Research on Parallel Control Strategy of Virtual Synchronous Generators with same capacity

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Abstract. In view of the public AC bus’s frequency stability problem of traditional droop control parallel inverters when load fluctuate frequently, virtual synchronous generator, VSG, is presented in this paper to instead traditional droop control in inverters parallel. The frequency stability of the public AC bus is improved and the output power is divided equally. In view of the VSG parallel preliminary synchronization, a preliminary synchronization method is designed based on phase-locked loop to realize the same phase between the VSG output voltage and public AC bus before paralleling. The simulation and experimental results verify the effectiveness of the proposed control strategy.

Keywords: Virtual Synchronous Generator; Power Allocation; Parallel Preliminary Synchronization; Droop Control.

1. Introduction

With the increasing popularity of distributed power sources in power systems, power electronic grid-connected inverter is increasingly applied in conventional distributed power generation, but it has many shortcomings, including fast response, no inertia, and they are difficult to participate in grid regulation and frequency support. Therefore, the Virtual Synchronous Generator (VSG) control algorithm proposed in this paper combines the power electronic grid-connected inverter control algorithm and the synchronous generator control algorithm to allow power electronic grid-connected inverter simulating the frequency and voltage control characteristics of the synchronous generator from the external characteristics.

A large number of inverters in the microgrid constitutes a multi-inverter environment, and the output voltage frequency, phase and amplitude of each inverter in parallel state must be consistent with the microgrid bus voltage, so it needs to conduct parallel pre-synchronization before accessing the parallel line.

The literature [1] designs the prime mover adjustment and excitation regulation, and it simulates the inertia moment of the synchronous generator, so the external interface of the new energy power station has the frequency and voltage amplitude droop characteristics, which solves the issue of the traditional microgrid inverter during operation, including small output impedance and small damping, and it improves the stability. However, the frequency stability when the load changes is not considered in this
paper; The literature [2] deduces and analyzes the relationship between VSG control and microgrid
frequency stability. It proposes a VSG-based distributed inverter power supply overall control strategy,
which effectively improves the frequency stability of the microgrid. It only studies and analyzes a single
VSG, it does not consider the VSG parallel control; the literature [3] proposes a VSG off-grid seamless
switching control strategy based on phase-locked loop. It quantitatively analyzes the influence of VSG
model parameter perturbation on grid-connected power tracking; the literature [4] analyzes the
traditional droop control strategy and its existing problems, and it proposes a voltage-current dual-loop
control strategy. The traditional droop control is improved to overcome the influence of line impedance
on power distribution. In literature [5], an algorithm for virtual synchronous generator is proposed to
solve inverter parallel issue. It proposes an algorithm for a virtual synchronous generator that ensures
that the parallel inverter outputs active and reactive power at a set capacity ratio.

In this paper, VSG is used to replace the traditional droop control inverter parallel connection, which
solves the problem that the traditional droop control inverter parallel public AC bus has poor frequency
stability when the load fluctuates frequently; it improves the frequency stability of the common AC bus,
and it realizes a sharing VSG output power. A pre-synchronization method based on phase-locked loop
is designed in this paper. The VSG output voltage and the common AC bus voltage are in the same phase.
The simulation and experimental results verify the effectiveness of the proposed control strategy.

2. Principle of VSG
The VSG parallel topology is shown in Fig. 1. The main circuit consists of a three-phase full-bridge
inverter circuit, LC filtering and local load.

Figure 1. The parallel VSG topology

The controller part mainly consists of the prime mover, the rotor motion equation, second-order
equation of exciter and second-order equation of virtual synchronous generator, as shown in Fig. 2. \( I_d \)
and \( I_q \) are the d axis component and q axis obtained by inverter filtering inductor current through dq
transformation.
3. Prime Mover and Rotor Motion Equation Adjuster

The rotor motion equation for the synchronous generator is:

\[
\begin{align*}
J \frac{d\omega}{dt} & = T_m - T_e - D\Delta \omega = \frac{P_m}{\omega} - \frac{P_e}{\omega} - D(\omega - \omega_0) \\
\frac{d\theta}{dt} & = \omega
\end{align*}
\]  

(1)

Where \(P_m\) and \(P_e\) are respectively virtual prime mover power and electromagnetic power; \(T_m\) and \(T_e\) are respectively virtual mechanical torque and electromagnetic torque; \(J\) is moment of inertia; \(\omega\) is synchronous electrical angular velocity; \(\omega_0\) is rated angular velocity; \(\theta\) is electrical angle.

