Research on Frequency Characteristics of VSG Virtual Parameter Adaptive Control Strategy Based on Fuzzy Control Theory

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Abstract—Traditional virtual synchronous generators (VSG) control inverters. Inverter output frequency characteristic of the virtual inertia (J) and virtual damping (D) coefficient, and the virtual parameters need to be modified and adjusted according to the purpose. To solve this problem, this paper proposes a virtual parameter adaptive control strategy based on fuzzy control theory to adjust the frequency characteristics of VSG. MATLAB /Simulink is used to build a simulation model to verify the correctness of the proposed fuzzy control theory's adaptive virtual parameter theory.

1. Introduction

With the introduction of distributed energy, the inverter transforms dc input into three-phase AC input to large power grid, optimizing the operation of power system[1-2]. However, traditional inverters lack the same rotational inertia[3] and damping[4]characteristics as synchronous generators, when the power grid fails, the inverters do not provide sufficient inertial support. With the introduction of VSG control strategy, the inverter can simulate the external characteristics of the synchronous generator, and can show certain inertia and damping characteristics when the voltage and frequency fluctuate[5-6].

The document[7-8] proposes a method to determine the virtual rotation inertia by damping ratio, but the method has limited ability to regulate the frequency of the system. By analyzing the frequency fluctuation of multiple VSG parallel operations, document[9] points out that primary frequency modulation is insufficient and the secondary frequency modulation control strategy is put forward, but the VSG parameters are fixed and the frequency regulation is not flexible enough. Document[10] is in silo mode, the adaptation of J control, but did not consider the effect of D on frequency. In document[11], J and D coordinated adaptive control strategy applied to VSG is proposed, and the over-tuning of frequency and the rate of change are realized under the condition of grid-connected, but the effect of adaptive change of VSG parameters on frequency is not analyzed in silo mode.

This paper proposes a VSG virtual parameter adaptive control based on fuzzy control theory[13-14]. Firstly, the mathematical model of the inverter VSG control strategy is established, the function frequency controller and excitation controller of VSG are designed, then the fuzzy control theory is introduced to realize adaptive control of virtual parameters, the frequency characteristics of the inverter are adjusted, and the simulation model is built to verify the correctness of the control strategy.
1.1 VSG Structure diagram

![Fig.1 VSG structure block diagram](image)

Figure 1 is a VSG structural block diagram, consisting of the main circuit and the control circuit. $U_{dc}$ is the DC input voltage, $e_a$, $e_b$, $e_c$ is the equivalent inductive electromotive force of the INverter AC side output, $R$ is the filter inductor internal resistance, $L_s$ is the filter inductor, $C$ is the filter capacitor, $u_a$, $u_b$, $u_c$ is the equivalent end voltage of the synchronous generator, $L_2$ is the line inductor, $u_g$ is the grid side voltage, $L_{load}$ is the load of the inverter. The introduction of rotating inertia and damping coefficients to simulate synchronous generator characteristics in the control circuit, combined with SVPWM modulators to achieve control of the inverter.

1.2 Power frequency controller

The synchronous generator rotor motion equation is:

$$\begin{cases}
J \frac{d\omega}{dt} = P_m - P_e - D\Delta\omega \\
\frac{d\delta}{dt} = \omega
\end{cases} \tag{1}$$

Where, the $\delta$ is the working angle of the synchronous generator, $J$ is the rotational inertia, $D$ is the damping coefficient, $\Delta\omega = \omega - \omega_N$, $\omega$ is the actual angular velocity, the $\omega_N$ is the rated angular speed, $P_m$ is mechanical power, and $P$ is electromagnetic power.

The function frequency controller of the virtual synchronous generator simulates the motion equation of the synchronous motor rotor, and simulates the mechanical power $p_m$ input of the synchronous generator's prime mover through the phase angle of the output excitation motor force correspondingly controlled by the rotor motion equation. $p_m$ consists of the active power reference value $P_{ref}$ and the frequency variation difference difference $\Delta P$

$$p_m = P_{ref} + \Delta P = P_{ref} + D_p \left( f_{ref} - f \right) \tag{2}$$
Where, \( D \) is the frequency modulation coefficient. \( f_{ref} \) is the frequency reference value.

