SPECIAL SECTION ON KEY ENABLING TECHNOLOGIES FOR PROSUMER ENERGY MANAGEMENT

Received January 14, 2021, accepted January 23, 2021, date of publication February 22, 2021, date of current version March 11, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3059678

Analysis of Inertia Characteristics of Photovoltaic Power Generation System Based on Generalized Droop Control

YUXIN ZHA[1], JIAN LIN[1], GUANJUN LI[2], (Member, IEEE), YUE WANG[1], AND YIZHANG[1]
[1]School of Automation, Nanjing Institute of Technology, Nanjing 211167, China
[2]China Electric Power Research Institute Company Ltd., Nanjing 210003, China

Corresponding author: Yuxin Zha (1027786502@qq.com)

This work was supported by Science and Technology Project of Jiangsu Electric Power Company: High efficient utilization and optimal control technology of medium voltage direct energy storage system supporting the construction of shared energy storage power station.

ABSTRACT Due to the lack of inertial support of the physical rotor of reliable power, the problem of weak inertia of the system is prominent when large-scale grid connection. Aiming at the weak inertia problem of new energy power systems, this paper takes the photovoltaic power generation system with generalized droop control as the research object. Firstly, the paper introduces the structure of the photovoltaic power generation system and the mathematical principle of generalized droop control At the same time, the electrical torque model of the system is established in order to reveal the inertia characteristics of the grid-tied inverter under the generalized droop control, moreover, the influencing factors of the system's inertia characteristics and the influence rules of parameters are analyzed and studied. Finally, simulation analysis verifies the correctness of the analysis. The research results show that the photovoltaic inverter system under the generalized droop control has obvious inertia characteristics, the change of inertia size is affected by the dominant zero pole of the controller, and the equivalent inertia coefficient has frequency domain characteristics.

INDEX TERMS New energy power, weak inertia characteristics, photovoltaic grid-tied system, generalized droop control, inertia characteristics analysis.

I. INTRODUCTION

In recent years, the large-scale grid-connection of electric vehicles and flexible transmission and distribution equipment and application of renewable energy have caused tremendous changes in the composition of structure in the traditional power system [1]–[4], and profoundly changed the dynamic behavior of the power system [5]–[7]. Since most of the renewable energy generation is connected to the grid through power electronic converters [8], [9] that lacks the rotor inertia support of the synchronous generator (SG), the frequency stability of the power system has become an increasingly prominent issue [10], [11].

In order to solve the problem of weak inertia caused by the injection of renewable energy sources, the virtual synchronous generator (VSG) control strategy has emerged [12], [13] based on the frequency operation characteristics of synchronous generators. Works in [14], [15] control the inverter through the equivalent emulation of the SG rotor motion equation, so that the output frequency characteristics are similar to the SG frequency response characteristics. [16] derived the accurate, dynamic VSG model, and analyzed the mechanism of synchronous frequency resonance phenomenon and its influence on system stability. It is noted that although the VSG strategy equips the inverter system with inertia characteristics, it can also easily cause system instability in the grid-connected mode. [17] pointed out that while the VSG strategy provides the SG inertia, it also inherits the risk that the SG is prone to oscillations, namely, when the system is disturbed, the system frequency will observe continuous oscillations. [18] and [19] analyzed the virtual torque characteristics and instability mechanism of the VSG. Focusing on the weak adaptability of VSG dynamic characteristics, [20] proposed an adaptive VSG inertia control strategy. A large number of literature studies have shown that the inertia characteristics required by VSG control are different for grid-tied and standalone operations, and it is difficult for the VSG control with a constant inertia coefficient to meet

The associate editor coordinating the review of this manuscript and approving it for publication was Bin Zhou.

inertia requirements under different operations. The power droop control, with its significant advantages such as independence of a communication system, high reliability, and strong flexibility, is widely used in grid-connected inverter system control [21]. Focusing on the drawbacks of droop control and VSG control, [22] proposed a generalized droop control of the inverter. Through the additional compensation control of the frequency-active power loop in the droop control, the inertia characteristics of the inverter are realized, meanwhile the operation under different working conditions is well realized. Most of the above-mentioned works focus on the emulation of the inertia characteristics on the inverter, yet have not conducted in-depth analysis and research on the mechanism of the virtual inertia characteristics. [23] summarized the stability analysis methods of grid-connected inverter systems, and pointed out that the equivalent characteristic coefficients of grid-connected inverters under the electric torque analysis have frequency-dependent characteristics, yet the conclusion was not verified in a specific system. [24] analyzes the inertia damping characteristics of conventional control inverter systems through the electrical torque analysis method and obtains equivalent coefficients that characterize the dynamic characteristics of the system, but the equivalent inertia damping coefficients are constant that not completely describe the dynamic behavior of the inverter system under control.

