Research Article

A Voltage Control Strategy of VSG Based on Self-Adaptive Inertia Coefficient and Droop Coefficient

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With the increasing penetration rate of distributed renewable energy in power systems, the control strategy of virtual synchronous generator (VSG) is widely used for several years. Some existing VSG control strategies have been able to solve the stability problems caused by the abnormal grid voltage, but the effects of the inertia coefficient and the droop coefficient on the voltage stability are not taken into account. In order to further improve the voltage stability of the microgrid system, a voltage control strategy of VSG based on self-adaptive inertia coefficient and droop coefficient is proposed in this paper. When the voltage is far from the steady state, the increase of the inertia coefficient can decrease the voltage deviation. On the contrary, when it is close to the steady state, the decrease of the inertia coefficient can make the system response speed accelerate. According to the real-time voltage deviation, the droop coefficient can change adaptively to decrease the adjusting time and the voltage deviation during the disturbance. Finally, the simulation model of VSG is built by MATLAB/Simulink for conducting simulation experiments. Compared with other strategies, the correctness and effectiveness of the proposed control strategy are validated.

1. Introduction

With the energy crisis and environmental pollution becoming increasingly serious, the penetration rate of distributed renewable energy in power systems is constantly increased. Therefore, the renewable energy such as solar and wind has been widely used and studied [1–4]. As an interface between the renewable energy and the grid, the grid-connected inverter plays a significant part in transmitting power to the grid [5, 6].

In order to participate in the voltage regulation and frequency modulation of the power grid, droop control is generally applied by the grid-connected inverter, such as the P - f (active power-frequency) characteristic and the Q - U (reactive power-voltage) characteristic. Depending on the capacity of the distributed renewable energy, load power is capable to be uniformly distributed when the microgrid operates in the island mode. Moreover, in the grid-connection mode, the power grid will be supported by the inverter when there is interference caused by power faults

[7–10]. However, the inertia characteristics of the synchronous machine cannot be simulated by droop control. It leads to the poor dynamic performance and weak anti-interference ability of the system [11, 12].

To provide inertial support for the system, the concept of virtual synchronous generator (VSG) is proposed by some scholars [13–17]. Based on the rotor motion equation of the synchronous generator, the mechanism and external characteristics can be simulated by VSG. In this way, the anti-interference ability of the grid-connected inverter is enhanced. Many stability problems will be caused when large-scale distributed energies are accessed to the power grid. Some of them can be effectively solved with the control strategies of VSG. Due to these advantages, VSG has been widely concerned and applied in recent years.

The control strategy of VSG provides an effective solution to the system stability problems caused by large-scale distributed energy access to power grid. At present, the research on VSG mostly focuses on the active power loop, which aims to simulate the moment of the inertia and the

damping characteristics of synchronous generator, so as to ensure the frequency stability of the power system. An adaptive VSG algorithm based on bang-bang control is proposed in the article [18], and the virtual inertia is adjusted to the set maximum or minimum value with the change of frequency, which improves the stability of the system frequency. In [19], based on the adaptive inertia control strategy, the relationship between the droop coefficient and the frequency stability is analyzed, and a comprehensive control algorithm combined adaptive inertia and damping is proposed to further improve the frequency stability of the system.

In addition to frequency, voltage is also an important indicator in the power system. In order to maintain the stability of system voltage, the regulation and control is generally realized through the reactive power loop. However, there are few research studies on the reactive power loop of the parameter design and voltage control strategy now. In the paper [20], an adaptive step search strategy is proposed to provide the stability region analysis approach for SoC-based droop control and obtain the droop coefficients coordinated stability region, which ensures that overcharge and overdischarge of battery will not happen. The literature [21] proposes an impedance-based approach to assess the droop coefficients stability region in the power system, which consists of numerous distributed generators.

