Research on Grid-Connected Control Strategies for Two-Stage Photovoltaic Inverters

Yiqi Cai [1, *], Zhiqiang Xu [1]

[1] School of Intelligent Manufacturing and Electrical Engineering, Guangzhou Institute of Technology, Guangzhou 510540, Guangdong, China.

Abstract. This paper conducts an in-depth study on the grid-connected control strategies for two-stage photovoltaic inverters, with a focus on the maximum power point tracking (MPPT) technology and the virtual synchronous generator (VSG) control technology. It analyzes the implementation algorithm of MPPT and its performance under temperature conditions, and elaborates on the principle of VSG control and the analysis of grid stability under low voltage conditions. Through simulations and experiments, it is verified that the proposed control strategies can effectively improve the power generation efficiency and grid-connected power quality of photovoltaic systems, and enhance the friendliness and adaptability of photovoltaic systems in the power grid.

Keywords: Two-stage photovoltaic inverter; Maximum power point tracking; Virtual synchronous generator; Grid-connected control; Low voltage ride through.

1. Introduction

Because solar energy does not consume solid energy such as oil and coal, solar energy comes from solar radiation to generate electricity, and the application of solar energy does not produce harmful substances, so the proportion of solar energy in the global energy further increased.Two-stage photovoltaic inverters are widely used due to their high conversion efficiency and flexible control performance. The output voltage and current of the photovoltaic array are greatly affected by illumination and temperature. For example, under cloudy weather conditions, the output power changes in real time according to the illumination intensity, and as a result, the output power and the voltage on the grid-connected side will fluctuate unstably, which will also lead to poor power quality of the generated electricity. Therefore, it is required that the control strategy of the photovoltaic inverter should have a certain ability to resist significant fluctuations in illumination and temperature so as to achieve the purpose of improving power quality and stabilizing the photovoltaic system. The photovoltaic array adopts the maximum power point tracking technology, which can ensure the maximum photovoltaic output power under different temperature conditions and reduce the power consumption of the photovoltaic system [1].

Traditional low voltage ride through control strategies, which often focus on limiting the output current of inverters and reactive power compensation, lack consideration of the overall dynamic characteristics of the system and thus it is difficult to achieve good collaborative operation with the power grid [2]. The low voltage crossing under VSG control strategy is to resist the effect of voltage plunge and current surge caused by low voltage crossing by simulating the inertia, damping, frequency modulation and voltage regulation characteristics of synchronous generator.

2. Maximum Power Point Tracking Technology

Since the output power of the photovoltaic column follows the influence of external factors such as light intensity and ambient temperature, there is a maximum power point on the power curve of the photovoltaic side. Traditionally, the maximum power point is tracked by disturbance tracking method with fixed step size disturbance voltage or current. A fixed step size requires a relatively long time to converge to the vicinity of the maximum power point [3].

This paper adopts a variable step size perturbation tracking algorithm. When the absolute value of dP/dV is relatively large, which also indicates that the found operating point is too far from the maximum power point, a large step size perturbation increment step size is adopted, which can find the maximum power point more quickly. When the absolute value of dP/dV is relatively small, a small step size perturbation increment step size is adopted to continuously perturb within a small range of the maximum power point and adjust the maximum power point. The specific algorithm flow is shown in Fig. 1.

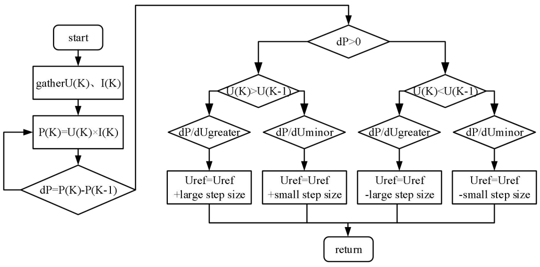

Figure. 1 Block diagram of the variable step size P&O algorithm

3. Virtual Synchronous Generator Control Technology

The essence of the virtual synchronous generator control strategy is to make the photovoltaic inverter simulate the operating characteristics of the synchronous generator. The virtual inertia and damping parameters are introduced into the inverter control strategy. By analyzing the underlying formula of virtual inertia and damping and the frequency and voltage of the power network, the purpose of adjusting the frequency and voltage of the power network is achieved. Active power control and reactive power control simulate voltage and frequency regulation, so that VSG control has the function of frequency and voltage regulation [4].

