Research on VSG Control Strategy of Microgrid

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Abstract. In order to solve the low inertia problem and damping effect brought by the large-scale integration of Distributed Generators (DGs) into the grid, the Virtual Synchronous Generator (VSG) control strategy is introduced. The VSG control strategy is applied to the distributed generators grid-connected inverter to make it have the characteristics of synchronous generator, which can provide voltage and frequency support for the grid. Based on the established model, a detailed and complete VSG parameter calculation process is given, and aiming at the problem of seamless switching operation of microgrid based on VSG control, a simplified pre-synchronization control method is presented, which can simplify the operation and improve the safety and stability of the microgrid. The simulation results based on Real-Time Digital Simulator prove that the proposed method can effectively improve the safety and stability and has good practicability.

1. Introduction
With the increasing scale of Distributed Generators (DGs) into the grid, the electronic inverter used to connect the grid cannot transmit damping and inertia to the grid, which affects the safety and stability of the grid [1]. In order to solve this problem, some scholars have proposed Virtual Synchronous Generator (VSG) technology [2, 3].

The Virtual Synchronous Generator technology is designed to simulate synchronous generator. Make electronic inverter has the same characteristics of the synchronous generator, and can transmit damping and inertia to the grid [4, 5]. At present, few articles can introduce the value requirements of various parameters inside the VSG in detail [6, 7], and the current VSG-based seamless switching operation is complicated, not conducive to the actual operation [8, 9]. Therefore, this paper will give a detailed parameter calculation process for most VSG control strategy parameter values, and provide a simplified seamless switching solution for VSG.

2. Modeling VSG
Inverter VSG control main circuit structure diagram are shown in Figure1. \( U_{dc} \) is the DC side voltage, and the three-phase inverter bridge is composed of the fully controlled devices Q1-Q6. The midpoint voltages \( e_a, e_b, e_c \) of the bridge arm are used to simulate the internal potential of the synchronous generator, and the inductor L1 and the capacitor C constitute LC filter of the inverter side. \( u_{oa}, u_{ob}, u_{oc} \) are the inverter output voltages, used to simulate the synchronous generator terminal voltage, \( i_{oa}, i_{ob}, i_{oc} \) are the inverter output current.
The inverter VSG control structure is shown in Figure 2. The VSG control structure consists of two parts, active-frequency control (active loop) and reactive-voltage control (reactive loop). Active-frequency control is used to simulate the inertia and primary frequency characteristics of synchronous generators. Reactive-voltage control is used to simulate the primary voltage regulation characteristics of a synchronous generator.

The mathematical equation is as follows:

\[ T_{aet}(t) + D_{e}(\omega_{e} - \omega) - T_{e} = J \frac{d\omega}{dt} \]  

(1)

\[ P_{aet} = T_{aet} \omega \approx T_{aet} \omega_{e} \]  

(2)

\[ P_{e} = T_{e} \omega \approx T_{e} \omega_{e} \]  

(3)

\[ \theta = \int \omega dt \]  

(4)

\[ Q_{aet} + \sqrt{2}D_{e}(U_{n} - U_{b}) - Q_{e} = K \frac{\sqrt{2}E_{e}}{dt} \]  

(5)
Where, \( T_{\text{set}} \) is the given torque value; \( D_p \) is the damping coefficient; \( \omega_n \) is the rated angular frequency; \( \omega \) is the VSG output angular frequency; \( T_e \) is the electromagnetic torque; \( J \) is the virtual inertia; \( P_{\text{set}} \) is the given active power value; \( Q_{\text{set}} \) is a given reactive power value; \( D_q \) is the droop coefficient; \( K \) is the integral coefficient. And the expression of the three-phase modulated wave is:

\[
E_a = \sqrt{2}E_m \sin \theta \\
E_b = \sqrt{2}E_m \sin (\theta - \frac{2\pi}{3}) \\
E_c = \sqrt{2}E_m \sin (\theta + \frac{2\pi}{3})
\]  

(6)

3. Controller Design

3.1. Controller Design

In the case of approximate decoupling, the loop gains \( T_p(s) \) and \( T_q(s) \) of the active and reactive loops are:

\[
T_p(s) = \frac{3u_e E_n}{X_e \omega_n} \frac{1}{D_p} \frac{1}{s} \frac{1}{s+1} \\
T_q(s) = \frac{3(2E_n - U_d)}{\sqrt{2}X_s} \frac{1}{D_q} \frac{1}{K} \frac{1}{s+1}
\]  

(7)

(8)

The specific parameters of the VSG control circuit are shown in Table 1. In this paper, the parameters in the table are taken as an example for parameter calculation.

| Parameters  | Value | Parameters  | Value |
|------------|-------|------------|-------|
| \( U_d/V \) | 800   | \( U_g/V \) | 220   |
| \( L_1/mH \) | 3     | \( P_g/kW \) | 40    |
| \( C/\mu F \) | 20    | \( Q_g/kvar \) | 0     |
| \( f_c/Hz \) | 50    | \( f_c/kHz \) | 10    |

In this paper, the design principle of the damping coefficient \( D_p \) is when the grid voltage changes by 1 Hz, and the VSG output active power changes by 100%; the design principle of the droop coefficient \( D_q \) is when the grid voltage amplitude changes by 10%, and the VSG output reactive power changes by 100%. Take 40kW active/reactive power as an example. \( D_p=20 \), \( D_q=1286 \).