Many power faults usually occur in the actual operation of the grid, including imbalanced three-phase voltage and harmonic distortion of voltage. Then, the stability of the system would be seriously damaged. In order to avoid excessive current on the system when the grid suffers voltage sag, a control strategy of VSG based on the reactive power compensation is put forward [22]. The negative sequence voltage components will appear when the grid voltage is unbalanced. To suppress the unbalanced current and power oscillations caused by the negative sequence voltage components, a comprehensive control strategy of VSG under unbalanced voltage conditions is proposed [23]. Three subsystems of voltage amplitude control, output power control, and virtual inertia control are added to suppress fault current after grid voltage sags. It is proved that the low voltage ride-through capability of VSG can be both effectively enhanced under the symmetrical and unsymmetrical sag types [24].

However, the parameters of the reactive power loop are not designed by the above literature studies from the requirements of open-loop gain and cutoff frequency. Besides, the dynamic response characteristics analysis of the system voltage was not deep enough. Hence, in order to further improve the stability of the system voltage, a control strategy of VSG based on self-adaptive inertia coefficient and droop coefficient is presented in this paper. In summary, the main contributions of this approach are described as follows.

- (1) Based on the traditional droop control strategy, the integral link is introduced into the reactive power loop of VSG, which alleviates the dynamic response process of the output voltage and the reactive power. At the same time, the impact on the system is reduced.

- (2) The characteristics of the inertia coefficient and the droop coefficient are analyzed. Meanwhile, the influence of the equivalent inertia coefficient and the droop coefficient on the system voltage stability is summarized. According to the change law of the output voltage change rate and voltage deviation, the inertia coefficient and the droop coefficient in the reactive power loop can be dynamically changed, so that the system voltage has a smaller deviation and a faster adjustment speed when the power grid fails, and then the dynamic characteristics of the system voltage is improved.

2. Basic Principles of VSG

The main circuit topology and control block diagram of VSG are shown in Figure 1. It mainly includes direct current (DC) voltage source, three-phase inverter bridge, LC filter, and transmission line impedance. The output active power P_e and reactive power Q_e of VSG are calculated by the instantaneous power theory [25], as follows:

$$\begin{aligned} P_e &= e_{o\alpha}i_\alpha + e_{o\beta}i_\beta, \\ Q_e &= e_{o\beta}i_\alpha - e_{o\alpha}i_\beta. \end{aligned} \quad (1)$$

Here, $e_{o\alpha}$ and $e_{o\beta}$ are the fundamental waves of the inverter bridge midpoint voltage in the $\alpha\beta$ coordinate system. i_α and i_β are the current of the filter inductor in the $\alpha\beta$ coordinate system.

The three-phase modulation waves e_a , e_b , and e_c can be acquired by the VSG module and the voltage and current double closed-loop control module. With the pulse width modulation (PWM) module, the driving signal of the three-phase bridge can be generated by three-phase modulation waves to control the switch. The Materials and Methods section should contain sufficient detail so that all procedures can be repeated. It may be divided into headed subsections if several methods are described.

The power control loop of VSG is divided into the active power loop and the reactive power loop. According to the rotor motion equation of the synchronous generator, the damping and the inertia characteristics of synchronous generator are simulated by the active power loop of VSG. The control block diagram of the active power loop is indicated in Figure 2.

$$\begin{cases} J \frac{d\omega}{dt} = \frac{P_{set}}{\omega_n} - \frac{P_e}{\omega_n} - \left(D_p + \frac{k_\omega}{\omega_n} \right) (\omega - \omega_n) \\ \frac{d\theta}{dt} = \omega. \end{cases}, \quad (2)$$

Here, ω is the mechanical angular velocity of the synchronous generator, ω_n is the rated rotor angular velocity, K_ω is the droop coefficient between active power and frequency, J is the virtual inertia, D_p is the damping coefficient, P_{set} and P_e are the given value of the active power and the output active power, respectively, and θ is the phase angle of output voltage.

FIGURE 1: The main circuit topology and control block diagram of VSG.

FIGURE 2: The active-power loop of VSG.

