = \Delta\omega \\ 2H\dfrac{d\Delta U_{dc}}{dt} = \Delta P_{in} - \Delta P_e \end{cases} \tag{5}$$

where δ is the power angle; ω is the angular frequency of the grid; U_{dc} is the DC side capacitor voltage; P_{in} is the input power of the energy transfer medium; P_e is the output power; $H = CU_{dc}^2/S_B$ is the inertial time constant of the system [14].

Too analyze the inertia, damping and synchronization characteristics of the grid-tied inverter system, (5) is usually rewritten into the following standard electric torque equation [14]:

$$\begin{cases} \dfrac{d\Delta\delta}{dt} = \Delta\omega \\ T_J \dfrac{d\Delta\omega}{dt} = -T_D\Delta\omega - T_S\Delta\delta \end{cases} \tag{6}$$

where T_J, T_D and T_S represent the equivalent inertia coefficient, damping coefficient and synchronization coefficient of the SSG model, respectively.

The above three parameters are important physical concepts that characterize the dynamic characteristics of a SSG system in the classical stability theory. The electrical torque analysis method based on the above concepts can analyze the stability of the system from the physical mechanism level, and T_J, T_D and T_S represent the grid-tied inertia level, damping and synchronization capabilities of the inverter system, respectively [14].

B. SSG MODEL OF THE GENERATION SYSTEM

Before establishing the SSG model of the generation system, the transient process of the grid-tied inverter is simplified and analyzed. This article simplifies the grid-tied inverter to a single-phase equivalent circuit shown in Figure 4. Among them, U_s represents the amplitude of the grid-tied inverter excitation potential; δ represents the phase angle difference between the grid-tied inverter and the grid voltage; U_g represents the terminal voltage amplitude of the grid-tied inverter.

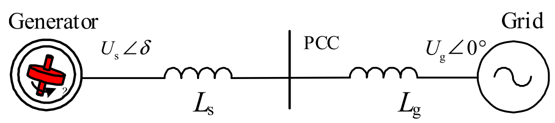

FIGURE 4. Single-phase simplified circuit diagram of the inverter.

When modeling and analyzing the grid-tied inverter system, they are often oriented according to the grid voltage. Under the premise of ignoring the line impedance, the vector diagram of the grid-tied inverter in the dq coordinate system based on the grid voltage orientation can be shown in Figure 5.

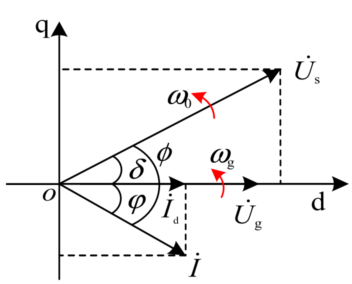

FIGURE 5. Vector illustration in dq system.

From the phasor diagram of the grid-tied inverter system shown in Figure 5, the expressions of the active power and active current output by the three-phase grid-connected inverter can be calculated by:

$$P_e = \frac{3}{2}\frac{U_s U_g}{X}\sin\delta \tag{7}$$

$$I_d = \frac{U_s}{X}\sin\delta \tag{8}$$

where X is the equivalent inductance connected to the grid, and $X = \omega_0 L$.

To study the inertia, damping and synchronization characteristics of the grid-tied photovoltaic power generation systems, the above-mentioned research methods are used as the theoretical basis to establish an SSG model of the grid-tied photovoltaic power generation system based on the DC voltage droop control.

