COLLABORATIVE ADAPTIVE CONTROL STRATEGY FOR ROTOR INERTIA AND DAMPING COEFFICIENT OF VIRTUAL SYNCHRONOUS GENERATOR

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As an effective method for renewable energy integration, virtual synchronous generator (VSG) control strategy of grid connected inverter has attracted more and more attention. In order to reduce power overshoot and speed up frequency response, a collaborative adaptive rotor inertia and damping coefficient control strategy of VSG is proposed. Interval judgement indicators of angular frequency offset degree and relative deviation are defined according to the active frequency characteristic curve of the system and the relationship between the virtual rotor inertia and damping coefficient and the system. Then, eight system oscillation intervals are proposed combining the change law of the system frequency change rate. Virtual rotor inertia and damping coefficient are adjusted collaboratively and adaptively by integrating the judgment index and interval. The proposed algorithm is verified by simulation results based on a MATLAB/Simulink VSG model.

Keywords: inverter; virtual synchronous generators; collaborative; adaptive control

1. Introduction

With the growing prominence of energy issues and environmental contamination, traditional fossil fuels can't meet sustainability, distributed power supply based on renewable energy has got wide and continuous concern [1, 2]. Majority of distributed power sources demand link with the grid through power electronics facility like invertors, power electronics devices constitute the inverter has a high dynamic performance, but it will change the structure of the traditional power supply, and the lack of inertia and damping effect will also cause constraints on the stability characteristics of the grid, to achieve a mass of new energy generation friendly access to grid urgently need to be addressed [3-5]. Therefore, research man has put forward virtual synchronous generator (VSG)

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control strategy, The VSG system enables distributed power supplies to provide oscillation damping, rotational inertia, and reactive power control by simulating the characteristics of a synchronous generator rotor make the inverter also possesses damping and inertia, enabling a mass of distributed power supplies to be connected with the grid in a friendly manner. Literature [6,7] proposed an adaptive regulation method based on rotor inertia by transient analysis of the power and angle characteristics, which was proved to be stable using Lyapunov theory, however, no adaptive expression was given. In the literature [8], fuzzy logic reasoning was used to determine the rotor inertia type adaptive regulation method, but the method only considered the virtual rotor inertia as a function of stability improvement without considering the effect of damping parameters for the transient stability of system. In the literature [9], an adaptive damping control method on the basis of the SG power angle characteristics is put forward, which is able to restrain transient frequency oscillations and make sure that the amplitude is in the range. Although active power overshoot and oscillations could be able to be cut down, the influence of is neglected. Literature [10] proposes a virtual rotational inertia adaptive control strategy using small-signal model analysis of distributed power systems but does not mention the principles for the selection of virtual rotational inertia and coefficients. In the literature [11], a method of adaptive rotor inertia is proposed to achieve dynamic tracking virtual rotor inertia depend on frequency variations. This adaptive scheme on the basis of bang-bang control but does not give a specific value for the inertia threshold. A method based on the dynamic adjustment of the virtual rotor inertia is proposed in literature [12], it rises the dynamic capability, but the effect of damping factor D on the active power oscillation is not discussed.

A parameter-coordinated adaptive control method for virtual rotor inertia and damping put into use grid-connected inverters is put forward in paper. The virtual rotor inertia is increased when the rotor angular velocity variation rate is large. When the angular velocity deviation is large, damping is increased to coordinate the two variables to master the frequency of excessive variation and excessive excursion to make sure the stability of system. MATLAB simulation outcome indicate the superiority of the coordinated adaptive control method, which promote the reaction speed of system, reduces the overshoot, and rises the dynamic capability of the system.

2. Control mode of virtual synchronous generator

The VSG control topology is shown by Fig. 1, where the grid-connected inverter can be simulated as a traditional synchronous generator through control methods.