As an important part of the synchronous generator, the excitation control system can maintain the constant voltage of generator terminal and improve the stability of power system. The traditional droop control is usually applied to simulate the excitation regulation of synchronous generator by VSG, as shown in Figure 3. However, the dynamic response of excitation regulation is usually described by the first-order inertia link. So, the reactive power control loop of VSG is improved as shown in Figure 4. The integral link is introduced into the reactive power loop to realize the no-difference control during the grid-connected operation, and the dynamic response process of the output voltage and reactive power can be alleviated [14, 15]. In the case of electricity interruption, the impact on the system can be reduced, and the anti-interference ability of the system is able to improve at the meantime.

$$Q_{set} - Q_e + D_q(\sqrt{2}U_n - \sqrt{2}E_m) = K \frac{d(\sqrt{2}E_m)}{dt}. \quad (3)$$

The control equation of the reactive power loop is depicted in equation (3). Q_{set} and Q_e are the given value of reactive power and the output reactive power, respectively. K is the inertia coefficient of the reactive power loop, D_q is the droop coefficient between reactive power and voltage, U_n is

the rated voltage amplitude, and E_m is the valid value of the reference voltage.

3. Adaptive Inertia Coefficient and Droop Coefficient Control Strategy

According to the characteristics of the synchronous generator model, it can be concluded that the voltage stability is closely linked with the inertia coefficient and droop coefficient of the reactive power loop.

Equation (3) is rearranged into another form, as follows:

$$K \frac{du}{dt} = \Delta Q - D_q \Delta u, \quad (4)$$

where ΔQ is the reactive power deviation and Δu is the voltage deviation.

As can be seen from Figure 5, the change rate of the output voltage is increased with the decrease of K . The microgrid system will be severely affected owing to the excessive change rate of output voltage. Therefore, the increase of K can weaken the voltage change rate. Then, the inertia coefficient K is a virtual analog quantity introduced through the virtual synchronous machine control, so it can be flexibly changed within its value range.

FIGURE 3: The traditional reactive power loop of VSG.

FIGURE 4: The improved reactive power loop of VSG.

FIGURE 5: The response characteristics of output voltage with different inertia coefficients.

Rearranging equation (4), the relation between the droop coefficient D_q and the voltage deviation Δu is depicted as follows:

$$D_q \Delta u = \Delta Q - K \frac{du}{dt}. \quad (5)$$

As shown from Figure 6, the steady-state voltage deviation Δu is decreased with the increase of D_q . Furthermore, the adjusting time is shortened when the output voltage tends to stabilize. Therefore, to further improve the response characteristics of the system voltage, the value of D_q can be increased appropriately during the voltage recovery process.

Through the above analysis, a self-adaptive control strategy of VSG is proposed as follows:

FIGURE 6: The response characteristics of output voltage with different droop coefficients.

$$K = \begin{cases} K_{\max}, & \Delta u \frac{du}{dt} > 0 \cap \left| \frac{du}{dt} \right| > V_k, \\ K_{\min}, & \Delta u \frac{du}{dt} \leq 0 \cap \left| \frac{du}{dt} \right| > V_k, \\ K_s, & \left| \frac{du}{dt} \right| \leq V_k, \end{cases} \quad (6)$$

$$D_q = \begin{cases} D_{q0}, & \Delta u \frac{du}{dt} > 0, \\ D_{q0} + k_d |\Delta u|, & \Delta u \frac{du}{dt} \leq 0 \cap \left| \frac{du}{dt} \right| > V_d, \\ D_{q0}, & \Delta u \frac{du}{dt} \leq 0 \cap \left| \frac{du}{dt} \right| \leq V_d, \end{cases} \quad (7)$$

where $K_{\max}$ and $K_{\min}$ are the maximum and minimum values of the inertia coefficient, respectively, K_s is the inertia coefficient in steady state, D_{q0} is the initial droop coefficient of the reactive power loop, V_k and V_d are the threshold of the output voltage change rate, and k_d is the regulation coefficient between the voltage deviation and the droop coefficient.

As the system is in steady state, small disturbance of the output voltage will result in frequent changes of the inertia coefficient K . The threshold V_k is set to filter out the fluctuations when the change rate du/dt is near zero. When du/dt exceeds V_k , the inertia coefficient K is adaptively changed to the maximum or minimum values with the product of the voltage change rate and the voltage deviation. Meanwhile, the steady inertia coefficient K_s is set for the case that du/dt is less than V_k . K_s is selected between the minimum and maximum values of the inertia coefficient.