Incorporating (4) into (3), we have:

$$I_d = -\left[\frac{1}{D_p}(\omega_g - \omega_0) + U_{dc0} - U_{dc}\right]\left(K_p + \frac{K_i}{s}\right) \tag{9}$$

Combining (8) and (9), we have:

$$\frac{U_s}{X}\sin\delta = -\left[\frac{1}{D_p}(\omega_g - \omega_0) + U_{dc0} - U_{dc}\right]\left(K_p + \frac{K_i}{s}\right) \tag{10}$$

For the stability analysis in the case of the small disturbance, the incremental relationship between variables is generally considered, and (10) can be linearized to obtain the following equation, i.e.:

$$sK\Delta\delta = -\left(sK_p + K_i\right)\left(\frac{1}{D_p}\Delta\omega - \Delta U_{dc}\right) \tag{11}$$

where δ_0 is the power angle of the grid-tied inverter system in the steady state. And K is defined as:

$$K = \frac{3}{2}\frac{U_s}{X}\cos\delta_0$$

The linearization of (7) is:

$$\Delta P_e = \frac{3}{2}\frac{U_s U_g}{X}\cos\delta_0\Delta\delta \tag{12}$$

(2) and (12) are incorporated into (5), and the expression of voltage increment can be obtained:

$$\Delta U_{dc} = -\frac{3KU_g}{4Hs}\Delta\delta \tag{13}$$

Using the classic electrical torque method, we can analyze the inertia, damping characteristics of the grid-tied photovoltaic power generation system. Taking (13) into the incremental equation (11), we can eliminate the voltage increment, and we can organize it into the form of the standard electric torque equation in (6). The available SSG model of the grid-tied photovoltaic power generation system based on the DC voltage droop control can be obtained as follows:

$$\begin{cases} \dfrac{\mathrm{d}\Delta\delta}{\mathrm{d}t} = \Delta\omega \\ 2H\dfrac{K_\mathrm{p}}{D_\mathrm{p}}\dfrac{\mathrm{d}^2\Delta\omega}{\mathrm{d}t^2} + \left(2HK + 2H\dfrac{K_\mathrm{i}}{D_\mathrm{p}}\right)\dfrac{\mathrm{d}\Delta\omega}{\mathrm{d}t} \\ = -\dfrac{3}{2}KU_\mathrm{g}K_\mathrm{p}\Delta\omega - \dfrac{3}{2}KU_\mathrm{g}K_\mathrm{i}\Delta\delta \end{cases} \tag{14}$$

In the actual operation of the power grid, the grid frequency does not change too much, and the rate of change of frequency (RoCoF) is relatively small. Therefore, for the frequency change rate in (14), the quadratic term is a high-order infinitesimal quantity and can be ignored, i.e.:

$$2H\left(K + \frac{K_\mathrm{i}}{D_\mathrm{p}}\right)\frac{\mathrm{d}\Delta\omega}{\mathrm{d}t} = -\frac{3}{2}KU_\mathrm{g}K_\mathrm{p}\Delta\omega - \frac{3}{2}KU_\mathrm{g}K_\mathrm{i}\Delta\delta \tag{15}$$

Comparing (14) with (6), it is easy to get the equivalent inertia parameter T_J, the equivalent damping parameter T_D and the equivalent synchronization parameter T_S of the system, i.e.:

$$\begin{cases} T_\mathrm{J} = 2HK + 2\dfrac{HK_\mathrm{i}}{D_\mathrm{p}} \\ T_\mathrm{D} = \dfrac{3}{2}KU_\mathrm{g}K_\mathrm{p} \\ T_\mathrm{S} = \dfrac{3}{2}KU_\mathrm{g}K_\mathrm{i} \end{cases} \tag{16}$$

It can be seen from (16) that the grid-tied photovoltaic power generation system under the DC voltage droop control has the certain inertia level, damping capacity and synchronization characteristics, which are determined by the control parameters, the structural parameters, and the steady-state operating point parameters of the system. The structure parameters mainly include the equivalent inductance X, the DC capacitance C and the grid voltage level U_g. The steady-state operating point parameters mainly include steady-state power angle δ_0, DC side capacitance voltage U_DC and the inverter equivalent internal potential U_s.

