Research on virtual synchronous generator grid-connection based on phase-locked loop

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Abstract. When a single Virtual Synchronous Generator (VSG) is connected to the grid, the output voltage amplitude and frequency are significantly different from the grid voltage, which will impact the power grid. In order to solve this problem, the paper proposes a grid-connected pre-synchronization control method. By controlling the virtual synchronous generator based on the Phase Locked Loop (PLL) pre-synchronization unit, the voltage amplitude, frequency and phase of the VSG output before the grid connection can be consistent with the grid side, reducing the instantaneous impact of the grid. At the same time of the current, the output voltage of the virtual synchronous generator is stabilized. The single-machine VSG grid-connected model was built on the MATLAB/Simulink simulation platform and the effectiveness of the method was verified.

1. Introduction
When the VSG control system operated by the island is merged into the large power grid, in order to prevent the grid-connected impact from the difference between the VSG output voltage amplitude and the frequency and the grid voltage, a certain technology is needed to make the VSG output voltage before the grid-connected switch is closed. This technology is called pre-synchronization technology [1-3]. Literatures [4-6] proposed a variety of distributed energy quasi-synchronous grid connection methods by using the idea of quasi-synchronous parallel devices to achieve single pre-synchronous grid connection. In literatures [7-9], a pre-synchronization technique using droop control is proposed to regulate the voltage output of the inverter through indirect control of voltage, phase Angle and frequency. Literature [10] studies the micro-grid system composed of different power sources, and the regulation instructions in the power control system with low inertia, and then proposes the pre-synchronous control method suitable for the micro-grid with multiple power sources. The grid connection method controlled by detecting the phase Angle difference of VSG is simple to operate, but slow to respond, requiring several seconds [11]. Based on the Phase Locked Loop (PLL) grid-connected method, the Phase Angle difference between the output voltage of the power grid and the system is detected, and the closed-loop control of Phase Angle difference is realized through the PI regulator [12-15].

2. VSG control strategy
2.1. Basic principle of control system
As shown in figure 1, the voltage source three-phase full bridge topology is selected as the carrier of VSG in this paper, and the energy storage is replaced by an ideal DC source. From left to right are DC voltage source, DC support capacitor, inverter, LC filter, switch and power grid at PCC parallel point. The inverter inverts the DC voltage and the LC filter can filter out the high harmonics near the
switching frequency. PCC is the public connection point between micro grid and large power grid. By closing the switch at the PCC point, the inverter can achieve grid-connected operation mode. While the switch is turned on, the inverter is self-contained, forming island operation mode.

2.2. Phase-locked loop control

To achieve the purpose of VSG and grid voltage synchronization, PLL control technology first obtains the frequency, amplitude and phase of VSG and grid voltage, and then controls them. Vector diagram model is shown in FIG. 2. Constant power Park variation is adopted for coordinate change, as shown in equation (1).

\[
C_{abc/dq} = \frac{2}{3} \begin{bmatrix}
\cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{4\pi}{3}) \\
-\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{4\pi}{3})
\end{bmatrix}
\]

When the VSG is connected to the grid, the controller detects the voltage difference between the two sides of the PCC in real time. When the effective value of \(\Delta u\) is less than the threshold value \(311 \times 10^{\%} \approx 30\text{V}\), it indicates that the voltage difference between the two sides of the PCC is small enough to realize the synchronization of the voltage of the VSG and the voltage of the power grid, and the VSG can be connected to the grid.

The schematic diagram of PLL-based VSG synchronization control is shown in figure 3. In the figure, \(U_s\) is the voltage amplitude setting value of VSG control system, \(U_m\) is the voltage amplitude of the machine terminal, \(U'_{ref}\) is the voltage amplitude instruction value of the machine terminal, \(\Delta U_s\) is the voltage amplitude synchronization quantity of the power grid, and \(\Delta \omega_s\) is the phase synchronization quantity. The three-phase PLL is used to obtain the phase, amplitude and frequency of the grid, and \(\Delta U_s\) and \(\Delta \omega_s\) are controlled to 0 to achieve synchronization with the grid.

Figure 4 shows the simulation waveform of synchronous grid connection. In the figure(a), \(\omega t_1\) is the phase of the grid, \(\omega t_2\) is the phase of VSG. In the figure(b), \(u_{ga}\) is the a-phase waveform of power grid voltage, and \(u_a\) is the a-phase waveform of VSG voltage. Add the pre-synchronization control strategy.
on the VSG model to realize the smooth grid connection of VSG. Take the output voltage of VSG and the phase of the grid and control it through the phase-locked loop, so that the $q$-axis component is 0 and the $d$-axis component is the amplitude of the grid (the $q$-axis component of the grid is 0 and the $d$-axis component is its amplitude), so as to realize pre-synchronization.

![Figure 4. Synchronous grid connection waveform.](image)

3. Experimental simulation verification
As shown in figure 5, the VSG control model was built.

![Figure 5. VSG simulation model.](image)

System parameters are selected as shown in table 1 below:

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $U_{dc}$ (V) | 800 | $Q_{ref}$ (Var) | 0 |
| $U_g$ (V) | 220 | $L$ (mH) | 8 |
| $f_0$ (Hz) | 50 | $P_{ref}$ (W) | 6000 |
| $f_c$ (KHz) | 20 | $C$ (µF) | 3 |
The inverter under the control of VSG is connected with 6kW load when it is off-grid and connected with 5kW load in parallel at 0.1s. The inverter adopts LC filter, and the output reference active/reactive power instruction of the inverter is 6kW/0kVar. After parameter setting, the system is simulated and analyzed.