Furthermore, depending on the real-time voltage deviation, the droop coefficient D_q is adaptively increased so that the dynamic response speed of the system will be accelerated.

4. Stability Proof and Parameter Range Setting

4.1. Stability Proof. The conditions for stable operation of grid-connected inverters are stipulated by the network operation standard EN 50438. The grid voltage amplitude shall be maintained between 90% and 110% of the rated voltage amplitude [26]. According to the above operation standard, the initial droop coefficient of the reactive power loop can be set with a reasonable setting principle [27]. The rated capacity of a single inverter is assumed to be 10 kV A. It is required that the change of 100% output reactive power ($\Delta Q_{\max} = 10 \text{ kvar}$) corresponds to the change of 10% grid nominal voltage. So, the initial droop coefficient D_{q0} can be obtained as follows:

$$D_{q0} = \frac{\Delta Q_{\max}}{\Delta U_{\max}} = \frac{10000}{220\sqrt{2} \times 10\%} = 321 \left(\frac{\text{var}}{\text{V}} \right). \quad (8)$$

The equivalent circuit of VSG operating in grid-connected mode is shown in Figure 7, where $E\angle\delta$ and Z_o are the output voltage and the equivalent output impedance of the inverter, respectively. U_g is the grid voltage, Z_g is the line impedance between the output point of the inverter and the point of common coupling (PCC), Z is defined as the sum of Z_o and Z_g , and R and X_s are the resistive and inductive parts of Z . It is generally that the value of X_s is much greater than that of R . The active and reactive power transmitted to the grid power by the inverter, are shown in equations (9) and (10), respectively.

$$P = \frac{3EU_g}{X_s} \sin \delta, \quad (9)$$

$$Q = \frac{3(E - U_g \cos \delta)E}{X_s}. \quad (10)$$

In order to simplify the analysis, the control between the active power loop and the reactive power loop can be regarded as approximate decoupling in this paper. According to Figure 7 and equations (2), (3), (9), and (10), the small signal equivalent model of VSG in s domain can be obtained in Figure 8.

According to the small signal equivalent model of VSG, the open-loop transfer function and the closed-loop transfer function of the reactive power loop can be deduced, as shown in equations $S_1(s)$ and $S_2(s)$:

$$S_1(s) = \frac{3(2E_n - U_g)}{\sqrt{2}X_s Ks + \sqrt{2}X_s D_q}, \quad (11)$$

$$S_2(s) = \frac{3(2E_n - U_g)}{\sqrt{2}X_s Ks + \sqrt{2}X_s D_q + 3(2E_n - U_g)}. \quad (12)$$

FIGURE 7: The equivalent circuit of VSG operating in the grid-connected mode.

Using the inertia coefficient K and the droop coefficient D_q as variables, respectively, the Bode diagram and the closed-loop pole distribution diagram of the transfer function $S_2(s)$ are drawn. Meanwhile, the influence of the two coefficients on the dynamic characteristics of the reactive power loop is analyzed.

The Bode diagram of the transfer function $S_2(s)$ is depicted in Figure 9. It can be seen that when the droop coefficient D_q remains unchanged, the increase of the equivalent inertia coefficient K will reduce the bandwidth of the reactive power loop. When K remains unchanged, the bandwidth of the reactive power loop decreases with the increase of D_q .

The pole distribution diagram of the closed-loop transfer function $S_2(s)$ is depicted in Figure 10. With the increase of the inertia coefficient K , the closed-loop poles of the reactive power loop will gradually get closer to the virtual axis, and the distribution becomes more and more intensive. At the same time, the absolute value of the closed-loop pole decreases gradually, and the response speed of the system slows down. In addition, with the increase of the droop coefficient D_q , the closed-loop poles gradually move away from the imaginary axis, and the distribution is relatively uniform. Meanwhile, the absolute value of the closed-loop pole increases gradually, and then, the response speed of the system increases accordingly.

4.2. Parameter Range Setting. It is described from equation (11) that the reactive power loop is a typical first-order inertia link, including the proportional module P_i and the first-order low pass filter module $G(s)$.