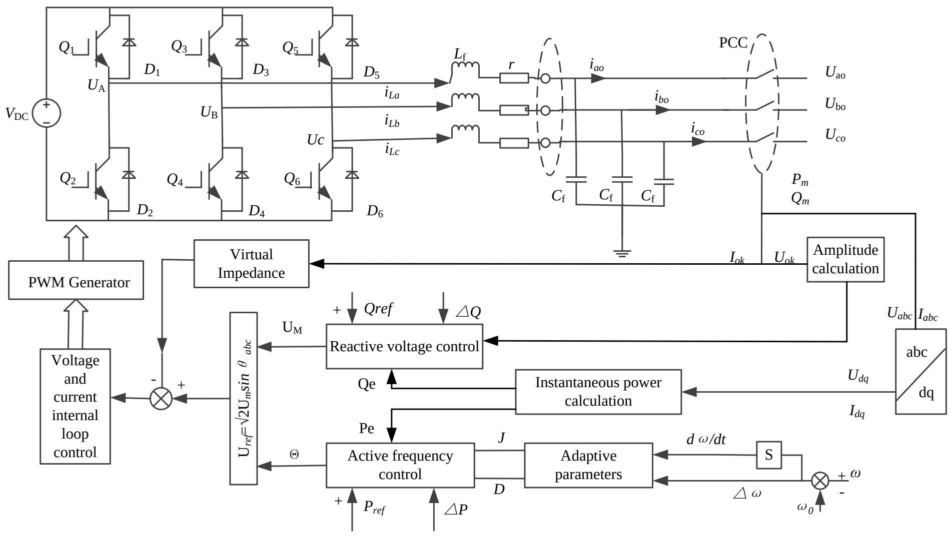

Fig. 1. VSG control topology

2.1 Virtual governor with active power and frequency control

The active power and frequency simulates the rotor movement of SG and the speed adjustment of the prime mover through the inverter, i.e., it relies on adjusting the mechanical torque T_m of the prime mover to change to accomplish the purpose of regulating the active power output, so the sag characteristics of active power and frequency are able to represent by the mechanical torque T_m of the prime mover. The governor equation of the prime mover can be written as:

$$P_m = P_{ref} + K_{\mathrm{f}}(\omega_0 - \omega) \tag{1}$$

In formula (1), P_m is the output when the synchronous motor is operating, P_{ref} is the specified value of the active power of synchronous generator in W, and K_{f} is the adjustment factor.

The damping coefficient of synchronous generator system changes base on the occurrence of the primary frequency regulation of synchronous generator, and there is a clear correlation between them. Then, equation (2) can be obtained.

$$J\frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega_0) = \frac{P_{ref}}{\omega_0} + \frac{K_{\mathrm{f}}(\omega_0 - \omega)}{\omega_0} - \frac{P_e}{\omega_0} - D(\omega - \omega_0) \tag{2}$$

The active frequency control of VSG increases the inertia control unit than the traditional active frequency control, and the frequency deviation of the access point is adjusted so as to realize the control of J .

2.2 Virtual exciter with reactive power and voltage control

The VSG system actually imitates the excitation regulation function of synchronous generator for the VSG system voltage regulation, which makes inverter have primary voltage regulation characteristics of synchronous generator, it is serve to show the droop characteristics among the system reactive power and voltage. It can transform the reactive power output and realize the function of regulating voltage function. The reactive power and voltage droop control strategy are able to represented as:

$$E_m = E_{ref} + K_u(Q_{ref} - Q_e) \tag{3}$$

Where, E_m is the internal electric potential of the VSG, Q_{ref} is the reference value of reactive power, Q_e is the reactive power input to the system, and E_{ref} is the reference value of the internal electric potential of the VSG, which usually represents the rated voltage. K_u is the voltage drop factor, defined similarly to K_f.

