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Research on Active Power Reserve Grid Support Control Strategy of Single-stage Grid-connected inverter

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Abstract

In recent years, photovoltaic power generation has developed rapidly. But photovoltaic power generation has randomness and volatility, a large number of photovoltaics are integrated into the power grid, which brings challenges to the power balance of the power grid. At the same time, due to the limited absorptive capacity in some areas, photovoltaic power stations have a certain degree of light abandonment. In order to make the photovoltaic system obtain the ability of frequency regulation and voltage regulation, and improve the utilization rate of light energy, this paper proposes an active power reserve (APR) grid support control strategy based on single-stage three-level grid-connected inverter. The control strategy does not require energy storage equipment. The inverter can quickly switch between the traditional MPPT mode and the active power reserve mode. In the active power reserve mode, the system can reduce the photovoltaic output, and has the ability of primary frequency regulation and primary voltage regulation to actively support the grid. In addition, aiming at the problem of inaccurate active power reserve control when the external conditions change suddenly, this paper proposes a constant power voltage monitoring method, which can find the maximum power in time when the environment changes, and ensure the accuracy of reserve power control. In this paper, the operation mode and basic working principle of active power reserve are analyzed, and the parameters are designed. Then the algorithm principle of constant power voltage monitoring method is introduced. Finally, the simulation model and 10kW experimental platform are built to verify the effectiveness and feasibility of the proposed control strategy.

1 Introduction

In recent years, the photovoltaic industry has developed rapidly and has become an important source of power energy in China. However, the large-scale photovoltaic grid-connected also brings new challenges to the traditional power grid system. The increasing penetration of new energy in the power system leads to a relative decrease in the capacity of traditional power stations such as thermal power, which will reduce the total inertia of the power system. In some areas, it may show the characteristics of low inertia and underdamping. At this time, the system does not have good regulation performance, which may cause instability of the power grid. In response to this problem, many countries and regions have new standards for photovoltaic power generation, requiring photovoltaic power plants to have a certain frequency regulation capability before they are allowed to be integrated into the local power grid. In addition, photovoltaic power generation has the characteristics of regional and time mismatch. With the increase of the total installed capacity of photovoltaic power generation, it may cause excess power and the problem of photovoltaic consumption is becoming more and more serious.

In order to make the photovoltaic power station have the ability to actively support the power grid, improve the friendliness of the photovoltaic power grid connection system, and solve the photovoltaic consumption problem to a certain extent. At present, there are two common solutions. One is to add energy storage to the photovoltaic system to form an optical storage combined system, which provides additional power by energy storage. However, the current energy storage technology is not mature. At the same time, energy storage has expensive construction and operation and maintenance costs, and there is still a problem of coordination with existing photovoltaic systems. Another scheme is to use the active power reserve control strategy, which is equivalent to the energy storage system through the active power reserve. When the grid frequency fluctuates, the inverter system can flexibly control the reserve power to perform primary frequency regulation, inertia support and primary voltage regulation on the grid. The advantage of active power reserve is that it does not need to add an energy storage system and is easy to implement. In recent years, it has been widely studied by researchers [1].

At present, the research on the active power reserve control strategy is mostly based on the two-stage inverter system. The power control is realized by the pre-

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stage boost circuit, and the post-stage inverter only completes the function of grid connection or support. Reference [2] introduced some reserve power measurement methods and the selection of operating points based on two-stage photovoltaic system. Reference [3] introduced a new method for real-time estimation of maximum power point power and voltage. Reference [4] studied power estimation algorithm based on boost converter. The reserve power could be estimated with any separated sampled pair of voltage and current in proposed control instead of direct measurement or estimation via curve fitting. At present, there are few studies on the single-stage inverter system, but the single-stage system has been applied in practical engineering. Therefore, this paper proposes an active power reserve grid support control strategy based on the single-stage grid-connected inverter. The advantage of this control strategy is that the inverter can quickly switch between the traditional MPPT mode and the active power reserve mode. In the MPPT mode, the power generation is fully generated, and the active power reserve mode actively supports the grid. According to the pre-illumination situation and the power generation instruction, it can quickly switch between the two modes.

In addition, one of the key points of active power reserve technology is that the system needs to find the maximum power point of the photovoltaic array in real time, and control the power reserve based on the current maximum power[5]. In the two-stage system, the algorithm of maximum power estimation using the front-end circuit is a research hotspot[3,4]. However, the maximum power estimation algorithm in the single-stage system is more complex, so the direct measurement method is mostly used, and the MPPT mode is cut back every certain time to measure the high power. The disadvantage of this method is that the system cannot measure the maximum power in real time when the external illumination conditions change suddenly, resulting in inaccurate active reserve power control. In order to solve this problem, this paper proposes a constant power voltage monitoring algorithm, which can re-find the maximum power in time when the environment changes, and ensure the accuracy of reserve power control.