The expressions of P_i and $G(s)$ are shown in equations (14) and (15):

$$S_1(s) = \frac{3(2E_n - U_g)}{\sqrt{2}X_s D_q} \cdot \frac{1}{(K/D_q)s + 1} = P_i \cdot G(s), \quad (13)$$

$$P_i = \frac{3(2E_n - U_g)}{\sqrt{2}X_s D_q}, \quad (14)$$

$$G(s) = \frac{1}{(K/D_q)s + 1}. \quad (15)$$

FIGURE 8: The small signal equivalent model of VSG in s domain.

FIGURE 9: The Bode diagram of the transfer function $S_2(s)$.

For restraining the impact of twice the power frequency pulsation in the reactive power on the output voltage amplitude, the corner frequency f_{LQ} of the first-order low pass filter should be less than 10% of twice the power frequency pulsation:

$$f_{LQ} = \frac{D_q}{2\pi K} < \frac{1}{10} 2f_p. \quad (16)$$

By rearranging equation (16), the minimum value of the inertia coefficient K can be obtained as follows:

$$K > \frac{5D_q}{2\pi f_p}. \quad (17)$$

According to the grid operation standards GB/T 31464–2015, the principles of hierarchical partition and local

balance need to be taken for the strategies of grid voltage control. Therefore, the response time of grid voltage regulation is significantly less than that of frequency modulation for the system. The dynamic response time of grid voltage can be controlled within 1 second by the existing research studies, which are concerning hierarchical and zonal coordinated control of grid voltage. Assume that the response time t_s of VSG participating in grid voltage regulation is approximately equal to the response time t_{sq} of the reactive power loop:

$$T = \frac{K}{D_q}, \quad (18)$$

$$t_{sq} = 3T = \frac{3K}{D_q}. \quad (19)$$

FIGURE 10: The pole distribution diagram of the closed-loop transfer function S_2 (s).

As shown in equations (18) and (19), T is the constant time of the first-order system. According to the definition of dynamic performance metrics for the first-order system, t_{sq} is triple the constant time T .

Furthermore, a certain margin should be considered, so the response time t_{sq} is set to $t_{sq} < 0.4$ s. Combining equations (18) and (19), the maximum value of K can be obtained by

$$K < \frac{2}{15} D_q \quad (20)$$

5. Simulation Results

In order to verify the validity of the proposed control strategy in this paper, the simulation model of VSG is built by MATLAB/Simulink for conducting simulation experiments. The main parameter settings of the VSG control system are listed in Table 1.

For the strategy I, the traditional droop control is applied in the reactive power loop of VSG, as rendered in Figure 3. The main parameters are set as $k_q = 0.006$ and $U_n = 220$ V. For the strategy II, the inertia coefficient K and the droop coefficient D_q of the reactive power loop are set as 21 var·s/V and 321 var/V, respectively. For the strategy III proposed in this paper, the control strategies are shown in formulas (6) and (7). Some main simulation parameters of the strategy III are set in Table 2.

The structure diagram of a single VSG is shown in Figure 11. When the simulation model is running in the grid-connected mode, the active power of 2 kW is transmitted from the inverter to the grid in the initial. In order to simulate the situation of grid voltage faults, the amplitude of the grid phase voltage is made to drop by 10% at 1.6 s suddenly, and then it will restore to the rated value after 0.1 s. The control effects of the three strategies are compared in the same simulation conditions.

The simulation results are shown in Figure 12. When the grid voltage drops suddenly at 1.6 s. For the strategy I, the output voltage will drop rapidly due to the lack of inertia in the voltage regulation. Compared with the other two strategies, the strategy I has a much larger voltage deviation. With the reactive power loop of VSG improved, the voltage deviation of the strategy II can be reduced to 18.542 V. Among the three strategies, the strategy III has the smallest voltage deviation about 15.179 V, which is reduced by 18.137% relative to the strategy II. Furthermore, the strategy III has the shortest adjusting time and the smallest oscillation amplitude in the process of voltage restoration to the rated value.