Inertia and damping in VSG control can enhance the stability of the power grid [5].Its control links mainly include active power control, reactive power control, virtual impedance control and voltage and current double closed-loop control. As shown in Fig. 2, there is the overall control block diagram of VSG.

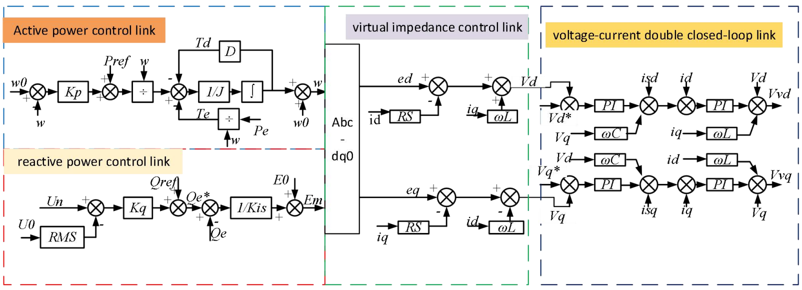

Figure. 2 VSG control block diagram

3.1 The active power frequency modulation section of VSG

When fluctuations occur in the grid frequency, such as when the frequency rises or falls due to sudden changes in the load or variations in the power generation power, the active power frequency modulation section of the VSG can respond rapidly and automatically adjust the active power output according to the frequency deviation.

VSG's active power frequency modulation control combines the mechanical equation and the primary frequency modulation characteristic equation.[6].

$$\begin{cases} J\dfrac{d\omega}{dt} = T_m - T_e - T_d = T_m - T_e - D(\omega - \omega_0) \\ P_m = P_{ref} + K_p(\omega - \omega_0) \end{cases}$$

Obtain

$$\omega = \frac{1}{J} \cdot \frac{1}{S} \cdot \frac{P_{ref} + K_p(\omega - \omega_0) - P_e}{\omega} - \frac{D(\omega - \omega_0)}{J \cdot S} + \omega_0$$

3.2 The reactive power voltage regulation section of the VSG

When a grid fault leads to a sudden voltage drop, the reactive power section can respond rapidly, helping the grid restore normal operation as soon as possible and enhancing the grid's fault ride-through capability. In the reactive power voltage regulation characteristics of VSG, the Q-E control is adopted to adjust the output reactive power, thus ensuring the stability of the generator terminal voltage and realizing voltage regulation.

$$\begin{cases} E_0 - E_m = -n \cdot (Q^* - {Q_e}^*) \\ Q^* = {K_q}^* \cdot ({U_n}^* - {U_0}^*) + {Q_{ref}}^* \end{cases}$$

Sort out

$$E_m = n \cdot \left[{K_q}^* \cdot ({U_n}^* - {U_0}^*) + {Q_{ref}}^* - {Q_e}^*\right] + E_0$$

3.3 The Virtual Impedance Control Section of VSG

The virtual impedance control of VSG simulates the stator resistance and synchronous reactance of the synchronous machine, and equates VSG and its control system to a circuit model with specific impedance characteristics.Virtual impedance is to analyze the relationship between the hardware topology of photovoltaic inverter and the voltage and current in the circuit, and use impedance to simulate and get the expression of virtual impedance.

3.4 The Voltage-Current Double Closed-Loop Section of VSG

In VSG control strategy, voltage and current double closed loop control is used to adjust pulse width modulation output to control pulse duty ratio. In voltage and current double closed loop control, DQ axis component of grid-connected side, voltage of grid-connected side and frequency are controlled.The voltage outer loop makes the output voltage of VSG match the amplitude of the grid voltage, while the current inner loop controls the output current to be in phase with the grid current, thus realizing the rapid and accurate synchronization between VSG and the power grid and ensuring the smoothness and reliability of the grid connection process.

Using the voltage-current double closed-loop section in VSG control can improve the control precision and stability and improve the dynamic response[7]. In the operation process of the control system, the current inner loop plays a key role, which generates the voltage reference signal through specific operations, and then generates the drive signal accurately with the help of advanced pulse width modulation technology, and then effectively controls the switching devices equipped with the photovoltaic virtual synchronous generator to ensure the stable and efficient operation of the entire system.