In summary, this paper first analyzes the operation mode and basic working principle of active power reserve, and designs the parameters. Then it introduces the algorithm principle of constant power voltage monitoring method. Finally, the simulation model and 10 kW experimental platform are built to verify the effectiveness and feasibility of the proposed control strategy.

2 Proposed Active Power Reserve Control Strategy

2.1 Single-stage Three-level Grid-connected System Topology

Compared with the traditional two-level inverter, the three-level inverter has the advantages of small switch voltage stress, high efficiency, small output current harmonics and good power quality. It is widely used at present. The topology of the single-stage T-type three-level grid-connected inverter studied in this paper is shown in Fig.1.

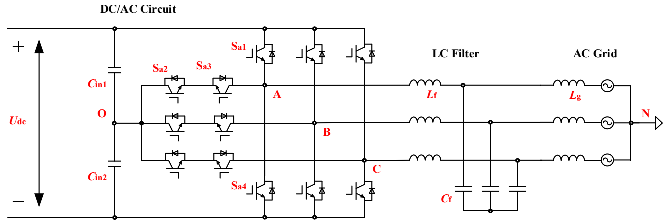

Fig. 1. Main circuit topology diagram of T-type three-level inverter

The main circuit is divided into three parts: input support capacitor, switch circuit and filter. The support capacitor adopts the neutral point voltage division type, and the midpoint O point potential of the capacitor is zero. The midpoints of the three-phase bridge arms are A, B, and C points, respectively. The midpoint of the three-phase grid is N point. The A-phase switch tubes are S_{a1}, S_{a2}, S_{a3}, and S_{a4}, respectively. The filter inductance is L_f, and the filter inductance is C_f. Taking phase A as an example, the inverter has three modes, which are denoted as P mode, O mode and N mode. In order to facilitate control, S_{a1} and S_{a3} are complementary, and S_{a2} and S_{a4} are complementary. In P mode, S_{a1} and S_{a2} are turned on, S_{a3} and S_{a4} are turned off, and the midpoint of the bridge arm of phase A is connected with the positive bus. At this time, the output voltage is $+U_{dc}/2$; in the O mode, S_{a2} and S_{a3} are turned on, S_{a1} and S_{a4} are turned off, and the midpoint of the bridge arm is connected with the midpoint of the support capacitor. At this time, the output voltage is 0; in N mode, S_{a3} and S_{a4} are turned on, S_{a1} and S_{a2} are turned off, and the midpoint of the bridge arm is connected to the negative bus. At this time, the output voltage is $-U_{dc}/2$.

2.2 Analysis of Operation Mode of Active Power Reserve System

In order to reduce the waste of light energy, the active power reserve control strategy is only used in the period of noon when the photovoltaic power generation is surplus, or when the power grid superior issues the abandonment light power limit instruction, as shown in Fig.2.

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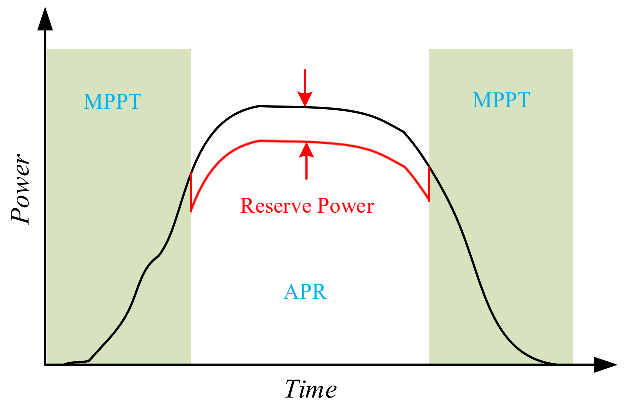

Fig. 2. Operation period of active reserve control strategy

One of the key points of active power reserve control is that the system needs to find the maximum power point of the photovoltaic string in real time, and carry out reserve control according to the maximum power. In this paper, a control strategy based on direct measurement of maximum power point is adopted. Under this control strategy, the operation mode of the system is shown in Fig.3. In the figure, point O is the maximum power point, the corresponding power is P_{mpp}, the corresponding voltage is U_{mpp}, point B is the active reserve power point, the corresponding power is P_B, the corresponding voltage is U_B, point C is the open-circuit operating point, and the corresponding voltage is U_{oc}. Firstly, according to the transient power balance between the DC side voltage and the AC output power, the right side of the maximum power point can be determined as the stable working area. Based on this, the working mode of active power reserve is analyzed.