3. Virtual synchronous generator control system analysis

3.1 Effect of rotor inertia and damping on the system

The rotor inertia J of VSG decide on the oscillation frequency in the course of the dynamic response when the output active power is output. The damping D decide on the oscillation decay frequency of the active power. Active power output P_g and reactive power output Q_g of VSG system can be able to show as:

$$\begin{cases} P_e = \dfrac{3U_g}{Z}\left\{E\cos(a-\theta) - U_g\cos a\right\} \\ Q_e = \dfrac{3U_g}{Z}\left\{\mathrm{j}E\sin(a-\theta) - \mathrm{j}U_g\sin a\right\} \end{cases} \tag{4}$$

Neglecting the effect due to the resistance, for an inductor and a small power angle, then:

$$\begin{cases} P_e = \dfrac{EU_g}{Z}\theta = K_t\theta \\ Q_e = \dfrac{EU_g - U_g^2}{Z} \end{cases} \tag{5}$$

Where, K_t represents the VSG moment coefficient. Equation (5) show that the value of active power is tightly connection with the power angle, while the value of reactive power varies with the voltage amplitude.

Use the model analysis method for synchronous generators, the natural oscillation angular frequency ω_n and damping ratio ξ determine time answer of the second-order system. Most conventional synchronous generator systems are characterized by constant natural oscillation angular frequency ω_n and damping ratio ξ. In contrast, for VSG control, it optimizes the constant natural oscillation angle frequency ω_n and damping ratio ξ, making the choice of coefficients more flexible and variable. Given both P_e and Q_e, the dynamic performance of the second-order system is decided by virtual rotor inertia J, the damping factor D.

However, it is worth noting that the virtual rotor inertia J and the damping factor D are not constant values.

3.2 Effect of rotor inertia and damping on frequency characteristics

It be able to obtain:

$$\begin{cases} \Delta\omega = \dfrac{T_m - T_e - J\dfrac{d\omega}{dt}}{D} \\ \dfrac{d\omega}{dt} = \dfrac{T_m - T_e - D(\omega-\omega_0)}{J} \end{cases} \tag{6}$$

When considering the damping term, assuming $T_m - T_e - J\dfrac{d\omega}{dt}$ is constant, then if D becomes large, $\Delta\omega$ will become smaller; assuming $T_m - T_e - D(\omega-\omega_0)$ is constant, As frequency difference in a definite limit, the angular frequency change $\dfrac{d\omega}{dt}$ is inversely proportional to rotor inertia J , the system frequency change rate and relationship between the rotor inertia, the greater the rotor inertia J set, the littler system frequency fluctuations, steadier the system; for insuring steadiness of frequency, can be adjusted by adjusting the J and D can be adjusted to hold $\dfrac{d\omega}{dt}$ and $\Delta\omega$. Therefore, the parameters need to be set logically to insure the regular operation of system.

4. Parametric coordinated adaptive control

Fig. 2 shows power angle curve and frequency fluctuation curve of the synchronous generator.

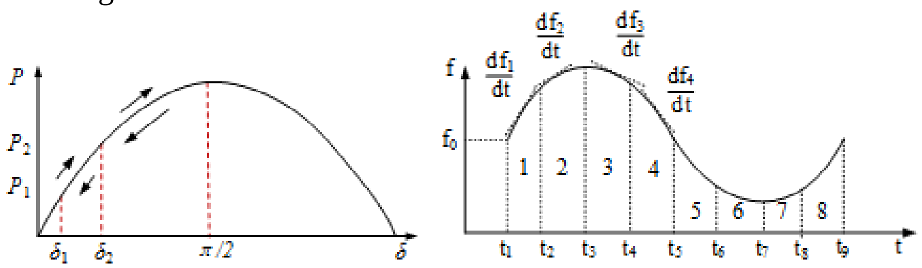

Fig. 2. VSG active frequency fluctuation curve

At the time t_1 due to the sudden increase in the mechanical power input to VSG system, the kinetic energy of the VSG system increases, the angular velocity ω rises, and the frequency of VSG is greater than the grid frequency $f > f_0$. The electromagnetic power of the VSG system starts to increase in order to maintain a stable operating state because of the sudden increase in the mechanical power, which produces to the rate of change of the VSG system frequency $\dfrac{df}{dt} > 0$,