The power frequency controllers of VSG are available by formulas (1) and (2) as shown in Figure 2.

![Fig. 2 Block diagram of VSG power frequency controller](image)

**1.3 Excitation controller**

The active power and end voltage regulated by the excitation system in the synchronous generator. Therefore, the excitation controller needs to control both voltage difference and reactive power, in order to simplify the control process, the first-order inertia link is used to model. So the excitation formula for VSG is derived

\[
K \frac{dE}{dt} = Q_{ref} + D_q(U_N - U) - Q
\]  

(3)

Where, \( K \) is the inertial coefficient, \( E \) is the magnitude of the modulated voltage, \( D_q \) is the sagging factor, \( U_N \) is the rated voltage of the output, \( U \) is the actual voltage of the output, \( Q_{ref} \) is the reactive power given value, and \( Q \) is the reactive power detection value.

\[
Q = [(u_a - u_b)i_a + (u_b - u_c)i_b + (u_c - u_a)i_c]/\sqrt{3}
\]  

(4)

Where, \( u_a, u_b, u_c \) is the three-phase voltage output of the inverter, and \( i_a, i_b, i_c \) are the three-phase current output of the inverter.

The excitation controllers of VSG are available by formulas (3) and (4) as shown in Figure 3.

![Fig. 3 Block diagram of VSG excitation unit controller](image)

In summary, after obtaining the output voltage phase angle and modulation voltage, the command voltage of VSG is obtained

\[
E = \begin{bmatrix}
\sqrt{2}E \sin \delta \\
\sqrt{2}E \sin(\delta - 2\pi / 3) \\
\sqrt{2}E \sin(\delta + 2\pi / 3)
\end{bmatrix}
\]  

(5)

**2. The adaptive parameter control of fuzzy control theory**

Power angle and angular frequency oscillation curve of synchronous generator
In the t0-t1 stage, the inverter output angle frequency is higher than the rating due to the increase in output power, and the angular frequency is increasing. At this stage, the stability of the output angular frequency can be maintained by reducing the rate of change of the angular frequency. In the t1-t2 phase, the inverter output angle frequency value is continuously reduced from the maximum value, and eventually reaches the rated angular frequency of $\omega_N$, which requires increasing the rate of change of the angular frequency and reducing the adjustment time of dynamic response, and the t2-t3 and t3-t4 stages are similar to the analysis process of the t0-t1 and t1-t2 stages, respectively.

When the angular frequency change curve is in the t0-t1 stage, the VSG angle frequency is increasing and the angular frequency change rate ($d\omega/dt$) is greater than zero, at which stage, the formula (1) can be obtained, if the rotational inertia $J$ is increased, the rate of change of angular frequency can be reduced, thus reducing the increase of angular frequency, and at this time the amount of angular frequency change ($\omega-\omega_N$) is greater than zero, and if the damping coefficient $D$ increases, the rate of change of angular frequency can also be reduced, thereby reducing the increase rate of angular frequency. In the t1-t2 stage, The angular frequency change rate or VSG is less than zero, in this stage, if the rotational inertia $J$ is reduced, it will be reduced, but its absolute value increase, can speed up the process of angular frequency reduction; The t2-t3 stage is similar to the t0-t1 stage in that the angular frequency changes in the direction of departure from the rated angle frequency, so it is also necessary to increase the rotational inertia and damping coefficient.

In order to take into account the influence of angular frequency change rate and angular frequency change on virtual parameter selection, this paper adopts a method of controlling virtual parameters by fuzzy controller, so that virtual parameters can adjust the output frequency of the system according to the dynamic change of angular frequency rate and angular frequency change. Therefore, the angular frequency change rate and the amount of angular frequency change are used as the input of the fuzzy controller, and the output is set to the virtual parameters $J$ and $D$.

Set the angle frequency change rate and the amount of angular frequency change input fuzzy set selection {NB,NS,Z,PS,PB}, output virtual parameters $J$ and $D$ fuzzy set pick {NB,NM,NS,Z,PS,PM,PB}, membership function selection isosceles triangle, de-fuzzy selection center of gravity method\[15\].