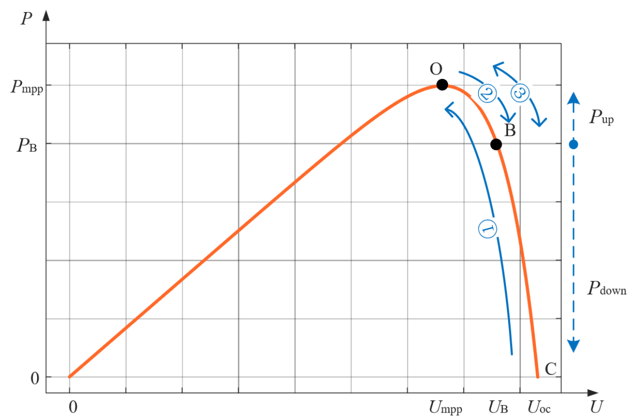

Fig. 3. Analysis of active reserve working mode

There are two working modes when the photovoltaic system works. The first is the MPPT mode, which corresponds to the stage ① in Fig.3. In this mode, the system performs maximum power tracking according to the traditional perturbation and observation method, and finally works at O point. The second is the active reserve mode, corresponding to the stage ② in Fig.3, which is the constant power control mode. In this mode, the system works at the reserve point B according to the given reserve rate. At this time, the power difference between P_{mpp} and P_B is recorded as the reserve power P_{down}, as in (1). When the grid frequency drops, the P_{down} is released for frequency regulation support; the power difference between P_B and 0 is denoted as P_{up}, as shown in (2). When the grid frequency rises, the reserve rate is increased to reduce the power output, thereby suppressing the rise of the grid frequency.

$$P_{\mathrm{down}} = P_{\mathrm{mpp}} - P_{\mathrm{B}} \tag{1}$$

$$P_{\mathrm{up}} = P_{\mathrm{B}} \tag{2}$$

The reserve rate is r, which is related to the above power as formula (3).

$$P_{\mathrm{B}} = (1\text{-}r) \cdot P_{\mathrm{mpp}} \tag{3}$$

When the system is started, it first works in the traditional MPPT mode, records after finding the maximum power point, then cuts into the active reserve mode, and performs constant power control according to the set reserve rate r. In this mode, the photovoltaic system supports the frequency of the power grid, and the system has the ability of primary frequency regulation and inertia support. In order to prevent the inaccurate reserve power control caused by the change of the maximum power point, the system cuts back to the MPPT mode every certain time, corresponding to the stage ③ in Fig.3. Then continue to work circularly between the two modes.

2.3 Principle Analysis of Active Support Control Strategy

In this paper, the current source VSG algorithm is used to realize the active support of grid connection. Compared with the voltage source VSG algorithm, the algorithm is easier to realize the fast switching between MPPT mode and active power reserve mode[6].

Firstly, the stator voltage equation and rotor motion equation of the synchronous generator can be obtained by modeling the synchronous generator, such as (4) and (5).

$$\vec{E} = \vec{U} + \vec{I} \cdot (R + jX) \tag{4}$$

$$\begin{cases} J \cdot \dfrac{d\omega}{dt} = T_m - T_e - D \cdot (\omega - \omega_0) \\ \dfrac{d\delta}{dt} = (\omega - \omega_0) \end{cases} \tag{5}$$

In addition, according to the droop characteristics of the synchronous generator, the active and reactive power droop control functions of the inverter can be obtained as follows:

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$$P_{\text{out}} = P_{\text{ref}} - K_f \cdot (\omega - \omega_f) \tag{6}$$

$$Q_{\text{out}} = Q_{\text{ref}} - K_{\text{V}} \cdot (U - U_0) \tag{7}$$

In the photovoltaic system control, the droop characteristics of the synchronous generator and the rotor motion equation can be combined to simulate the characteristics of the synchronous generator through the control mode of the virtual synchronous machine. Combining (5) and (6), the equivalent control function of the photovoltaic inverter can be obtained as follows :

$$\begin{cases} J \cdot \dfrac{d\omega}{dt} = \dfrac{P_{\text{ref}}}{\omega_f} - \dfrac{P_{\text{out}}}{\omega_f} - K_f \cdot (\omega - \omega_f) \\ \Delta\omega = (\omega - \omega_f) \end{cases} \tag{8}$$