$f > f_0$ and gradually increases to the maximum value at this stage. But VSG by the process of t_1-t_2, it follows that the VSG system frequency change rate of change after $\frac{df}{dt}$ the two stages of 1 and 2. 1 stage system $\frac{df_1}{dt}$ and 2 stage system $\frac{df_2}{dt}$ is different, according to the straight line from the lower left to the upper right when the slope of the steeper the slope is greater, the slope of the smaller the slope of the theorem, the slope in this case is always positive, you can learn that the 1 stage VSG system $\frac{df_1}{dt} > \frac{df_2}{dt}$, by transient process analysis, we can get the VSG system kinetic energy increase phase need to increase the virtual rotor inertia to weaken the virtual rotor system frequency change rate, to prevent the frequency overshoot due to the acceleration too fast and thus become larger. With the damping factor D increases, the peak frequency excursion of the VSG system should be decreased, but to make the frequency of the VSG system reach the peak faster, the measure to restrain the increase of the angular frequency of the system is to increase virtual inertia of system J and the damping factor D accordingly. In the interval 2, the frequency of the VSG system still far exceeds the grid reference frequency, but the angular frequency rate of change decreases slowly at this time, i.e., $\frac{df_1}{dt} > \frac{df_2}{dt}$, so the measure to prevent the frequency increase is to continuously increase the virtual inertia and the damping coefficient.

The virtual synchronous generator system reaches power equilibrium between interval 2 and interval 3, but the frequency difference Δf reaches its maximum and the electromagnetic power continues to increase due to the presence of inertia, the frequency of the VSG slowly starts to decrease from its maximum value, but is still greater than the system stable frequency until the frequency reaches equilibrium at the time t_4. At this time the VSG system by the process of t_3-t_4, it follows that the system frequency change rate $\frac{df}{dt}$ also went through two stages: 3 and 4 stages. From Fig. 2, it can be visualized that the $\frac{df_3}{dt}$ of the 3-stage system is different from the $\frac{df_4}{dt}$ of the 4-stage system. The VSG system frequency change rate extends from top left to bottom right, and the slope of the slope is smaller at this time, and the slope of the smaller slope is larger, and the slope is always negative, and we can get $\frac{df}{dt} < 0$ is $\frac{df_3}{dt} < \frac{df_4}{dt}$. If increase the virtual inertia will reduce the value of $\frac{df}{dt}$, which is not conducive to the rapidly stabilization. In the process of reducing the kinetic energy of the system, the inertia cuts down, and the decay rate of frequency is accelerated by weakening the suppression of frequency fluctuations by the VSG system, and the damping can be increased at this stage to further increase the decay of energy, so that the frequency can be restored to stability as soon as possible. Therefore, the kinetic energy of the virtual synchronous generator system decreases in stage 3, so the virtual inertia needs to be reduced to make the frequency adjust as fast as possible. Because of $\frac{df_3}{dt} < \frac{df_4}{dt}$ in stage 4, the virtual inertia should continue to be reduced in order to make the frequency change stabilize more quickly. Also, because the reduction of the damping amount D increases the peak time when J decreases, the measure of the damping factor D of the VSG system should continue to be increased in stages 3 and 4.

In summary, $\Delta f \frac{df}{dt} > 0$ is defined as the kinetic acceleration phase of the VSG system and vice versa as the deceleration phase of the VSG system, and the concept of frequency offset degree is defined according to the two phases, i.e., when $f > f_0$, $\frac{\pi}{4}(0+\mathrm{n}) - \frac{\pi}{4}(1+\mathrm{n})$ is the frequency offset degree of this phase, where n is 0 or 1. As the frequency state of the VSG system slowly returns to the initial state frequency of the system, i.e., $f < f_0$, define $\frac{\pi}{4}(0+\mathrm{n}) - \frac{\pi}{4}(1+\mathrm{n})$ the frequency offset of the VSG system for this phase, where n is 2 or 3.