4. Implementation of Grid-Connection Control Strategies for Two-Stage Photovoltaic Inverters

4.1 Overall Control Architecture Design

The grid-connected control architecture of two-stage PV inverter based on the combination of maximum power point tracking and virtual synchronous generator is constructed in this paper.The preceding DC-DC is controlled by the BOOST converter and the variable step size P&O (Perturb and Observe) algorithm. The rear stage DC-AC is controlled by a double-level inverter and VSG control strategy, and the coordinated control between the two is realized by DC bus voltage.The photovoltaic inverter grid-connected system is shown in Fig. 3.

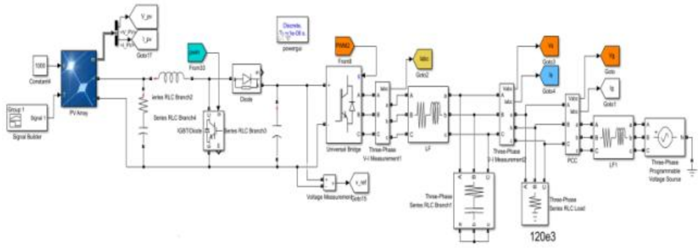

Figure. 3 Overall Framework Diagram of the Photovoltaic Inverter Grid-connection System

In the front-stage circuit, a BOOST boost circuit is used in combination with voltage-stabilizing and filtering inductors. This circuit stabilizes the voltage and filters out certain noise. This circuit performs a boosting operation on the direct current voltage by using an appropriate duty cycle to provide a suitable voltage for the subsequent inverter circuit[8].

By controlling the on-off time of the switch tube in the BOOST circuit, the DC voltage regulation and maximum power point tracking on the photovoltaic side can be realized. When the light intensity and ambient temperature change, the variable step size P&O control strategy adjusts the duty cycle of the BOOST circuit, adjusts the output voltage of the photovoltaic side, so that the photovoltaic array works near the maximum power point, and improves the output power efficiency of the photovoltaic power generation system.

In the hardware topology of the latter circuit, the two-level inverter circuit and LC filter circuit are adopted. The LC filter circuit is connected to the output end of the inverter circuit, which is used to filter out the high-frequency harmonic components generated during the inverter process, so that the waveform of the output AC electric energy is close to the ideal sine wave, and then effectively reduce the harmonic penetration into the power grid and reduce the pollution degree of the power grid environment. LC filter has better performance of high frequency harmonic suppression, and increases capacitor current feedback control to ensure the stability of the system.

The simulation time is 2.5 s. The switching frequencies of both the front-stage and rear-stage circuits are 10e3 Hz. The local user load is 120e3 W. The temperature of the photovoltaic array is 45 degrees from 0.98 to 1.5 s, and 25 degrees at other times. The power grid operates at 80% of the 380 V voltage from 0.8 to 1.7 s.

4.2 Simulation Analysis

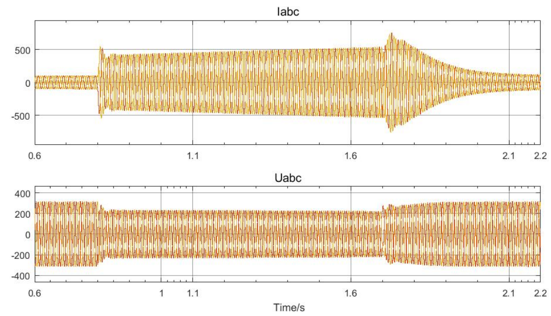

Figure. 4 Diagram of voltage and current changes on the grid-connected side

In Fig. 4, which shows the changes in voltage and current on the grid-connected side, it can be seen that when the power grid voltage drops by 80% from 0.8 to 1.7 s in the system setting, during the low voltage ride through process, when the power grid fails and the voltage drops, the voltage decreases slowly and the current increases slowly. At the end of the low voltage ride through at 1.8

s, the current also overshoots, and then the current quickly stabilizes to the normal level, indicating that the VSG control system has a mitigating effect on the changes in voltage and current under low voltage ride through conditions.

