Adaptive control of grid connected inverter based on virtual synchronous machine

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Abstract. In recent years, with the rapid development of distributed generation, virtual synchronous generator (VSG) control technology for distributed generation is proposed. On the basis of droop control, VSG further simulates the inertia and damping characteristics of synchronous generator. Compared with droop control, VSG control technology makes distributed energy have the damping and inertia characteristics of synchronous machine, but it can not guarantee the dynamic regulation performance of frequency and power at the same time. To solve this problem, the adaptive control of VSG is realized by establishing the relationship between the moment of inertia and the damping coefficient. Finally, an experimental platform of VSG adaptive control model is built in Matlab / Simulink. The simulation and experimental results verify the effectiveness and correctness of the proposed control strategy.

1. Introduction
In recent years, the installed capacity of distributed generation has grown rapidly, which is expected to reach a very high level in the next few decades. Because of the difference of voltage frequency and amplitude with the grid, most of the distributed energy needs to be connected to the grid through power electronic converter. The traditional power electronic inverter interface has the characteristics of low inertia and no damping. With the increase of new energy generation permeability, it will have a negative impact on the stable operation of the system, especially in the island operation of the micro grid, the decline of frequency and voltage regulation ability will cause the system instability. The traditional power system is dominated by synchronous generator. Because the rotor of synchronous generator has certain inertia, when the system is disturbed, the synchronous generator can alleviate the influence of disturbance on the system under the control of excitation, governor and other links. Inspired by the operation of traditional power system, the idea of virtual synchronous generator (VSG) is proposed in reference [1-3]. Through the reasonable control of inverter, the inverter can have the excellent characteristics of synchronous generator. When the power imbalance occurs in the system, VSG can use virtual inertia and damping to suppress the fluctuation of frequency and output power, and at the same time, it can also play a buffer role for the oscillation of the system.

In recent years, based on the virtual synchronous generator control, the related research at home and abroad has been relatively mature. Literature [4-6] summarizes the current development of virtual synchronous control technology at home and abroad from the aspects of operation control, stability analysis and typical applications, and summarizes the current problems and prospects. In reference [7], a hybrid energy storage unit is introduced into the photovoltaic system to effectively reduce the
fluctuation of photovoltaic grid connected power according to the frequency band of photovoltaic output fluctuation and achieve a certain degree of photovoltaic power dispatching. Reference [8] according to the composition and operation mechanism of the traditional synchronous generator, the power is decoupled through modeling analysis; then, the static rotor and virtual regulating valve are introduced into the structure of the virtual synchronous motor in combination with the operation characteristics of different types of batteries, which can simulate the external characteristics of the synchronous machine well and have good control effect of the inverter power supply. In reference [9], the virtual moment of inertia J is dynamically adjusted according to the angular velocity deviation and the rate of change of the virtual synchronous machine to make the system have high rapidity at the initial stage of load change, and when it is close to stability, j is increased to reduce the frequency oscillation of the system and obtain sufficient frequency stability. According to the characteristics of VSG virtual inertia and damping coefficient, the optimization model of VSG transient response is established in reference [10-12], and the adaptive adjustment strategy of VSG virtual inertia and damping coefficient is proposed. By designing a reasonable trigger mechanism, a virtual synchronous control scheme of parameter self-adaptive adjustment is proposed. In the control process, when certain conditions are triggered, the virtual inertia and damping parameters can be dynamically adjusted, so as to improve the stability control effect of microgrid.

Different from the traditional synchronous machine, the virtual inertia and damping parameters controlled by the virtual synchronous machine can be adjusted dynamically and flexibly to obtain better stability control effect. Based on this consideration, the whole model of VSG with fixed control parameters is built in this paper, and the step response of VSG with different damping coefficients is made. Based on the analysis of the small signal model of the virtual synchronous machine, an adaptive control strategy is proposed, which takes into account the transient overshoot and regulation time of the system, so that the system can maintain stability as fast as possible. Finally, the VSG experimental platform built by Matlab / Simulink is used to verify the proposed adaptive control method.