\[
D_p(s) = \frac{\Delta T_{\text{max}}}{\Delta \omega_{\text{max}}} = \frac{\Delta P_{\text{max}}}{\omega_n \Delta \omega_{\text{max}}} \\
D_q(s) = \frac{\Delta Q_{\text{max}}}{\Delta U_{\text{max}}}
\]  

(9)

(10)

When at the active-loop cutoff frequency \( f_{\text{cp}} \), the magnitude of the system loop gain is equal to 1. Let equation (9) equal 1:
To ensure that the root number is greater than or equal to 0, there is

\[ f_{cp} \leq \frac{3U_eE_n}{2\pi\omega_nX_D} \]  

(12)

In order to meet the requirements of the phase margin PM, the virtual inertia \( J \) needs to be satisfied as follow

\[ J \leq \frac{D_p}{2\pi f_{cp}} \cot PM \]  

(13)

Combining equations (13) and (15), there is

\[ \sqrt{\frac{3U_eE_n}{2\pi f_{cp}\omega_nX_D}^2 - 1} \leq \cot PM \]  

(14)

Take the phase angle margin as 45°, and combined with equations (12) and (14) and brought into the parameters in Table 1, which could get \( f_{cp} \). Bring \( f_{cp} \) into equation (13) to get \( J \).

It can be seen from equation (9) that the reactive loop contains a low-pass filtering, and its corner frequency \( f_{lq} \) is determined by \( K \) and \( D_q \).

\[ f_{lq} = \frac{D_q}{2\pi K} \]  

(15)

When the reactive loop is at the cutoff frequency, there is at most a phase shift of -90°, so the phase margin of the reactive loop is required to be at least 90°. When at the reactive loop cutoff frequency \( f_{cq} \), the magnitude of the system loop gain is equal to 1, and let the equation (9) equal to 1:

\[ K = \frac{D_s}{2\pi f_{cq}} \sqrt{\frac{3(2E_n - U_e)}{\sqrt{2X_{Dq}}}} - 1 \]  

(16)

After brought in the parameters in Table 1, the result in the root is less than zero, indicating that there is no cutoff frequency in the reactive loop, and the loop gain of the reactive loop is lower than 0 dB. In order to suppress the double power frequency pulsation in the reactive power, the corner frequency of the low-pass filter in the reactive loop is generally within 1/10 of the double power frequency.

\[ \frac{D_{q}}{2\pi K} \leq \frac{1}{10} \times 2f_s \]  

(17)

By taking the above parameters into equations (9) and (10), the Bode diagram of the active loop gain and the reactive loop gain can be plotted, which shown in Figure 3.
It can be seen from Figure 3 that the cutoff frequency of the active loop is 5 Hz and the phase angle margin is 66.7°; the cutoff frequency of the reactive loop is 7 Hz, and the phase angle margin is 90°, which satisfies the design requirements.

3.2. Smooth and seamless switching Design
When switching from the off-grid to the grid-connected, the voltage phase of the VSG output is deviated from the grid phase. Therefore, a certain impact may occur, and resulting in grid connection failure. Therefore, before switching from the off-grid to the grid-connected, a pre-synchronization control strategy should be used to reduce the impact and achieve smooth and seamless switching.

The pre-synchronization control proposed in this paper is divided into a phase pre-synchronization part and an amplitude pre-synchronization part, and the principle is shown in equation (23).

\[
\begin{align*}
\omega &= \omega_0 + \Delta \omega = \omega_0 + (K_{p\omega} + \frac{K_m}{s})(\theta - \theta_0) \\
E &= E_0 + \Delta E = E_0 + (K_{pE} + \frac{K_m}{s})(E - E_0)
\end{align*}
\] (18)

In equation (23), \(\omega_0\) is the frequency of the VSG output voltage, \(\theta\) is the phase of the grid voltage, \(\theta_0\) is the phase of the VSG output voltage, \(E_0\) is the magnitude of the VSG output voltage, and \(E\) is the magnitude of the grid voltage.
4. Results and discussion
In order to verify the correctness of the above method, a VSG controlled photovoltaic power generation system was built in the RTDS. The main circuit parameters are shown in Table 1. When the VSG control strategy is adopted, the switching from the grid-connected to the off-grid does not cause huge impact, and can be switched smoothly. Shown as Figure 4.

Figure 4. VSG output waveform when switching to off-grid

Figure 4 shows that there is no significant impact on the voltage and current output from the VSG, but the phase of the output voltage begins to deviate from the phase of the grid.

According to the Figure 4, since there is a deviation between the VSG output voltage and the grid voltage, direct grid connection will cause impact to voltage and current, resulting in switching failure. Therefore, before grid connected, the pre-synchronization control should be turned on to reduce the voltage and current impact. The simulation result of turn on the pre-synchronization is shown in Figure 5.

Figure 5. VSG output waveform when turn on the pre-synchronization

It can be seen from Figure 5 that after the pre-synchronization is turned on, the VSG output voltage phase is continuously close to the phase of the grid. The simulation result of switched from the off-grid to the grid-connected is shown in Figure 6.
Figure 6. VSG output waveform when connect to grid

It can be seen from Figure 6 that the VSG output voltage phase is perfectly matched with the grid voltage phase when grid connected. The VSG output voltage and the output current have very little impact, which can realize seamless and smooth switching from the off-grid to the grid-connected.

5. Conclusion
In this paper, a detailed and complete VSG parameter calculation process is given, and a simplified seamless switching control is presented.

The simulation on RTDS shows that the parameters obtained by the given calculation process fully meet the requirement of VSG active/reactive loop phase angle margin, and the simplified seamless switching control scheme is simple to operate, which can significantly improve the security and stability during system switching.

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