Based on the above-mentioned literature, this paper takes the photovoltaic power generation system with generalized droop control as the research target, analyzes and studies the system inertia characteristics, and reveals the nature of the system inertia characteristics under control and the influential law of parameter changes affecting the inertia characteristics. Finally, the simulation analysis verifies the effectiveness of the inertia characteristic analysis in this paper.

II. STRUCTURE OF PHOTOVOLTAIC POWER GENERATION SYSTEM

A. STRUCTURE OF PHOTOVOLTAIC POWER GENERATION SYSTEM

The structure of the photovoltaic power generation system is shown in Figure 1. The system mainly includes photovoltaic cells, a DC boost circuit, an inverter and the control system. In order to equip the photovoltaic power generation system with voltage and frequency adjustment capabilities, the DC side is generally connected to the energy storage block. In the Figure 1, i_{pv} is the output current of photovoltaic generation, u_{dc} is the DC bus voltage, i_{abc} is the inverter output current, $u$abc is the voltage at the PCC point, and L_1, L_2, and C_f are the filter inductors and capacitor, respectively.

The DC/DC controller in Figure 1 mainly implements the DC voltage control of photovoltaic generation, and the inverter controller mainly implements the grid-connection control and provides voltage and frequency support to the system [9], [24]. It is worth noting that the photovoltaic generation system with generalized droop control can either operate in grid-tied mode, or in standalone mode, and it has a good dynamic performance.

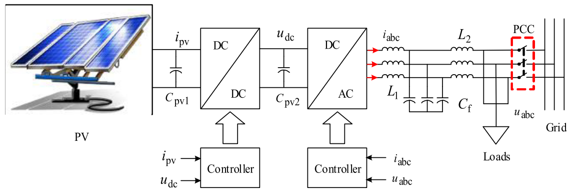


FIGURE 1. Graphical representation of grid-tied PV generation.

B. CONTROL PRINCIPLE OF GRID-CONNECTED PHOTOVOLTAIC INVERTER UNDER GENERALIZED DROOP CONTROL

Conventional droop control can realize the autonomous synchronous operation of the inverter. However, since frequency and power are proportional, the system output characteristics do not have inertia capability. The frequency-active power equation under inverter droop control can be expressed as:

$$f = f_0 - m\frac{\omega_c}{s+\omega_c}(P - P_0) \tag{1}$$

where f and f_0 are the frequency and nominal frequency of the system, respectively, m is the droop coefficient, P and P_0 are the output power and rated power of the system, ω_c is the cutoff frequency of the low-pass filter, and s is the differential operator.

By linearizing (1), the small-signal model of frequency-active power drooped control can be obtained as:

$$\frac{\Delta f}{\Delta P} = -m\frac{\omega_c}{s+\omega_c} = -m\frac{1}{s/\omega_c + 1} \tag{2}$$

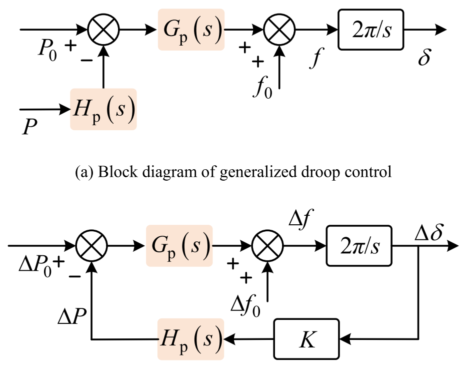
According to (2), it is known from the control theory that the frequency change rate of the system under a step disturbance is ω_c. For a general value of ω_c taken as 200, the rate of change of frequency (ROCOF) is 200, which far exceeds the current ROCOF operating standard, and is not conducive to the safe and stable operation of the system frequency.

In order to solve the large ROCOF issue caused by the droop control, the generalized droop control is formed by modifying the droop loop [23]. The block diagram of generalized droop control is shown in Figure 2. In the Figure 2, $G_p(s)$ is the generalized droop controller, $H_p(s)$ is the low-pass filter of the power calculation block, K is the synchronization coefficient and $K = EV/X$, where E and V are the inverter output voltage and grid voltage, respectively, and X is the linkage impedance.