2. Overview of virtual synchronous machine

2.1. Mathematical model of VSG

The virtual synchronous machine control system of single three-phase grid connected inverter is shown in Figure 1. In the figure, the distributed energy side (such as fan, solar panel, etc.) is equivalent to the ideal DC power supply (UDC), which is connected to the power grid after the three-phase inverter converter and filter circuit filtering. Among them, Q1 – Q6 constitutes the three-phase inverter bridge, and the inverter side inductance Ls, filter capacitor C and network side inductance Lf constitute the LCL filter.

**Figure 1.** Topology of VSG.
From the point of view of the equivalence of the main circuit of the grid connected inverter and the electrical part of the synchronous generator, it can be considered that the fundamental waves of the neutral point voltage of the three-phase bridge arm of the grid connected inverter, $E_a$, $E_b$, $E_c$, simulate the internal potential of the synchronous generator, the inductors on the inverter side, simulate the synchronous reactance of the synchronous generator, and the inverter output voltage (capacitor voltage), $V_a$, $V_b$, $V_c$, simulate the. The active power $P_e$ and reactive power $Q_e$ of VSG output are calculated by instantaneous power theory:

$$P_e = e_\alpha i_\alpha + e_\beta i_\beta$$

$$Q_e = e_\beta i_\alpha - e_\alpha i_\beta$$

According to the analysis of synchronous machine, ignoring the influence of damping winding, the expression of mechanical motion equation of synchronous generator rotor is as follows (3):

$$T_m - T_e = \frac{P_m}{\omega_n} - \frac{P_e}{\omega_n} = j \frac{d\omega}{dt}$$

Among them, $P_m$ is the mechanical power provided by the prime mover, $P_e$ is the electromagnetic power of the synchronous generator, $j$ is the moment of inertia of the synchronous generator, and $\omega_n$ is the rated angular frequency.

In order to realize the primary frequency regulation function of the generator set, the prime mover in the generator set is equipped with a governor. The relationship between the mechanical power output of the prime mover and the voltage angle frequency of the grid is as follows:

$$P_m = P_{set} + D_p (\omega_n - \omega)$$

In combination (3) (4), the mechanical movement of the synchronous generator rotor after considering the governor action can be obtained as shown in formula (5):

$$P_{set} + D_p (\omega_n - \omega) - P_e \approx J \omega_n \frac{d\omega}{dt} = J \omega_n \frac{d^2\theta}{dt^2}$$

For synchronous generator, the closed-loop control equation of excitation controller can only adjust the amplitude of internal potential indirectly by adjusting its excitation current. For VSG, the reactive loop only needs to simulate the primary voltage regulation characteristics of synchronous generator without introducing the intermediate variable of excitation current. Therefore, the output of excitation regulator can be directly the amplitude of VSG modulation wave voltage. Then the excitation regulating type can be rewritten as:

$$\sqrt{2}E_m = \frac{1}{K} \left[ D \left( \sqrt{2}V_n - \sqrt{2}V_0 \right) + (Q_0 - Q_e) \right]$$

To sum up, it is a complete virtual synchronous control strategy applied to the three-phase grid connected inverter. From the above mathematical model, the control structure diagram of VSG can be deduced as shown in Figure 2. It can be seen that its essence is to simulate the motion equation of the synchronous machine rotor on the basis of the traditional droop control and add the virtual inertia and damping, and the virtual inertia time constant $J$ and damping coefficient $D$ in the corresponding formula (1). In the actual inverter control process, the inertia parameters and damping parameters can be dynamically adjusted to give full play to the VSG control effect on power and frequency fluctuations.
Figure 2. Control block diagram of VSG.