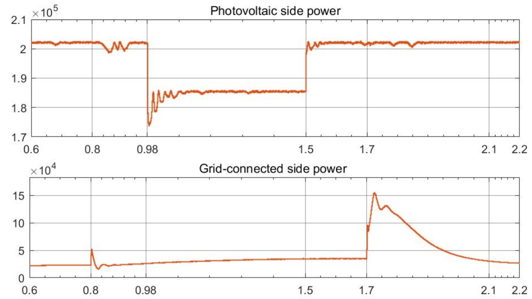

Figure. 5 Diagram of power changes

In Fig. 5, it can be seen that during the temperature change time from 0.98 to 1.5 s, on the photovoltaic side power, it can be seen that the maximum power point of the photovoltaic is tracked by the variable step size P&O in a very short time. At the beginning and end of the low voltage ride through, although the sudden changes in the power on the grid-connected side also caused changes in the power on the photovoltaic side, under the control of VSG, the changes in the power on the photovoltaic side quickly returned to the level before the failure. The power on the grid-connected side did not cause a sudden change, indicating that the VSG control has a certain anti-interference performance against the randomness of the previous-stage photovoltaic power generation.

At 0.3 seconds after the termination of the low-voltage crossing process, corresponding to the 2.1 second node of the entire system running time scale, the harmonic analysis results based on the fast Fourier transform (FFT) show that: The accurate measurement value of harmonic distortion rate of grid-connected voltage is only 0.3%, at the same time, the harmonic distortion rate of grid-connected current is also controlled at a low level of 0.51%, and the above indicators strictly meet the requirements of the power system on the grid-connected harmonic rate should not be higher than 5%, effectively ensuring the power quality and system stability of grid-connected operation.

The results show that under the control of the variable step size P&O and VSG, the photovoltaic array can stably operate near the maximum power point, the grid-connected current waveform of the inverter has a high sinusoidal degree and low harmonic content, and the grid voltage and frequency can achieve low voltage ride through, verifying the effectiveness of the proposed control strategies.

5. Conclusion

Simulation and experiment verify that the control strategy is effective. On the one hand, the maximum power point tracking of the photovoltaic system is accurately optimized to improve power generation efficiency; On the other hand, fine regulation of the inverter output, suppression of harmonics, smooth fluctuations, so that grid-connected energy standards, ensure the stable and efficient power supply of photovoltaic systems, and help the development of new energy power.

References

[1] Zhu Zhen. Research on Power Optimization Strategies for Photovoltaic Arrays under Non-uniform Irradiation Conditions [D]. Shandong University, 2021. DOI: 10.27272/d.cnki.gshdu.2021.004511.

[2] Wang Yuqiang. VSG Low Voltage Ride Through Control Strategy Based on Flexible Adjustment of Power Angle and Current [J]. Electrical Applications, 2024, 43(09): 106-112.

[3] Chen Wenqian, Xin Xiaonan, Cheng Zhiping. Grid-Connected Power Generation Control Technology for Photovoltaic and Energy Storage Based on Virtual Synchronous Generator [J]. Transactions of China Electrotechnical Society, 2018, 33(S2): 538-545.

[4] Fan Haifeng, Liu Guopeng. Research on the Application of a Variable Step Size Perturbation and Observation Method for Maximum Power Point Tracking in Photovoltaic Power Generation in Coal Mine Goafs [J]. Shanxi Electric Power, 2023, (04): 47-50.

[5] Zhang Guanfeng. Research on the Joint Frequency Modulation Strategy of Wind Power and Energy Storage Based on Virtual Synchronous Generator [D]. Shenyang University of Technology, 2021.

[6] An Kexu, Gao Yifan. Research on Voltage Control Strategies for Distributed Photovoltaic Grid-Connected Inverters [J]. Technology and Market, 2024, 31(11): 65-68.

[7] Chongyang Z, Wei C, Beibei R, et al. Analysis of Sub-Synchronous Oscillation of Virtual Synchronous Generator and Research on Suppression Strategy in Weak Grid [J]. Energy Engineering, 2023, 120(11): 2683-2705.

[8] Huang Guanling, Feng Can. Research on Photovoltaic Grid-Connected Technology in Substations [J]. Light Sources & Lighting, 2024, (08): 108-110.