According to the design principle in [18], the generalized droop controller $G_p(s)$ can be expressed as:

$$G_p(s) = m\frac{(1+\tau_1 s)}{(1+T_1 s)(1+T_2 s)} \tag{3}$$

In (3), τ_1, T_1, and T_2 are time constants. By adjusting the time constant, the inverter can have better inertia characteristics and dynamic performance. Although the generalized



(a) Block diagram of generalized droop control

(b) small-signal model for generalized droop control.

FIGURE 2. Generalized droop control principle.

droop control allows the inverter to obtain the inertia characteristics, the physical meaning is not clear, the inertia influential factors and laws cannot be intuitively reflected, and the inertia obtained by the inverter cannot be effectively evaluated. The inertia characteristics of generalized droop control will be analyzed in detail as follows.

III. INERTIA CHARACTERISTICS ANALYSIS OF PHOTOVOLTAIC GRID-CONNECTED POWER GENERATION SYSTEM

In traditional power systems, the inertia mainly refers to that of the generator rotor. Generally, the equivalent inertia time constant H (or T) is used to describe the inertia level of the power system. The inertial time constant of the SG is defined as:

$$H = \frac{J\omega_0^2}{S_n} \tag{4}$$

where J is the SG's moment of inertia, ω_0 is the rated electric angular velocity, and S_n is the reference power. By comparing to the inertia characteristics generated by the generalized droop control, it can be seen that the inverter system has neither real J and ω_0, nor "virtual J" as in VSG control, but it has inertia response characteristics. This inertia characteristic was not analyzed or explained in [9]. In this manuscript, the electric torque analysis will be adopted to express and quantify the inertia characteristics of the generalized droop control, in a similar manner to that of a SG.

A. ANALYSIS OF INERTIA CHARACTERISTICS OF PHOTOVOLTAIC POWER GENERATION SYSTEM BASED ON GENERALIZED DROOP CONTROL

According to the electric torque analysis, the dynamic characteristics of the inverter system can be described by the electric torque equation as [24]:

$$H_s \frac{d\Delta\omega}{dt} = -T_D(s)\Delta\omega - T_S(s)\Delta\delta \tag{5}$$

where H(s), T_D(s), and T_S(s) are the equivalent inertia, damping and synchronization coefficients of the system respectively, which represent the inertia level, damping capacity and synchronization capacity of the system [23], and reflect the system dynamic characteristics.

In order to describe the inertia characteristics of the grid-tied photovoltaic system with generalized droop control, the small-signal model of the system is combined with the droop controller model, and the electric torque model of the system can be obtained as shown in Figure 3.

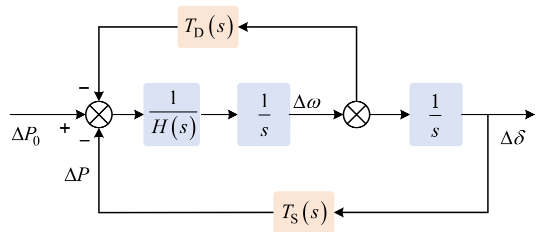


FIGURE 3. Electromagnetic torque model based on generalized droop control.

According to (1) and Figure 3, the characteristic coefficients of the photovoltaic inverter system with generalized droop control can be obtained as:

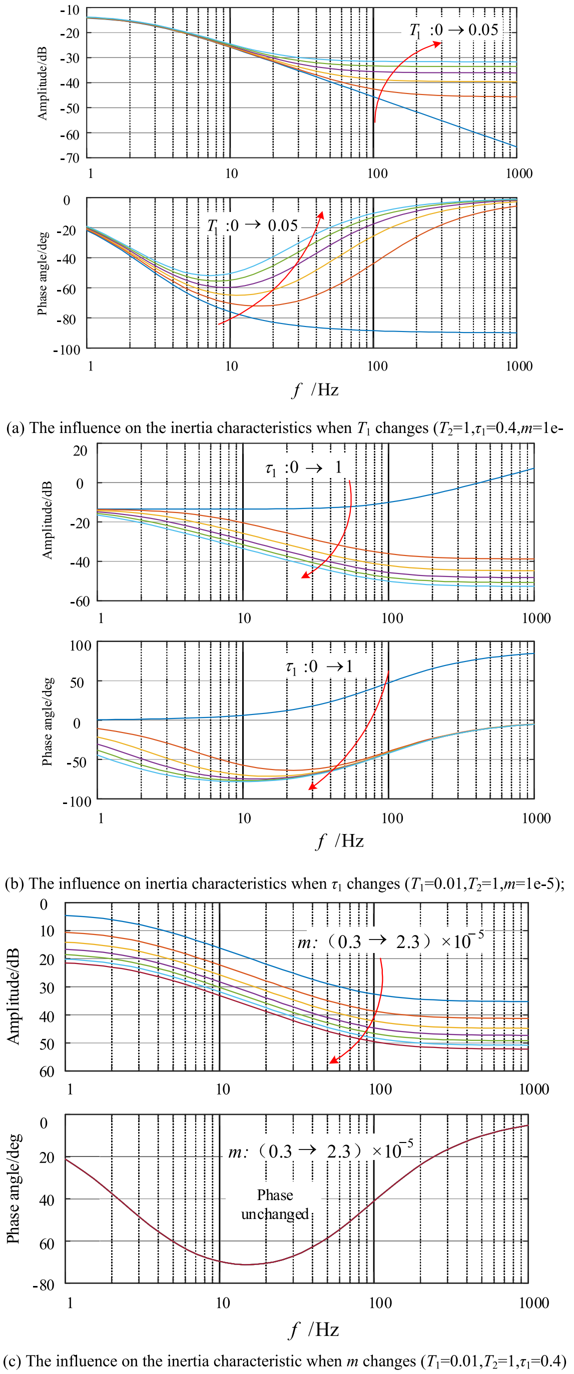
$$\begin{cases} H(s) = \dfrac{T_1 + T_2 + T_1 T_2 s}{m(1+\tau s)} \\ T_D(s) = \dfrac{1}{m(1+\tau s)} \\ T_S(s) = \dfrac{K\omega_c}{s+\omega_c} \end{cases} \tag{6}$$

It can be seen from (6) that, different from the inertia coefficient H of SG shown in (1) (which is constant), the equivalent inertia coefficient of photovoltaic inverter system with generalized droop control has frequency-dependent characteristics, suggesting different inertia coefficient values at various frequencies. Besides, the equivalent inertia coefficient at different frequencies is mainly determined by the control parameters of m, T_1, T_2, and τ_1 simultaneously, namely, the change in inertia is affected by the dominant zero and pole of the controller G_p(s).

According to (6), the influential law of the system characteristic coefficient with the change of parameters can be obtained as shown in Figure 4. From Figure 4(a)(b), as T_1 increases from 0 to 0.05 or τ_1 decreases from 1 to 0, the phase margin and gain margin increase accordingly, namely, the system stability enhances, and the corresponding inertia coefficient is improved. As the gain, m only affects the amplitude movement, while the phase angle diagram remains unchanged.

B. STABILITY ANALYSIS OF PHOTOVOLTAIC POWER GENERATION SYSTEM WITH GENERALIZED DROOP CONTROL

Since the generalized droop control changes the original frequency-active power droop characteristics and has a certain impact on the power angle stability of the system, it is necessary to analyse the stability of the photovoltaic inverter system with the generalized droop control.



(a) The influence on the inertia characteristics when T_1 changes (T_2=1,τ_1=0.4,m=1e-

(b) The influence on inertia characteristics when τ_1 changes (T_1=0.01,T_2=1,m=1e-5);

(c) The influence on the inertia characteristic when m changes (T_1=0.01,T_2=1,τ_1=0.4)

FIGURE 4. The effect of parameter changes on the equivalent inertia coefficient.

According to the electric torque model, the system stability can be quantitatively analyzed by the open-loop transfer function composed of the acceleration change of the system frequency Δa_ω and the frequency change $\Delta\omega$ [9]. Figure 5 shows the structure of the open-loop system composed of Δa_ω and $\Delta\omega$. It can be seen from Figure 5 that the open-loop transfer function of $\Delta a_\omega/\Delta\omega$ is:

$$\frac{\Delta a_\omega}{\Delta\omega} = -\frac{sT_D(s) + T_S(s)}{sH(s)} \tag{7}$$