2.2. Parameter analysis of VSG

From the above mathematical model of VSG, the closed-loop transfer function from P0 to PE is derived as follows:

\[ G_r(s) = \frac{P_E}{P_0} = \frac{EU}{\omega_n X_s^2 + D\omega_n X_s + EU} \] (7)

If \( G_r(s) \) is a typical second-order system, then the damping ratio and \( \zeta \) natural oscillation frequency \( W_n \) of the system are as follows:

\[ \zeta = \frac{D}{2} \sqrt{\frac{X_s\omega_n}{D\omega_n X_s}} \] (8)
\[ W_n = \frac{EU}{\sqrt{D\omega_n X_s}} \] (9)

It can be seen from Eq. (8) and Eq. (9) that the damping ratio \( \zeta \) of the system is related to \( J \) and \( D \), increasing or decreasing \( J \) can increase the damping ratio; the natural oscillation frequency is only related to \( J \), increasing \( J \) can reduce the natural oscillation frequency. In the analysis of control theory, when the second-order system works in the underdamped system, the overshoot is determined by the damping ratio of the system. The larger \( \zeta \) is, the smaller overshoot is; the adjustment time is determined by the damping ratio of the system and the natural vibration frequency together. When the natural frequency is constant, the larger the damping ratio is, the shorter the adjustment time is.

In reference [13], the parameters \( D \) and \( J \) of VSG are analyzed by Bode diagram. It is pointed out that the bandwidth of the active loop is basically the same when the parameter \( d \) changes. With the increase of \( D \), the resonance peak value of active ring near the bandwidth frequency decreases. That is to say, parameter \( d \) does not affect the bandwidth of the active loop, but has a restraining effect on the resonance peak near the bandwidth frequency. For the resonant peak value, the resonant peak value will slightly increase with the increase of \( J \); for the bandwidth, the bandwidth of the active ring will gradually decrease with the increase of \( J \), so that the ability of the active ring to suppress the high-frequency interference at the input end will be improved, but at the same time, the ability of the active ring to track
the input signal will be weakened. Due to the contradiction among the performance indexes of the active loop, the balance among the performance indexes should be considered in the process of parameter selection. If the overshoot of the system is large and the oscillation is violent, D can be increased; if the response speed of the system is slow and the stability margin is small, D can be reduced. At the same time, by reducing J, the overshoot can be reduced, the response speed of the system can be accelerated, and the system oscillation can be weakened.

3. Adaptive control and experimental simulation of VSG

It can be seen from equation (9) that when the damping coefficient D is constant and there is a power shortage in the system, the rate of change of the angular frequency is inversely proportional to the moment of inertia, and then the rate of change of the frequency is inversely proportional to the moment of inertia:

\[ \frac{df}{dt} \propto \frac{1}{J} \]  \hspace{1cm} (10)

It can be seen from equation (10) that in theory, when the system is disturbed, the larger the setting of J, the smaller the \( \frac{df}{dt} \), and the more favorable the suppression of the frequency fluctuation, but the moment of inertia can not be set too large, and the excessive moment of inertia will cause the dynamic characteristics of the system to become worse, or even unstable. Accordingly, the setting of the moment of inertia can be changed flexibly according to the change rate of the frequency in the transient process, so as to ensure that the J value can change rapidly in time when the \( \frac{d\omega}{dt} \) changes greatly. In this paper, based on the scale function, the adaptive function of J is established as shown in formula (11).

\[ J = \begin{cases} J_0 + a \frac{d\omega}{dt} & \Delta\omega \frac{d\Delta\omega}{dt} > 0 \cap \left| \frac{d\Delta\omega}{dt} \right| > N \\ J_0 & \Delta\omega \frac{d\Delta\omega}{dt} \leq 0 \cup \left| \frac{d\Delta\omega}{dt} \right| < N \end{cases} \]  \hspace{1cm} (11)

Although the inertia coefficient can be adjusted due to the power fluctuation, the adjustment effect is limited only by the inertia coefficient, so it needs to be combined with the adjustment of damping parameters to achieve better effect. According to the analysis in the previous section, it is not appropriate to increase the damping at the beginning of frequency change, and the increase of damping coefficient can shorten the response time of the system, so the value of damping coefficient should be increased at the later stage. Therefore, the damping adaptive algorithm adopted in this paper is shown in equation (12):

\[ D = \begin{cases} D_0 - b|\Delta\omega| & \Delta\omega \frac{d\Delta\omega}{dt} > 0 \cap \left| \frac{d\Delta\omega}{dt} \right| > M \\ D_0 & \Delta\omega \frac{d\Delta\omega}{dt} \leq 0 \cup \left| \frac{d\Delta\omega}{dt} \right| \leq M \end{cases} \]  \hspace{1cm} (12)