In the case of no energy storage device, changing the inverter control parameters is the most simple and flexible method to make the photovoltaic power generation system participate in the grid frequency adjustment. The influence of control parameters on these characteristics is analyzed as below. It can be seen from (16): the equivalent inertia coefficient T_J of the system is jointly affected by the droop coefficient D_P and the proportional integral coefficient K_i of the outer DC voltage control loop, and the larger the $1/D_\mathrm{P}$ and K_i, the larger the T_J, the stronger the inertia level of the system; the equivalent damping coefficient T_D of the system is affected by the ratio coefficient K_p of the outer DC voltage control loop, and the larger the K_P, the larger the T_D, the stronger the damping effect of the system; the equivalent damping coefficient of the system is the same as that of the outer DC voltage control loop. The synchronization coefficient T_S is affected by the proportional integral coefficient K i of the outer DC voltage loop. The larger k_i is, the larger T_S is, and the stronger synchronization effect is. It should be noted that from (16), the part of the inertia coefficient of grid tied photovoltaic power generation system has nothing to do with the control parameters, indicating that the system has its own inertia effect.

From the physical point of view, the smaller the droop coefficient D_P is, that is, the larger the $1/D_\mathrm{p}$ is, the stronger the coupling between the DC voltage and the grid frequency is, the more the DC voltage drops, the more energy is released, and the stronger the inertia effect of the system is. The larger the proportional coefficient K_p of the outer DC voltage control loop is, the larger the voltage deviation is, and the damping changes according to the deviation law. The larger the deviation is, the larger the damping is, that is, the stronger the damping effect of the system is. The integral regulator is used to eliminate the deviation and realize no static error control. Therefore, the larger the proportional integral coefficient K_i of the DC voltage outer loop, the stronger the synchronization effect of the system.

IV. SIMULATION ANALYSIS

This paper uses the MATLAB/Simulink simulation platform to verify the theoretical analysis of the inertia, damping characteristics of the grid-tied photovoltaic power generation system. The topology of the simulation system is shown in Figure 1, and the main parameters of the simulation circuit are shown in Table 1. When the simulation operating condition is set to $t = 1$ s, the grid frequency drops by 0.2 Hz.

TABLE 1. The main parameters of the circuit.

parameter	value	parameter	value
PV side bus capacitance /μF	100	AC grid line-to-line voltage/V	380
DC bus capacitance /mF	5	L filter inductance /mH	3
DC filter inductance /mH	24	Grid frequency/Hz	50
DC side voltage /V	750	Line reactance /mH	0.5

A. ANALYSIS OF THE MECHANISM OF DROOP

In order to reflect the influence of introducing the frequency deviation to form the DC voltage droop on the system, the grid-tied photovoltaic power generation system with or without droop loop was simulated, as shown in Figure 6 and Figure 7. When the system does not have a droop loop, the DC/DC converter does not respond to the grid frequency changes, keeping constant power output and constant DC voltage. After the frequency deviation is introduced to form a droop loop, when the grid frequency drops, the DC side capacitor responds to the grid frequency change, the capacitor voltage drops to release the energy, and the system power increases.

B. INERTIA CHARACTERISTICS ANALYSIS

In the simulation of the grid-tied photovoltaic power generation system controlled by the DC voltage droop, K_p and K_i remain unchanged, and the influence of D_p change

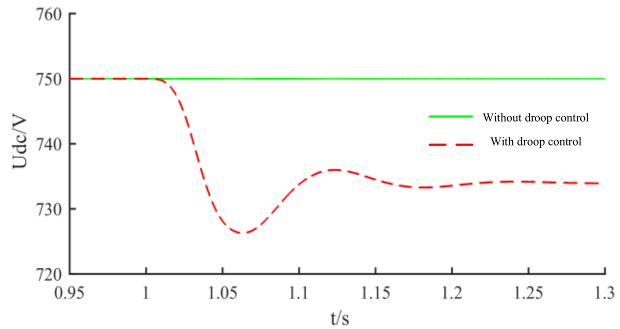

FIGURE 6. Influence of different parameter changes on system inertia.