In brief, the choice of virtual rotor inertia for VSG system is defined by the Δf and the $\frac{df}{dt}$; the choice of damping for the VSG system is determined only by the Δf. The choice of rotor inertia and damping for the VSG system under various states is displayed in Table 1.

Table 1

Rotor inertia and damping under different conditions

(A: accelerated; D: deceleration; ↑: increases; ↓: decreases)

Interval	System status	P	Offset degree	Δf	$\frac{df}{dt}$	J	D
1	A	↑	$0\text{-}\frac{\pi}{4}$	>0	≫0	↑	↓
2	A	↑	$\frac{\pi}{4}-\frac{\pi}{2}$	≫0	>0	↑	↓
3	D	↓	$\frac{\pi}{2}-\frac{3\pi}{4}$	≫0	<0	↓	↑
4	D	↓	$\frac{3\pi}{4}\text{-}\pi$	>0	≪0	↓	↑
5	A	↑	$0\text{-}\frac{\pi}{4}$	<0	≪0	↑	↓
6	A	↑	$\frac{\pi}{4}-\frac{\pi}{2}$	≪0	<0	↑	↓
7	D	↓	$\frac{\pi}{2}-\frac{3\pi}{4}$	≪0	>0	↓	↑
8	D	↓	$\frac{3\pi}{4}\text{-}\pi$	<0	≫0	↓	↑

According to the selection principle in Table 1, the correlation between the J and the $\frac{df}{dt}$, the virtual rotor inertia J can be written as:

$$J = \begin{cases} J_0, & \left|\frac{df}{dt}\right| < Y \\ J_0 + K_j X \tan^{-1}\frac{df}{dt}\Delta f, & \left|\frac{df}{dt}\right| \geq Y \cap \Delta f\frac{df}{dt} > 0 \\ J_0, & \Delta f\frac{df}{dt} \leq 0 \end{cases} \tag{7}$$

Where, J_0 is the value of the virtual inertia of the rotor during stable operation of the system; K_j is adaptive optimization coefficients for the virtual inertia of the rotor during system perturbations; Y is upper limits for adaptive optimization of the rotor virtual inertia during system perturbations.

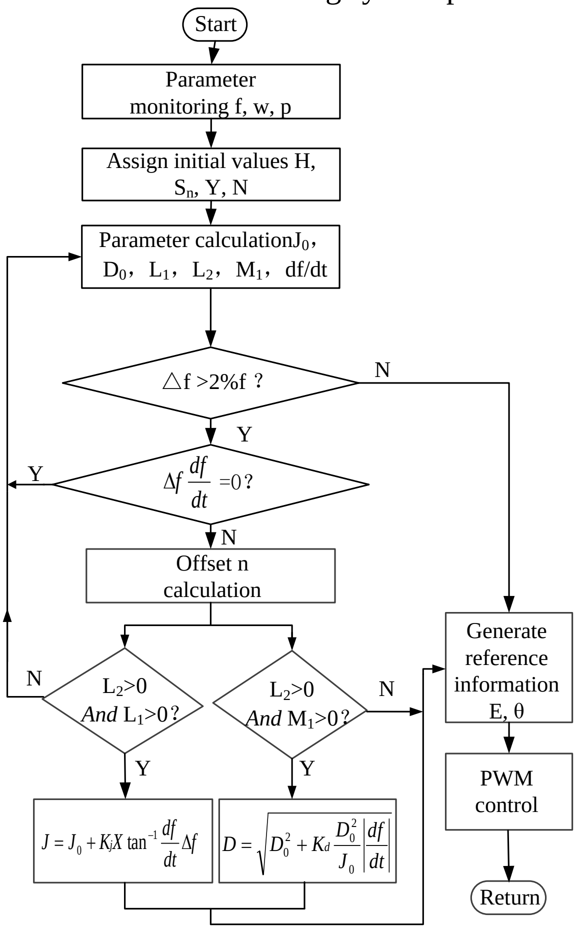

Fig. 3. Control strategy flow

The adaptive relationship between damping coefficient and frequency can be written as:

$$D=\begin{cases} D_0, & \left|\frac{df}{dt}\right|<N \\ \sqrt{D_0^2+K_d\frac{D_0^2}{J_0}\left|\frac{df}{dt}\right|}, & \left|\frac{df}{dt}\right|\geq N\cap\Delta f\frac{df}{dt}>0 \\ D_0, & \Delta f\frac{df}{dt}\leq 0 \end{cases} \tag{8}$$

Where, D_0 is damping during stable operation of the system; K_d is adaptive optimization coefficients for damping during system perturbations; N is upper limits for adaptive optimization of damping during system perturbations.

To facilitate the flow analysis, define the functions L_1, L_2 and M_1. L_1 is the virtual inertia threshold difference, L_2 is the product of frequency change rate and frequency change, and M_1 is the virtual damping threshold difference. The parameter cooperative adaptive control strategy flow shown in Fig. 3.

5. Experimental results and analysis

5.1 Experimental environment setup

The efficiency of the proposed control technique, as well as the impact of J and D on system operating stability, were tested, In MATLAB/Simulink, a VSG model is constructed. It includes the main circuit, the power calculation module, the VSG control module, the voltage and current inner loop control and the SPWM modulation module. The system adaptive control simulation parameters are shown in Table 2.

Table 2

Parameters settings for VSG algorithm

Parameter	Value	Parameter	Value
U_{dc}/V	800	J	0.2
U_n/V	220	D	15
$\omega_0/(\text{rad/s})$	314	K_j	0.2
L_1/mH	8	K_d	10
C_f/μf	3	N	2.5
R_g/Ω	0.2	Y	0.1
L_g/mH	50		

5.2 Simulation comparison analysis

The VSG grid-connected model is used for simulation, with a simulation time of 1.6s. the P_e suddenly increases to 12 kW and Q_e to 2 kVar when the load is connected on at 0.15s, and the P_e drops to 2 kW at 0.9 s. The dynamic processes of VSG output P_e and frequency under different control strategies are given in Fig. 4 and Fig. 5.