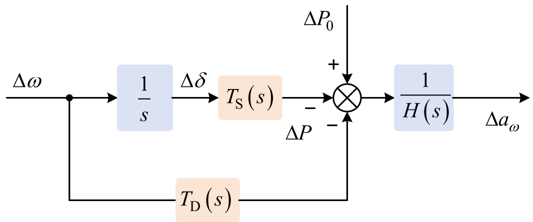
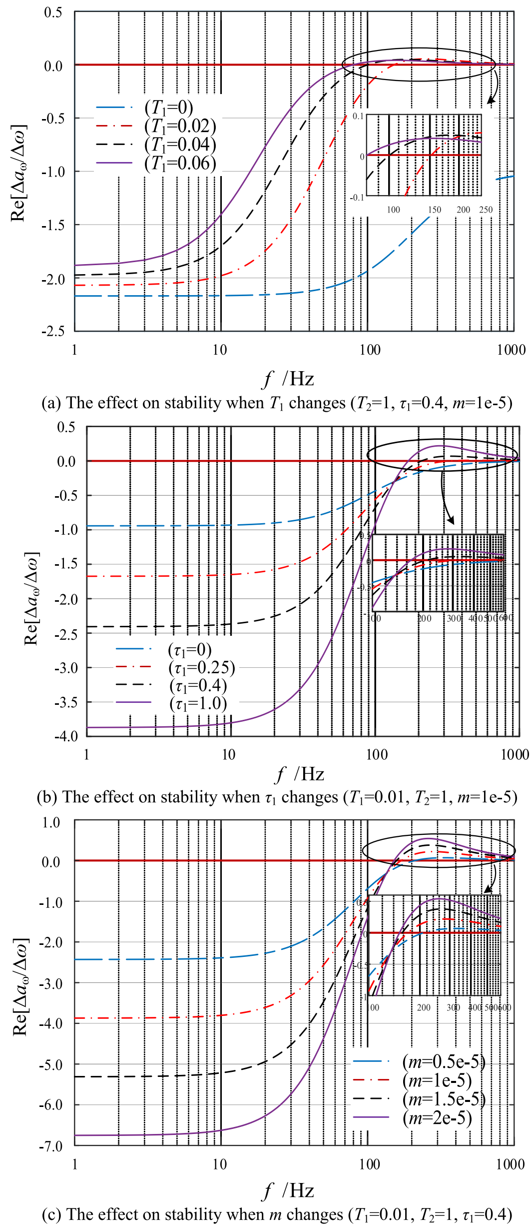


FIGURE 5. Open-loop transfer function structure diagram of $\Delta a_\omega/\Delta\omega$.



(a) The effect on stability when T_1 changes (T_2=1, τ_1=0.4, m=1e-5)

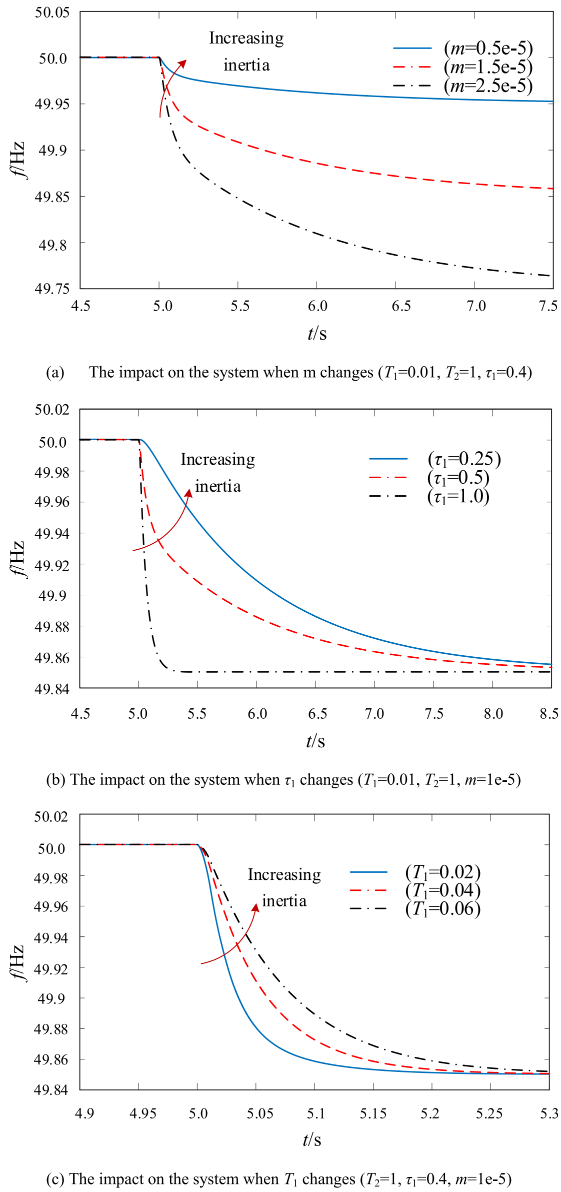
(b) The effect on stability when τ_1 changes (T_1=0.01, T_2=1, m=1e-5)