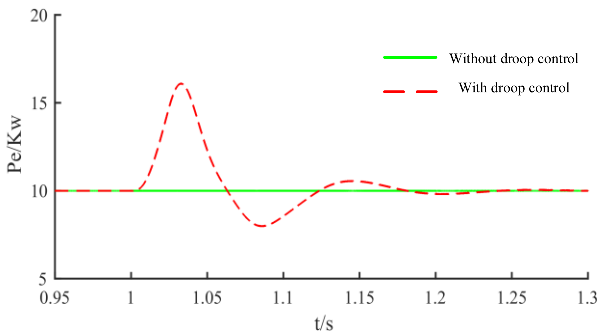

FIGURE 7. Influence of different parameter changes on system inertia.

on the inertia characteristics of the system, as shown in Figures 8 and 9.

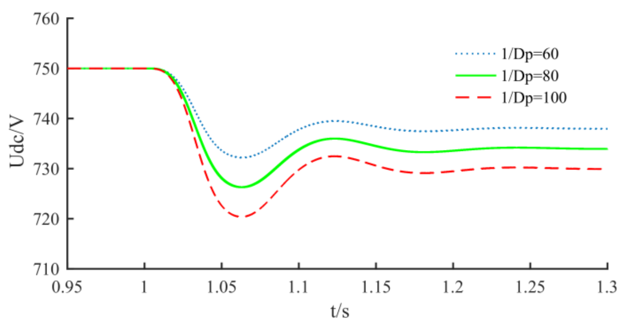

FIGURE 8. Influence of droop coefficient D_p on DC voltage.

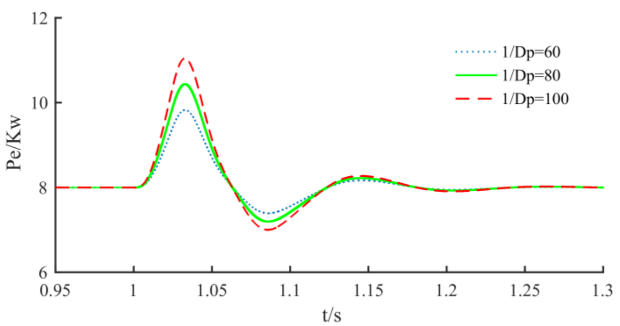

FIGURE 9. Influence of droop coefficient D_p on system power.

The simulation results show that as D_p decreases and $1/D_p$ increases, the oscillation amplitude of the DC side capacitor voltage increases, indicating that the more the capacitor voltage drops, the greater the released power, and the corresponding system power oscillation amplitude Bigger. In summary, the larger $1/D_p$, the stronger the inertia characteristic of the system, which is consistent with the conclusion drawn by (16).

C. DAMPING CHARACTERISTICS ANALYSIS

In the simulation of the grid-tied photovoltaic power generation system controlled by DC voltage droop, D_p and K_i remain unchanged, and the influence of K_p change on the damping characteristics of the system is shown in Figure 10 and Figure 11.

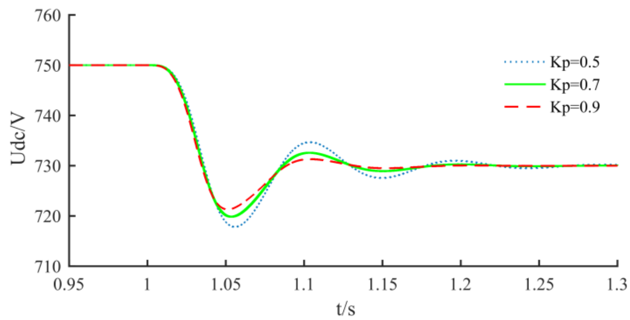

FIGURE 10. The influence of P controller on DC voltage.

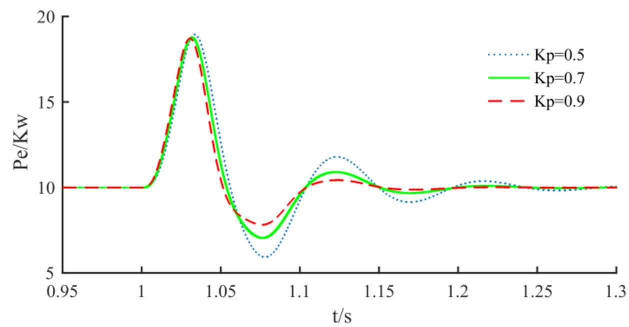

FIGURE 11. The influence of P controller on system power.