The change curves of the inertia coefficient K and droop coefficient D_q in the strategy III are, respectively, shown in Figures 13 and 14. It can be concluded from the simulation results that the response characteristics of the system voltage will be significantly improved by the self-adaptive control of K and D_q .

Similarly, the simulation experiments are conducted in the case that the amplitude of grid phase voltage rises suddenly. As the simulation results shown in Figure 15, the control effects of the three strategies are basically the same as those when the grid voltage drops.

To further verify the correctness and compatibility of the strategy III in different operating conditions, the simulation model of two VSGs running in parallel is also built, as shown in Figure 16. The rated capacity ratio of two VSGs is set to 3 : 2. Some main simulation parameters are listed in Table 3.

The simulation results can be obtained in Figures 17 and 18. The control effect of the strategy III is the best among the three strategies. It is observed that the strategy III has the shortest steady adjusting time and the minimum voltage deviation. Thus, when the two VSGs are running in parallel, the control effects of the three strategies are basically the same as those when a single VSG is running independently.

TABLE 1: VSG control system parameter settings.

Parameters	Descriptions	Values
U_{dc}	DC voltage	800 V
U_g	Grid voltage	220 V
L_1	Filter inductance	3.2 mH
L_g	Grid-side inductance	3.2 mH
C	Filter capacitor	14 μ F
S_N	Rated capacity of VSG	10 kV A
f_p	Power frequency	50 Hz
f_s	Switching frequency	5 kHz
J	Inertia coefficient	0.45 kg m ²
D_p	Droop coefficient	30 N m s/rad
D_{qo}	Initial droop coefficient	321 var/V

TABLE 2: Parameters settings for the strategy III.

Parameters	Description	Value
$K_{\min}$	Minimum inertia coefficient	6 var·s/V
K_s	Inertia coefficient in steady state	21 var·s/V
$K_{\max}$	Maximum inertia coefficient	36 var·s/V
V_k	Voltage change rate threshold	16 V·s ⁻¹
V_d	Voltage change rate threshold	4 V·s ⁻¹
k_d	Correlation coefficient	20 var·V ⁻²

FIGURE 11: The equivalent structure diagram of a single VSG.

FIGURE 12: The comparison of control effects among different strategies when the grid voltage drops.

FIGURE 13: The curve of inertia coefficient for the strategy III.

FIGURE 14: The curve of droop coefficient for the strategy III.

FIGURE 15: The comparison of control effects among different strategies when the grid voltage rises.

FIGURE 16: The structure diagram of parallel operation.

TABLE 3: Parameters settings of the two VSGs.

Parameter	Description	Value
J_1	Virtual inertia	$0.45 \text{ kg}\cdot\text{m}^2$
J_2	Virtual inertia	$0.3 \text{ kg}\cdot\text{m}^2$
D_{p1}	Droop coefficient	30 N m s/rad
D_{p2}	Droop coefficient	20 N m s/rad
K_1	Inertia coefficient	$21 \text{ var}\cdot\text{s/V}$
K_2	Inertia coefficient	$14 \text{ var}\cdot\text{s/V}$
D_{q1}	Droop coefficient	321 var/V
D_{q2}	Droop coefficient	214 var/V

FIGURE 17: The response curve of output voltage when the grid voltage drops. (a) Curve of VSG1. (b) Curve of VSG2.

FIGURE 18: The response curve of output voltage when the grid voltage rises. (a) Curve of VSG1. (b) Curve of VSG2.

To sum up, the validity and compatibility of the strategy III are proved by the simulation results.

6. Conclusions

In order to improve the voltage stability of the system, a self-adaptive control strategy of VSG combining the inertia coefficient, and the droop coefficient is presented in this paper. For the purpose to weaken the impact on the system, a larger inertia coefficient will be adopted to reduce the voltage change rate. Instead, the recovery speed of output voltage is accelerated with the reduction of inertia coefficient. In addition, the adjusting time and the voltage deviation can be decreased by self-adaptive control of the droop coefficient. The transient process of the system is shortened so that the output voltage can restore to the steady state much faster. Finally, the effectiveness of the proposed method is demonstrated through the simulation results.

Data Availability

All data generated or analyzed during this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest the regarding of the publication of this article.

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