The change times of moment of inertia and damping coefficient can be reduced by setting the thresholds N and M, so as to ensure the stable operation of the system is not affected. In order to ensure the stability of the system, the moment of inertia J and damping parameter d must be within the selected range.

In order to compare the advantages of the adaptive algorithm, this paper builds a simulation model of single VSG incorporated into the large power grid through MATLAB / Simulink simulation platform. According to the VSG model described above, the simulation model of single VSG incorporated into the large power grid is built through MATLAB / Simulink simulation platform. The parameters are shown in Table 1-1.
Table 1. Experimental simulation parameter setting

| Parameter                          | Value  |
|-----------------------------------|--------|
| Voltage reference                 | 380V   |
| Frequency reference value         | 50hz   |
| DC voltage                        | 400V   |
| Net side voltage                  | 380V   |
| Frequency reference value         | 50hz   |
| DC voltage                        | 400V   |
| Filter resistor                   | 0.1    |
| Filter inductance Ls              | 6mf    |
| Line inductance Lf                | 2mf    |
| Line resistance                   | 0.6    |
| Ratio coefficient of reactive power| 1990   |

The control effect of the proposed adaptive parameter VSG control is verified by simulation. In order to show the superiority of the proposed adaptive control method, the fixed parameter method (mode1) is compared with the inertia adaptive method (mode2) and the adaptive control method (Mode3). The simulation is based on the system frequency response and VSG The changes of other control parameters of output power are compared in many aspects. Among them, the fixed parameter method J = 0.1, D = 3; the adaptive method J takes D = 3, and j adapts according to formula (11). The active power dispatching instruction P0 changes step from 0.5kw to 1.2kw in t = 0.6s, and the active output waveform and virtual angular frequency waveform under different adaptive parameter adjustment modes are shown in Figure 3.

![Figure 3. Active power output under different control algorithms.](image3)

![Figure 4. Frequency waveform under different control algorithms.](image4)
It can be seen from Figure 10. The traditional fixed parameter VSG control (mode1) is adopted. When the disturbance occurs, the power and frequency fluctuate greatly, and the amplitude overshoot and oscillation amplitude are relatively large. When the inertial adaptive control mode (mode 2) is adopted, the frequency deviation is significantly reduced, and the power stability is also improved. When the inertial damping synchronous adaptive control mode (mode2) is adopted, it is compared with mode 1 and mode 2. The frequency deviation is further reduced and the stability is better. Compared with mode 0, the dynamic response of the system with adaptive parameter adjustment mode is slowed down to some extent. In contrast, the control method and adaptive control strategy proposed in this paper, considering rotor inertia, damping coefficient and other parameters, flexibly apply the control means. For the system frequency fluctuation and DC voltage fluctuation, the maximum offset of both is significantly reduced, and the effect of improving the dynamic stability of the system is obvious.

4. Conclusion
On the basis of the conventional VSG control algorithm, this paper puts forward the control strategy of adaptive moment of inertia and damping coefficient, and establishes the function of adaptive moment of inertia and damping coefficient, based on which the adaptive parameter adjustment mode can be flexibly switched to give full play to the stability control effect of virtual synchronous machine. The simulation and experimental verification are carried out on MATLAB / simulik and VSG experimental platform. The simulation and experimental results show that the proposed control strategy is effective and correct. At present, the adaptive control strategy in this paper is only applied to a single VSG inverter. In parallel operation of multiple machines, the damping coefficient and moment of inertia required under different working conditions will be different. How to solve the problem of power circulation, oscillation and power distribution better through adaptive control is the content of this paper which needs further research in the future.

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