The simulation results show that when the system power rises with the same amplitude, that is, when the capacitor releases a certain amount of energy, the larger the $K_{p,}$ the smaller the amplitude of the DC side capacitor voltage drop, and the smaller the amplitude of the voltage and power oscillations, which indicates that the damping capacity of the system is stronger. In summary, the larger the K_p, the stronger the damping effect of the system, which is consistent with the conclusion drawn by (16).

D. SYNCHRONIZATION CHARACTERISTICS ANALYSIS

In the simulation of grid-tied photovoltaic power generation system controlled by the DC voltage droop, K_p and D_p remain unchanged, and the influence of K_i change on the synchronization characteristics of the system is shown in Figure 12 and Figure 13. It should be noted that the (14)

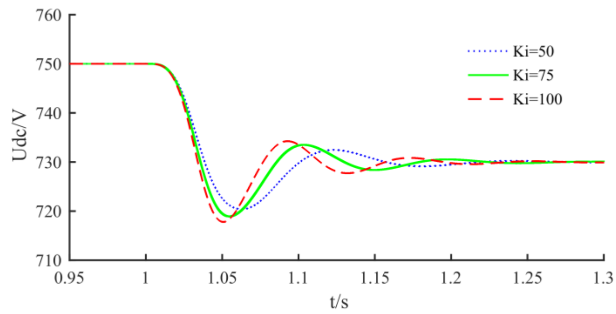

FIGURE 12. The influence of I controller on DC voltage.

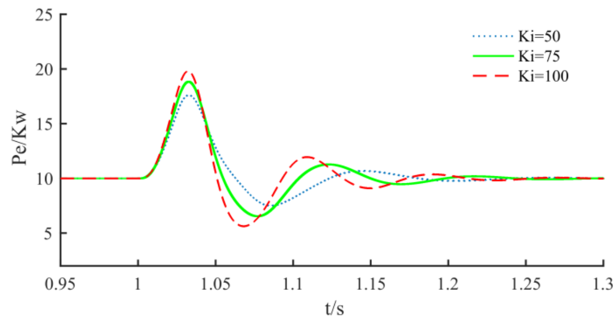

FIGURE 13. The influence of I controller on system power.

shows K_i also has a certain influence on the inertia characteristics of the system.

The simulation results show that with the increase of K_i, the oscillation period of the DC side capacitor voltage and the system power have changed significantly, and the oscillation amplitude and decay speed have not changed much. It shows that the change of K_i mainly affects the synchronization characteristics, and has little effect on the inertia characteristics. In summary, the larger the K_i, the stronger the synchronization capability of the system, which is consistent with the conclusion drawn by (16).

V. CONCLUSION

In the face of small disturbances, without adding new hardware equipment, this paper proposes a grid-connected photovoltaic power generation system control strategy that is based on the DC voltage droop control, and the inertia, damping and synchronization characteristics of the system are analyzed by establishing the system's SSG model. Research results indicate that:

(1) The inertia, damping and synchronization of the grid-tied photovoltaic power generation system based on DC voltage droop control are determined by the structural parameters, control parameters and steady-state operating points of the system.

(2) From the perspective of control parameters, the smaller the droop coefficient D_p, the stronger the inertia characteristic of the system; the larger the DC voltage outer loop proportional coefficient K_p, the stronger the damping effect of the system; the greater the DC voltage outer loop integral coefficient K_i Larger, the stronger the synchronization capability of the system.

(3) Under the DC voltage droop control strategy, the DC side capacitor of the system can exhibit the inertia characteristics, and the system can operate stably under the action of small disturbances.

The research conclusions of this paper have certain significance for improving the frequency stability of grid-connected photovoltaic power generation system under small disturbance, and lay a theoretical foundation for the friendly integration of photovoltaic power generation into the power grid.

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