After finishing, the final active power control expression can be obtained :

$$P_{\text{out}} = P_{\text{ref}} - J \cdot \omega_f \cdot \frac{d\omega}{dt} - K_f \cdot (\omega - \omega_f) \tag{9}$$

From this expression, the system can be controlled by the given power method, and the control block diagram of the active power part can be obtained. Similarly, the reactive power-voltage droop control block diagram can be derived according to the primary voltage regulation characteristics in (7). Finally, the block diagram of the active reserve power grid support control strategy proposed in this paper can be obtained as Fig.4.

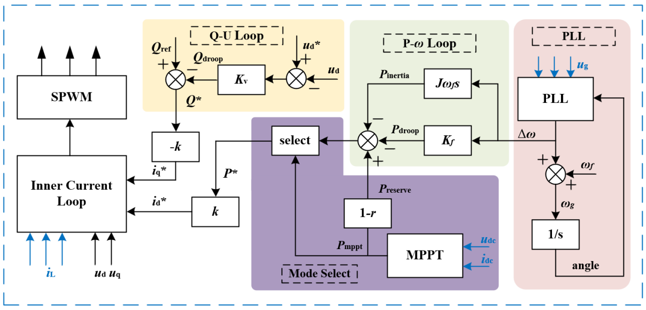

Fig.4. Active power reserve active support control block diagram

From the diagram, it can be seen that when the system is started, the control system works in the traditional MPPT mode through the select module. After tracking the maximum power, it is switched to the active power reserve mode. In the active power reserve mode, the power outer loop of the system adopts the current source VSG control algorithm to provide active support for the power grid. The dq axis decoupling control can flexibly and quickly control the power. The realization process of VSG frequency regulation is that the system first detects the angular frequency fluctuation value of the power grid through the phase-locked loop. After active droop and inertia control, the initial reserve power is superimposed to obtain the output active power reference value, and the grid-connected active power is regulated. The realization process of voltage regulation of VSG is to detect the fluctuation value of grid voltage. After reactive power droop control, the reference value of output reactive power is obtained by superimposing the initial reactive power command value, and the grid-connected reactive power is regulated.

3 Principle of Constant Power Voltage Detection Method

In this paper, the direct measurement method is used to realize the maximum power point detection. This method requires the system to cut back the MPPT mode every certain time and re-find the maximum power point to ensure the accuracy of the reserve power control. However, when the external conditions such as light intensity change suddenly, the system cannot respond in time, which will lead to an increase in the error of reserve power control. In order to alleviate this problem, this paper proposes a constant power voltage monitoring method. Fig.5 shows the change process of the working point of the system when the ambient temperature is constant and the light intensity changes in the active reserve mode.

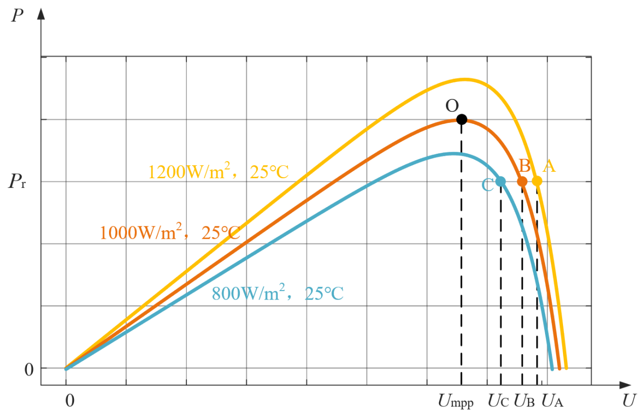

Fig. 5. Change diagram of active reserve working point when light intensity changes

The yellow, orange and blue curves in the figure correspond to the PV characteristic curves under different light intensities respectively, and A, B and C correspond to the active reserve operating points of the system under different light intensities respectively. It is assumed that the system initially works on the orange curve. At this time, the active reserve working point is B, the corresponding voltage is U_B, and the corresponding power is P_B. When the light intensity is constant, the current source VSG works normally and participates in the frequency regulation of the power grid. At this time, if the bus voltage changes, the photovoltaic power will change accordingly. At this time, if the light intensity suddenly decreases, the photovoltaic curve becomes a blue curve. Since the current source VSG is in a constant power control mode when the grid frequency is stable, the system operating point becomes a C point. It can be seen that the bus voltage decreases at this

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time, and the photovoltaic output power does not change significantly.