The prime mover governor equation is:

\[
P_m = P_{\text{ref}} + K_\omega (\omega_0 - \omega)
\]

(2)

Where \(P_{\text{ref}}\) is the active power command; \(K_\omega\) is the adjustment coefficient.

4. Exciter Regulator

The excitation regulator refers to the droop control and the typical excitation system in the synchronous generator. \(U_{\text{ref}}\) value refers to \(Q-U\) drooping terminal voltage amplitude, after PI adjusting the \(U_{\text{ref}}\) and the terminal voltage amplitude, the excitation voltage \(u_e\) is obtained.

\[
U_{\text{ref}} = U_N + K_v (Q_{\text{ref}} - Q)
\]

(3)

Where \(U_N\) is the rated voltage amplitude; \(Q_{\text{ref}}\) is the reactive reference; \(Q\) is the reactive feedback value; \(K_v\) is the reactive voltage droop coefficient.

5. Comparative Analysis of Traditional Droop Control and VSG

5.1. Traditional Droop Control

The traditional droop control simulates the primary frequency modulation and primary voltage regulation characteristics of the synchronous generator, and its control equation is as shown in equation (4).

\[
\begin{align*}
\{P_N - P_{\text{ref}} = m (f_N - f) \\
Q_N - Q_{\text{ref}} = n (U_N - U)\}
\end{align*}
\]  

(4)

Where \(f_N\) and \(f\) are respectively the rated frequency and the actual output frequency, \(P_N\) and \(P\) are respectively rated active power and actual output active power, \(Q_N\) and \(Q\) are respectively rated reactive power and actual output reactive power, \(m\) and \(n\) are active-frequency droop coefficient and reactive-voltage. As shown in equation (5), \(P_{\text{max}}\) and \(Q_{\text{max}}\) are the output maximum active and output maximum reactive power, respectively. \(f_{\text{min}}\) and \(U_{\text{min}}\) are the output minimum frequency and output minimum voltage, respectively.

\[
\begin{align*}
m & = \frac{P_{\text{max}} - P_N}{f_N - f_{\text{min}}} \\
n & = \frac{Q_{\text{max}} - Q_N}{U_N - U_{\text{min}}}
\end{align*}
\]  

(5)

The active-frequency droop characteristic is shown in Fig. 3. As can be seen from Figure 3, when the active power increases (or it decreases), \(f\) decreases (or it is increases).
The reactive-voltage droop characteristic is shown in Fig. 4. As can be seen from Figure 4, when the reactive power increases (or it decreases), $U$ is decreased (or it increases).

The traditional droop control simulates the primary frequency modulation and voltage regulation characteristics of the synchronous generator, but it does not simulate the rotor inertia. When the load fluctuates frequently, its frequency changes rapidly, which is not conducive to frequency stability.

5.2. VSG Control

The VSG control has two parts, a power frequency regulator and an excitation regulator. Firstly, the power frequency adjustment characteristics are analyzed. It is derived from the rotor motion equation (1) and the prime mover regulator equation (2). The relationship between the VSG output angular frequency and the active power is shown in equation (6):

$$\omega = \frac{K_w}{J_s + D} \left( \omega_n - \omega \right) + \frac{1}{J_s + D} \left( P_{at} - P \right) + \omega_n$$

Defining $\omega_0=\omega_N$, the power frequency regulator is simplified in Fig.6, and the equation (6) is simplified to equation (7).

$$\omega = \frac{K_w}{J_s + D} \left( \omega_n - \omega \right) + \frac{1}{J_s + D} \left( P_{at} - P \right) + \omega_n$$