(c) The effect on stability when m changes (T_1=0.01, T_2=1, τ_1=0.4)

FIGURE 6. The influence of parameter changes on $\Delta a_\omega/\Delta\omega$.

According to (7), the real part of the open-loop transfer function of $\Delta a_\omega/\Delta\omega$ in frequency domain can be obtained as:

$$\mathrm{Re}\left[\frac{\Delta a_\omega}{\Delta\omega}(j\omega)\right] = \mathrm{Re}\left[-\frac{j\omega T_D(j\omega) + T_S(j\omega)}{j\omega H(j\omega)}\right] \tag{8}$$

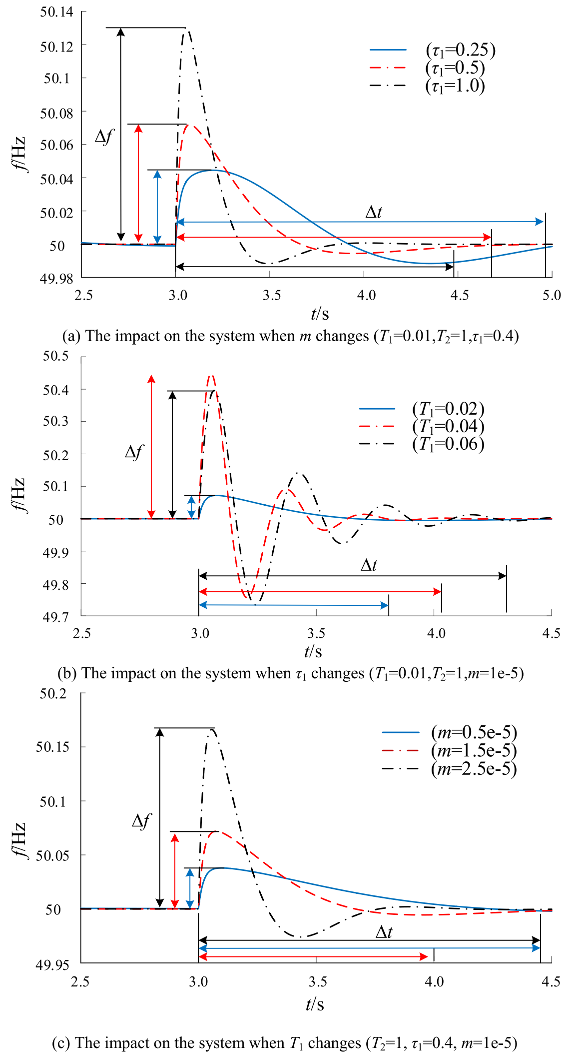


(a) The impact on the system when m changes (T_1=0.01, T_2=1, τ_1=0.4)

(b) The impact on the system when τ_1 changes (T_1=0.01, T_2=1, m=1e-5)

(c) The impact on the system when T_1 changes (T_2=1, τ_1=0.4, m=1e-5)

FIGURE 7. The influence of different parameter changes on system inertia on system inertia.



(a) The impact on the system when m changes (T_1=0.01,T_2=1,τ_1=0.4)

(b) The impact on the system when τ_1 changes (T_1=0.01,T_2=1,m=1e-5)

(c) The impact on the system when T_1 changes (T_2=1, τ_1=0.4, m=1e-5)

FIGURE 8. The influence of different parameter changes on system stability.

where ω is the oscillation frequency. Through the analysis of (8), the influence of different parameter changes on system stability can be obtained. The influential law of parameter changes on system stability is shown in Figure 6. In the low-frequency range, the larger T_1, the smaller the real part amplitude of the open-loop transfer function, and the more stable the system. With the increase of m and τ_1, the smaller the real part amplitude, the more stable the system. In the high frequency band exceeding the cut-off frequency of 200 Hz, the law is opposite. It can be seen from (8) that the system has certain frequency-dependent characteristics.