**Figure 6.** VSG voltage waveform.  **Figure 7.** VSG current waveform.

VSG closes the grid-connected switch PCC to realize the grid-connected operation of the system. When the power grid runs normally, its three-phase voltage is balanced, but the sudden change of load will lead to the fluctuation of the amplitude and frequency of the power grid voltage. When VSG is connected to the grid, its voltage is clamped by the grid, and the amplitude and phase can be synchronized, as shown in FIG. 6 and 7. The voltage and current connected to the grid have high sinuosids and low harmonic distortion rate.

**Figure 8.** Voltage waveform with sudden load.  **Figure 9.** Current waveform with sudden load.

**Figure 10.** Power waveform with sudden load.  **Figure 11.** Frequency waveform with sudden load.

The switch KM is closed and the load \( P_2=5kW \) is integrated at 0.5s. As shown in FIG. 8 and 9, the output voltage is always constant, not affected by load mutation, the stability of the system is good. As can be seen from FIG. 10 and 11, the grid-connected power can effectively track the command power, and the frequency of the system only fluctuates slightly, but quickly tends to be stable.

**4. Conclusions**

Based on the introduction of the basic principles of VSG, this paper builds a grid-connected inverter system model based on VSG control strategy on MATLAB/Simulink. The pre-synchronization unit
based on phase-locked loop controls the voltage amplitude, frequency and phase of VSG and make them consistent with the grid side, thereby reducing the instantaneous inrush current of the grid, and realizing the output voltage and frequency stability of the virtual synchronous generator. This paper only studies a VSG grid connection. When multiple VSGs are combined into a microgrid, they will also face the problem of active power allocation between VSGs. How to make each VSG output a suitable and stable active power is worthy of further study.

5. References
[1] Wang K. Research on Interface Characteristics of Wind Power Generation System Based on Virtual Synchronous Generator[D]. North China Electric Power University, 2015.
[2] Li D, Zhu Q, Lin S, et al. A Self-Adaptive Inertia and Damping Combination Control of VSG to Support Frequency Stability [J]. IEEE Transactions on Energy Conversion, 2017, 32(1):397-398.
[3] Zhang C, Chen M Y, Wang Z C, et al. Study on control scheme for smooth transition of microgrid operation modes [J]. Power System Protection and Control, 2011, 39(20).
[4] Balaguer I J, Lei Q L Q, Yang S Y S, et al. Control for Grid-Connected and Intentional Islanding Operations of Distributed Power Generation [J]. IEEE Transactions on Industrial Electronics, 2010, 58(1): 147-157.
[5] Gaztanaga H, Etxeberria-Otadui I, Bacha S, et al. Real-Time Analysis of the Control Structure and Management Functions of a Hybrid Microgrid System[C]. IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference on. IEEE, 2006.
[6] Yang X Z. Research on Microgrid Inverter and Coordinated Control Strategies of Multinverters[D]. Hefei University of Technology, 2011.
[7] Vasquez J C, Guerrero J M, Savaghebi M, et al. Modeling, Analysis, and Design of Stationary Reference Frame Droop Controlled Parallel Three-Phase Voltage Source Inverters[J]. IEEE Transactions on Industrial Electronics, 2013, 60(4): 1271-1280.
[8] Savaghebi M, Jalilian A, Vasquez J C, et al. Secondary Control Scheme for Voltage Unbalance Compensation in an Islanded Droop-Controlled Microgrid [J]. IEEE Transactions on Smart Grid, 2012, 3(2): 797-807.
[9] Du W, Jiang Q R, Chen J R. Frequency Control Strategy of Distributed Generations Based on Virtual Inertia in a Microgrid [J]. Automation of Electric Power System, 2011, 35(23): 26-31+36.
[10] Cho C, Jeon J H, Kim J Y, et al. Active Synchronizing Control of a Microgrid[J]. IEEE Transactions on Power Electronics, 2011, 26(12): 3707-3719.
[11] Wang K, Wang Z Z, Chai J Y, et al. Analysis of Grid-connection Pre-synchronized Process for Synchronously Controlled Inverter Power Source [J]. Automation of Electric Power System, 2015, 39(12): 152-158.
[12] Liang J G, Jin X M, Jing L, et al. An Improved Control Strategy for Quasi-Synchronous Grid-Connection of Microgrid [J]. Power System Technology, 2014, 38(11): 3071-3078.
[13] Yang L, Wang C, Lu Z P, et al. The Method of Pre-Synchronized Grid-Connection of Synchronverter [J]. Power System Technology, 2014(11): 3103-3108.
[14] Wu H. Control Strategy for Three-Phase-Four-Wire Virtual Synchronous Generator [D]. Nanjing University of Aeronautics and Astronautics, 2015.
[15] Guerrero J M, Vasquez J C, Matas J, et al. Hierarchical Control of Droop Controlled AC and DC Microgrids—A General Approach Toward Standardization [J]. IEEE Transactions on Industrial Electronics, 2011, 58(1): 158-172.

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