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$$\omega = \frac{K_w}{J_s + D} \left( \omega_n - \omega \right) + \frac{1}{J_s + D} \left( P_{at} - P \right) + \omega_n$$
The relationship between the change amount in frequency and the change amount in active power is given by equation (8):

\[
\omega_n - \omega = \frac{1}{J\omega_n s + D\omega_n} \left( P - P_{ref} \right) + \omega_n
\]

Sort (8) into a first-order inertia equation:

\[
\frac{\omega_n - \omega}{P - P_{ref}} = -\frac{1}{J\omega_n s + D\omega_n + K_n} = -\frac{m}{\tau s + 1}
\]

The following equation can be obtained:

\[
\begin{cases}
\tau = \frac{J\omega_n}{D\omega_n + K_n} \\
m = \frac{1}{D\omega_n + K_n}
\end{cases}
\]

Regardless of the influence of the active power measurement, it regards the VSG control as the droop control adding the inertia link in the \( P-f \) droop control link, where the droop coefficient is \( m \), the inertia time constant is \( \tau \), and the static characteristic of the output frequency is related to \( D, K_n, J \), the dynamic characteristics are related to \( D, K_n \), and \( J \). When the active power is suddenly changed, for the droop control that introduces the virtual inertia, due to the existence of the inertia link, the frequency changes slowly, which helps to enhance the stability of the system.

The excitation regulation characteristics are analyzed. The excitation regulator includes the droop control and the typical excitation system in the synchronous generator, as shown in Fig. 7.

\[ U_{ref} \rightarrow K_s \rightarrow U_n \rightarrow U_{ref} \rightarrow \text{[P]} \]

**Figure 7.** Exciter regulator

The VSG output voltage amplitude and reactive power relationship can be obtained:

\[
U_{ref} = U_n + K_s (Q_{ref} - Q)
\]

### 5.3. Parallel Pre-synchronization

Before paralleling, the output voltage frequency, phase and amplitude of the VSG must be consistent with the microgrid bus voltage. Therefore, before paralleling, parallel pre-synchronization needs to be enabled. The VSG is typically incorporated into the microgrid in an unloaded state, while the VSG no-load frequency is greater than the microgrid bus frequency. In order to reduce the transient current.
impact in parallel, this paper designs a pre-synchronization method based on PLL. The principle of the pre-synchronization method is shown in Fig. 8.

![Figure 8. Parallel preliminary synchronization principle of VSG](image)

The synchronization principle is as follows: the frequency adjustment amount $\Delta \omega$ generated by the $q$-axis voltage through the PI regulator needs to be superimposed on the output frequency $f$ in the VSG power frequency regulator, so the VSG internal voltage phase is consistent with the phase voltage of the microgrid bus. And when it is incorporated into the microgrid, the parallel synchronization is cut off so that $\Delta \omega=0$. At this time, the VSG share the load power supply task with other VSGs in the microgrid.

Fig. 9 is a schematic diagram for phase tracking. The $U_1$, who is the VSG1 output voltage vector, is rotated at an angular velocity $\omega_1$, and $U_2$, who is the VSG2 output voltage vector, is rotated at an angular velocity $\omega_2$. If the rotational speeds of $U_1$ and $U_2$ are adjusted to a same speed, that is $\Delta \theta=0$, the voltage between the VSGs is synchronized, which in turn reduces the current surge in the parallel pre-synchronization instant.

![Figure 9. Phase tracking diagram](image)

6. Simulation and Experimental Verification

6.1. Single VSG Simulation and Experimental Verification

6.1.1. Single VSG Simulation. The simulation parameters are as follows: DC side voltage is $U_{dc}=700$V, LC filter parameters are 2mH and 50$\mu$F, virtual impedance is 5mH, moment of inertia is $J=2$kg$\cdot$m$^2$, $K_\omega=2000$. $D=12$, reactive power droop coefficient is $n=0.001$.  

![Graph a: VSG Output Active Power Waveform](image)  
(b): Droop control and VSG output frequency waveform

![Graph b: VSG Output Frequency of Droop Control and VSG](image)
The simulation results are analyzed as follows: Fig. 10 shows the droop control and VSG output frequency waveform. It can be seen that the VSG output frequency changes slowly compared to the droop control, which is beneficial to frequency stability.