IV. SIMULATION ANALYSIS

In order to verify the effectiveness of the proposed analysis in terms of the inertia characteristics of the grid-connected photovoltaic inverter system with generalized droop control, the MATLAB/Simulink simulation platform was used to build a system model for analysis and verification. The main parameters of the photovoltaic inverter system are shown in Table 1.

TABLE 1. The main parameters of the photovoltaic inverter system.

parameter	value	parameter	value
PV capacity /kW	20	DC side voltage /V	500
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	Line reactance on the grid side /mH	5
DC/DC switching frequency /kHz	20	DC/AC switching frequency /kHz	10

Figure 7 shows the grid-side frequency change after the grid-connected system is disturbed at 5 s. It can be seen from Figure 7 (a) and (b) that, when other parameters remain unchanged, the smaller the droop coefficient m or zero of $G_p(s)$ τ_1, the smaller the instantaneous ROCOF when the disturbance occurs, viz., the larger inertia of the system.

Analogously, it can be seen from Figure 7(c) that as the pole T_1 of controller $G_p(s)$ increases, the inertia of the photovoltaic system controlled by the generalized droop increases, which is consistent with the conclusion of (6).

Figure 8 shows the stability of the standalone system when the load is increased at 3 s. It can be seen from Figure 8(a) and (b) that as m or τ_1 decreases, the highest frequency deviation Δf when disturbance occurs becomes smaller, and the stability of the system seems to have improved. However, while pursuing stability, the problem of rapidity also needs to be taken into consideration. As τ_1 decreases, the stability is improved, and the time Δt to restore balance is also extended. Similarly, in Figure 8(c), changing the time constant T_1 to minimize Δf cannot guarantee the shortest restoration time Δt.

V. CONCLUSION

Based on the structure of photovoltaic power generation system and the mathematical principles of generalized droop control, this article uses electric torque analysis to express the inertia characteristics analogous to the SG, and quantitatively characterizes the inertia characteristics brought by generalized droop control. The research results found:

(1) The photovoltaic inverter system has obvious inertia characteristics under generalized droop control, which enables the system to balance load fluctuations.

(2) By adjusting the time constant, the inverter can have better inertia characteristics and better dynamic performance, and the equivalent inertia coefficient has frequency dependent characteristics.

(3) When adjusting a parameter, the speed, stability and accuracy cannot be guaranteed at the same time.

The above research conclusions can be used as the theoretical basis for engineering practice to rationally design the inertia, damping, and synchronization characteristics of the grid-connected photovoltaic power generation system and make it more friendly injected to the grid. However, because the control parameters have a certain coupling relationship on the inertia, damping, and synchronization characteristics of the system, it is impossible to excessively change the control parameter range in order to pursue the large inertia and strong damping characteristics of the system, so that the system enters the unstable region. Hence, the optimization design of the control parameters is also an issue worth studying.

REFERENCES

[1] D. Xu, Q. Wu, B. Zhou, C. Li, L. Bai, and S. Huang, "Distributed multi-energy operation of coupled electricity, heating, and natural gas networks," *IEEE Trans. Sustain. Energy*, vol. 11, no. 4, pp. 2457–2469, Oct. 2020.

[2] L. Xiong, F. Zhuo, X. Liu, Z. Xu, and Y. Zhu, "Fault-tolerant control of CPS-PWM-Based cascaded multilevel inverter with faulty units," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 7, no. 4, pp. 2486–2497, Dec. 2019.

[3] Z. Zhou, Y. Cai, S. Su, X. Tang, and Y. Cao, "Electric vehicles scale evolution model considering social attributes," *IEEE Access*, vol. 8, pp. 168784–168792, 2020.

[4] Y. Li, Z. Xu, L. Xiong, G. Song, J. Zhang, D. Qi, and H. Yang, "A cascading power sharing control for microgrid embedded with wind and solar generation," *Renew. Energy*, vol. 132, pp. 846–860, Mar. 2019.

[5] W. Binbing, X. Abuduwayiti, C. Yuxi, and T. Yizhi, "RoCoF droop control of PMSG-based wind turbines for system inertia response rapidly," *IEEE Access*, vol. 8, pp. 181154–181162, 2020, doi: 10.1109/ACCESS.2020.3027740.