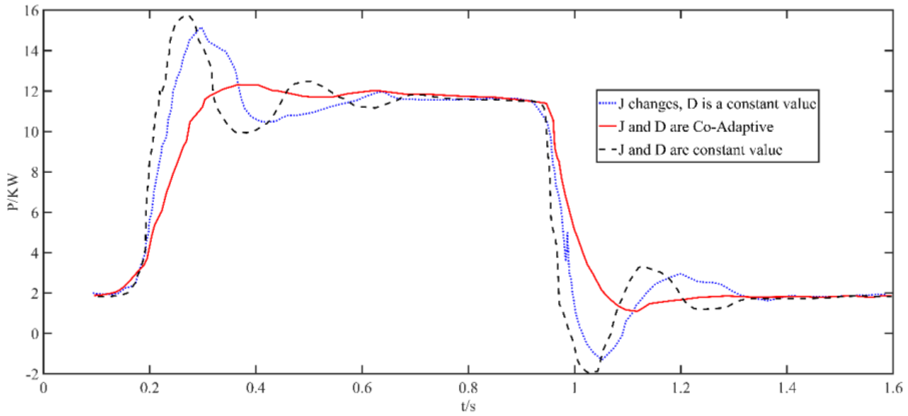

Fig. 4. Active power fluctuation curves of different control strategies

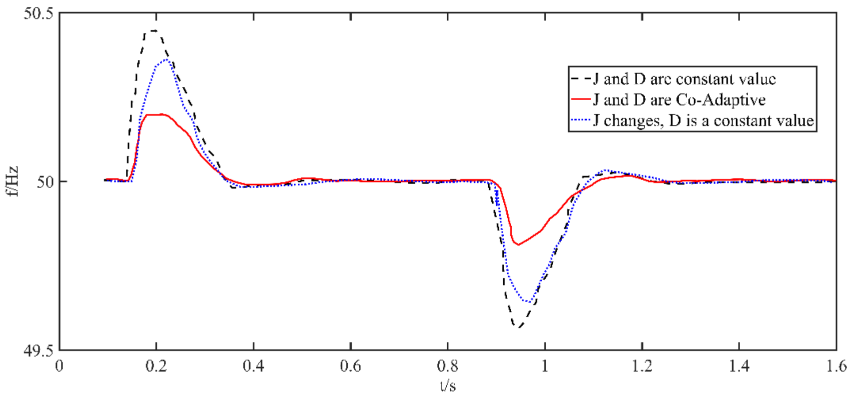

Fig. 5. Frequency fluctuation curves of different control strategies

The values of the instantaneous variation of the P_e and frequency at the highest point of the curve for different control strategies of the virtual synchronous generator system can be obtained as represented in Table 3.

Table 3

Power and frequency simulation data

Different control strategies	Load variation maximum instantaneous power（kW）	Grid-connected power（kW）	Power fluctuation value（kW）	Load variation maximum instantaneous frequency（Hz）	Grid connection frequency（Hz）	Frequency fluctuation value（Hz）
J and D fixed	15.14	12	3.14	50.45	50	0.45
J change, D fixed	13.92	12	1.92	50.32	50	0.32
J and D adaptive	12.09	12	0.09	50.18	50	0.18

If the virtual rotor inertia and damping are constant, when the reference active power suddenly increases, the frequency offset is 0.45Hz, the active power offset is about 3kW, the active overshoot reaches 25%, the adjustment time is about 0.3s, the frequency and power offset is large, and the oscillation is more serious. Under the virtual rotor inertia adaptive control, when the reference active power suddenly increases, the frequency offset is about 0.3Hz and the active power offset is about 2kW. Due to the introduction of the changing virtual inertia, the rate of frequency and power change due to load perturbation is slightly slowed down, but its fluctuation is still large. Compared to VSG control with virtual inertia and damping coefficient, the output overshoot of the virtual rotor inertia adaptive control is smaller, about 16%, the change time is more limited, about 0.28s. when reference active power increases, the angular frequency offset is about 0.2Hz and the active power offset is about 0.1kW, about 0.18s. With a slower rate of change of frequency and power, and a smaller offset, and the oscillation is effectively suppressed, while the recovery time to stability is significantly shortened.

The adaptive control of virtual rotor inertia and damping coefficient coordination has a good performance in the suppression of output active power fluctuation, overshoot was reduced by about 17%, the tweaks process is reduced by approximative 0.12s. The adaptive optimal control of virtual rotor inertia and damping coordination has good frequency fluctuation suppression ability, which just can’t slow down frequency fluctuation, it can also reduce the frequency deviation, reduce frequency overshoot, shorten the response time and improve frequency stability.

6. Conclusions

Draw the following conclusions through theoretical analysis and simulation results.

(1) The grid-connected inverter controlled by virtual synchronous generator has the transient and damping characteristics of synchronous generator, and can not only provide electric power to the grid but also participate in maintaining the stability of the grid, which is helpful to solve the problem of insufficient inertia of the grid system caused by large-scale distributed generator grid connected.

(2) The proposed rotor inertia and damping coefficient co-adaptive control strategy, considering both the rotor inertia and damping coefficient change regulation, defines the system kinetic acceleration and deceleration according to the product of the system frequency change rate and frequency deviation and adjusts the two parameters by it, so that the system can reduce the frequency deviation in the acceleration phase and output less electromagnetic power when the system decelerates, and adjusts the rotor inertia change rate by the inverse

tangent function, so that the VSG parameters change more flexibly and quickly, which is more conducive to the rapid recovery of system stability.

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