The control idea of fuzzy controller is to increase the rotational inertia and damping coefficient when the angular frequency changes in the direction of divergence from the rated angle frequency, and change in the direction of the angle frequency towards the recovery rating, reduce the rotational inertia and
increase the damping coefficient. So the fuzzy control rules tables for virtual parameters J and D are shown in Tables 1 and 2.

| Table 1 J Fuzzy control rule table |
|-----------------------------------|
| \( J \) | \( \Delta \omega \) |
| NB | NB | Z | PS | PB |
| NB | PB | PM | PS | NM | NB |
| NS | PM | PS | PS | NS | NM |
| Z | PS | Z | Z | Z | NS |
| PS | Z | NS | Z | PS | Z |
| PB | NB | NM | NS | PM | PB |

| Table 2 D Fuzzy control rule table |
|-----------------------------------|
| \( D \) | \( \Delta \omega \) |
| NB | NB | PM | PS | PS | PM | PB |
| NB | PB | PM | PS | PM | PB |
| NS | PM | PS | Z | PS | PM |
| Z | PS | Z | Z | Z | PS |
| PS | PM | PS | Z | PS | PM |
| PB | PB | PM | PS | PM | PB |

The actual angular frequency change rate and angular frequency change amount are blurred as the input of the fuzzy controller, and the actual output value is defunctioned by the reasoning of the fuzzy rules to the output values J and D. Wherein the range of values of \( d\omega/dt \) is [-0.6, 0.6], the range of value of \( \Delta \omega \) is [-0.5, 0.5], the range of value of J is [0.2, 0.4], and the range of value of D is [2, 4].

### 3. Simulation verification

In order to verify the adaptive selection of virtual parameters proposed above, an inverter system is set up on matLAB/Simulink platform, and its control circuit is using virtual synchronous generator, and the simulation is carried out in silo mode. The system parameters are shown in Table 3.

| Table 3 The simulation parameters |
|-----------------------------------|
| Parameter | Parameter value |
| DC voltage \( u_{dc}/V \) | 330 |
| Inverter side filter inductor \( L_2/mH \) | 3 |
| Line resistance \( R/\Omega \) | 0.01 |
| Filter capacitor \( C/\mu F \) | 70 |
| VSG virtual inertia \( J/kg\cdot m^2 \) | 0.3 |
| VSG damping coefficient | 3 |
| Frequency modulation coefficient \( D_p \) | 400 |
| Reactive inertia coefficient \( K_q \) | 20 |
| Rated frequency \( f_s/Hz \) | 50 |

In silo mode, the inverter output is connected to a active load of 10000W and a reactive load of 5000Var in the initial state. At 1.5s, the inverter adds an active load of 5000W to the given power. At 2s,
cut off the increased 5000W active load. Observe the frequency waveforms output of the system in different J and D situations.

![Frequency waveform of different J and D situations](image)

(a) Change the inertia.

![Frequency waveform of different D](image)

(b) Change damping coefficient.

Fig.5  Frequency wave form of different J and D

As can be seen from Figure 5, if the rotation inertia increases, the initial frequency change rate decreases, but the adjustment time is longer, and the damping coefficient increases, the frequency deviation can be reduced. Therefore, selecting the appropriate rotational inertia and damping coefficient can improve the dynamic change process of frequency.

In order to verify the effect of the proposed fuzzy control virtual parameter adaptive regulation on frequency change. The remaining simulation conditions remain unchanged, the rotational inertia and damping coefficient are added to the fuzzy control, and then the two parameters are used at the same time fuzzy control, the output frequency simulation results of the system as shown in the figure 6.

![Frequency waveform of adaptive control](image)

(a) Adaptive control of inertia adaptive.
4. Conclusion
In view of the problem that the frequency characteristics of the inverter output are affected by the different frequency characteristics of the virtual rotation inertia and virtual damping coefficient in the control of the traditional VSG control strategy, and the virtual parameters need to be constantly modified and adjusted, this paper proposes a virtual parameter adaptive adjustment method based on fuzzy control, and adaptively adjusts the frequency response of the output of the virtual rotation inertia J and damping coefficient D regulation system. The simulation proves that adaptively adjusting the virtual rotation inertia J and damping coefficient D can suppress the fluctuation of the system frequency. It can reduce both the frequency change rate and the frequency change. The dynamic performance of this control policy frequency recovery is further optimized.
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