6.1.2. Single VSG Experiment Verification. The experimental parameters are as follows: DC side voltage is $U_{dc}=200\,\text{V}$, LC filter parameters are $6\,\text{mH}$ and $10\,\mu\text{F}$, virtual impedance is $5\,\text{mH}$, moment of inertia is $J=2\,\text{kg}\cdot\text{m}^2$, $K_\omega=2000$, $D=12$, the load is $10\,\Omega$.

![Image](image_url)

(a) The active frequency waveform when $J=0.01$

(b) The active frequency waveform when $J=0.06$

**Figure 11.** The active frequency waveform when $J$ changes

The experimental results are analyzed as follows: Fig. 11(a) and Fig.11(b) are active frequency waveform diagrams when $J$ changes, and it can be seen that as $J$ increases, the VSG output frequency decreases slowly and the inertia increases.

6.2. VSG Parallel Simulation and Experimental Verification

6.2.1. VSG Parallel Simulation Verification with the Same Capacity. The simulation parameters are as follows: DC side voltage is $U_{dc}=700\,\text{V}$, LC filter parameters are $2\,\text{mH}$ and $50\,\mu\text{F}$, virtual impedance is $5\,\text{mH}$, moment of inertia is $J=2\,\text{kg}\cdot\text{m}^2$, $K_\omega=2000$, $D=12$, reactive power droop coefficient is $n=0.001$.

The simulation steps are as follows: the first VSG has a resistive load and the second VSG has no load with a pre-sync status.

![Image](image_url)

**Figure 12.** Simulation waveform of output voltage of VSG and AC bus voltage
The simulation results are analyzed as follows: Fig.12 shows the VSG output voltage and AC bus voltage simulation waveform. It can be seen that the pre-synchronization method in this paper enables the second VSG no-load output voltage to be synchronized with the common AC bus voltage.

![Waveform](image1.png)

(a): Load total active power waveform and two VSG output active power waveforms

(b): Load total reactive power waveform and two VSG output reactive power waveforms

**Figure 13.** Simulation waveforms of the same capacity of parallel VSG output power

The simulation results are analyzed as follows: As can be seen from Fig. 13(a) and Fig. 13(b), the control strategy proposed in this paper can achieve power sharing when VSGs with the same capacity are operated in parallel.

### 6.2.2. VSG parallel experiment verification with the same capacity

The experimental parameters are as follows: DC side voltage is $U_{dc}=200\text{V}$, LC filter parameters are $6\text{mH}$ and $10\mu\text{F}$, virtual impedance is $7\text{mH}$, moment of inertia is $J=2\text{kg}\cdot\text{m}^2$, $K_\omega=2000$, $D=12$, the load resistance is $11\Omega/22\Omega$.

![Waveform](image2.png)

(a): Phase A voltage and $\theta$ waveform  (b): VSG output voltage and bus voltage waveform

**Figure 14.** Experimental waveforms of parallel synchronization

The experimental results are analyzed as follows: Fig.14(a) shows the common AC bus (1# VSG) voltage and 2# VSG output phase, and it can be seen that the we obtain Phase A voltage phase; Fig. 14(b) shows the 1# VSG output line voltage and 2 # VSG output line voltage, it can be seen that the two line voltage phases are basically same.
The experimental results are shown as follows: Fig.15 (a) and Fig.15 (b) show the output voltage and current waveforms when the VSG is connected in parallel with the load. It can be seen that the two VSGs can achieve power sharing when loading or load shedding.

7. Conclusion
Firstly, in this paper, a single VSG simulation experiment is carried out to verify that the frequency stability of the control algorithm in the paper is better than that of the traditional droop control when the load changes frequently. Secondly, the VSG parallel simulation and experiment are carried out to realize the VSG output power sharing in parallel operation. It is verified that the pre-synchronization algorithm allows the output voltage frequency, phase and amplitude to be consistent with the microgrid bus voltage before the VSG is connected in parallel, and it reduces the current surge in the parallel moment. Simulation results and experimental results verify the effectiveness of the control strategy proposed in this paper.

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