[6] L. Xiong, X. Liu, C. Zhao, and F. Zhuo, "A fast and robust real-time detection algorithm of decaying DC transient and harmonic components in three-phase systems," *IEEE Trans. Power Electron.*, vol. 35, no. 4, pp. 3332–3336, Apr. 2020.

[7] Y. Chi, B. Tang, J. Hu, X. Tian, H. Tang, Y. Li, S. Sun, L. Shi, and L. Shuai, "Overview of mechanism and mitigation measures on multi-frequency oscillation caused by large-scale integration of wind power," *CSEE J. Power Energy Syst.*, vol. 5, no. 4, pp. 433–443, 2019.

[8] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184–1194, Sep. 2004.

[9] L. Xiong, X. Liu, Y. Liu, and F. Zhuo, "Modeling and stability issues of voltage-source converter dominated power systems: A review," *CSEE J. Power Energy Syst.*, early access, Nov. 20, 2020, doi: 10.17775/CSEEJPES.2020.03590.

[10] S. Wei, Y. Zhou, and Y. Huang, "Synchronous motor-generator pair to enhance small signal and transient stability of power system with high penetration of renewable energy," *IEEE Access*, vol. 5, pp. 11505–11512, 2017.

[11] L. Xiong, X. Liu, D. Zhang, and Y. Liu, "Rapid power compensation based frequency response strategy for low inertia power systems," *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, Oct. 19, 2020, doi: 10.1109/JESTPE.2020.3032063.

[12] T. Shintai, Y. Miura, and T. Ise, "Oscillation damping of a distributed generator using a virtual synchronous generator," *IEEE Trans. Power Del.*, vol. 29, no. 2, pp. 668–676, Apr. 2014.

[13] H. Bevrani, T. Ise, and Y. Miura, "Virtual synchronous generators: A survey and new perspectives," *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 244–254, Jan. 2014.

[14] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.

[15] M. Li, L. Xiong, H. Chai, L. Xiu, and J. Hao, "Mechanism of PV generation system damping electromechanical oscillations," *IEEE Access*, vol. 8, pp. 135853–135865, 2020.

[16] N. Soni, S. Doolla, and M. C. Chandorkar, "Improvement of transient response in microgrids using virtual inertia," *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1830–1838, Jul. 2013.

[17] O. A. Ilhan, S. G. Kasimov, U. S. Madraximov, and H. M. Baskonus, "Solvability of the mixed problem of a high-order PDE with fractional time derivatives, Sturm-Liouville operators on spatial variables and non-local boundary conditions," *Rocky Mountain J. Math.*, vol. 49, no. 4, pp. 1191–1206, 2019.

[18] L. Huang, H. Xin, and Z. Wang, "Damping low-frequency oscillations through VSC-HVDC stations operated as virtual synchronous machines," *IEEE Trans. Power Electron.*, vol. 34, no. 6, pp. 5803–5818, Jun. 2018.

[19] W. Du, H. Wang, and L.-Y. Xiao, "Power system small-signal stability as affected by grid?connected photovoltaic generation," *Eur. Trans. Elect. Power*, vol. 22, no. 5, pp. 688–703, 2012.

[20] J. Alipoor, Y. Miura, and T. Ise, "Power system stabilization using virtual synchronous generator with alternating moment of inertia," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 2, pp. 451–458, Jun. 2015.

[21] L. Xiong, X. Liu, and Y. Liu, "Decaying DC and harmonic components detection for absorbing impact load currents in weak grids," *IEEE Trans. Power Del.*, early access, Nov. 16, 2020, doi: 10.1109/TPWRD.2020.3038077.

[22] B. Wu, T. Yizhi, C. Yuxi, X. Abuduwayiti, and L. Xiong, "Virtual frequency construction based vector current control for grid-tied inverter under imbalanced voltage," *IEEE Access*, vol. 8, pp. 199654–199663, 2020.

[23] X. Meng, J. Liu, and Z. Liu, "A generalized droop control for gridsupporting inverter based on comparison be-tween traditional droop control and virtual synchronous generator control," *IEEE Trans. Power Electron.*, vol. 34, no. 6, pp. 5416–5438, Sep. 2018.

[24] L. Xiong, F. Zhuo, F. Wang, X. Liu, Y. Chen, M. Zhu, and H. Yi, "Static synchronous generator model: A new per-spective to inves-tigate dynamic characteristics and stability issues of grid-tied PWM inverter," *IEEE Trans. Power Electron.*, vol. 31, no. 9, pp. 6264–6280, Sep. 2016.