It can be seen from the above analysis that the system can monitor the bus voltage in real time, and determine whether the light intensity changes at this time by judging whether the photovoltaic power changes accordingly when the bus voltage changes. If the bus voltage changes, the photovoltaic output power changes accordingly, indicating that the system is in primary frequency regulation at this time, the system can be maintained in active reserve mode. If the bus voltage changes, the photovoltaic output power is still constant, which proves that the light intensity changes at this time, and the maximum power tracking needs to be performed again, then the system cuts back to the MPPT mode.

After the constant power voltage monitoring algorithm is added to the system, the light intensity can be monitored to a certain extent, and the accuracy of reserve power control is improved.

4 Simulation and Experimental Verification

In order to verify the correctness of the proposed control strategy, a 10 kW photovoltaic grid-connected inverter simulation platform and a hardware circuit platform are built. The parameters of the experimental platform are shown in Table 1, and the hardware experimental platform is shown in Fig.5.

Tab. 1. Main parameters of experimental platform

Parameter name	Value
Rated output power	10kW
Rated output voltage	380Vac / 50Hz
Switching frequency	16kHz
Active power reserve coefficient	20%
Primary frequency regulation coefficient	25
Primary voltage regulation coefficient	3.1
Moment of inertia	160

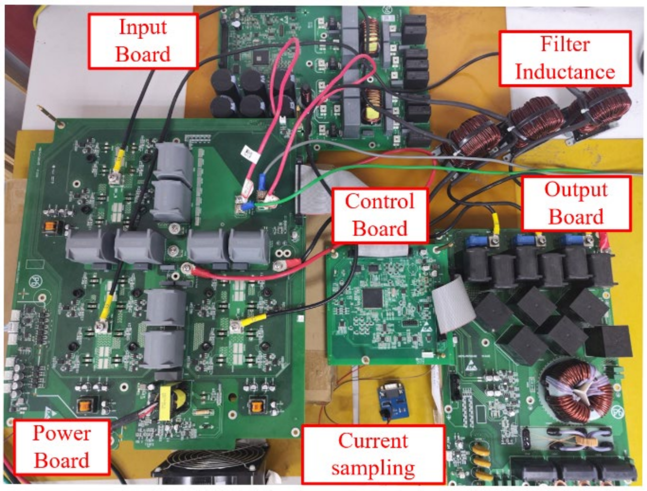

Fig. 5. Grid-connected inverter experimental platform

4.1 Experimental Verification of Active Power Reserve Control Strategy

The primary frequency regulation function is verified by experiments. Fig. 6 shows the experimental waveform of 10 kW primary frequency regulation. The curves of output active power and frequency are shown respectively. The active reserve rate set in this experiment is 20%. It can be seen from the figure that the system starts to do MPPT at 8s, and the maximum power point is successfully found at an interval of about 12s. The active reserve mode is successfully cut in at 23s, and the load shedding power is about 2kW, which meets the control target and realizes the fast switching between MPPT mode and active reserve mode. Under the frequency regulation parameters set in the experiment, the grid frequency fluctuates by 0.2Hz, and the grid-connected output active power is adjusted by 1 kW accordingly. As shown in the figure, the active reserve mode is switched on at 23s. At 32s, the grid frequency increases by 0.2Hz. The primary frequency regulation of the inverter reduces the output active power by 1kW. At 38s, the grid frequency recovers. At 46s, the grid frequency drops by 0.2Hz. The primary frequency regulation of the inverter increases the output active power by 1kW, and the grid frequency recovers at 54s. It is proved that the system can perform primary frequency regulation according to the design goal.

After that, a voltage regulation function is verified. Fig.7 shows a voltage regulation experiment waveform. The variation curves of the output reactive power and the effective value of the phase voltage of the A-phase power grid are shown in the diagram. Under the voltage regulation parameters set in the experiment, the effective value of the grid phase voltage fluctuates by 5V, and the grid-connected output reactive power is adjusted by 1kVar accordingly. As shown in the figure, the system has entered the active reserve state at 23s. At this time, the effective value of the rated phase voltage of the power grid is 155V.At 31s, the phase

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voltage of the power grid increases by 5V. The inverter adjusts the voltage to absorb the reactive power 1kVar. At 39s, the grid voltage recovers. At 45s, the grid voltage drops 5V, and the inverter adjusts the voltage to emit reactive power 1kVar.At 52s, the grid voltage recovers. It is proved that the system can adjust the voltage once according to the control target.

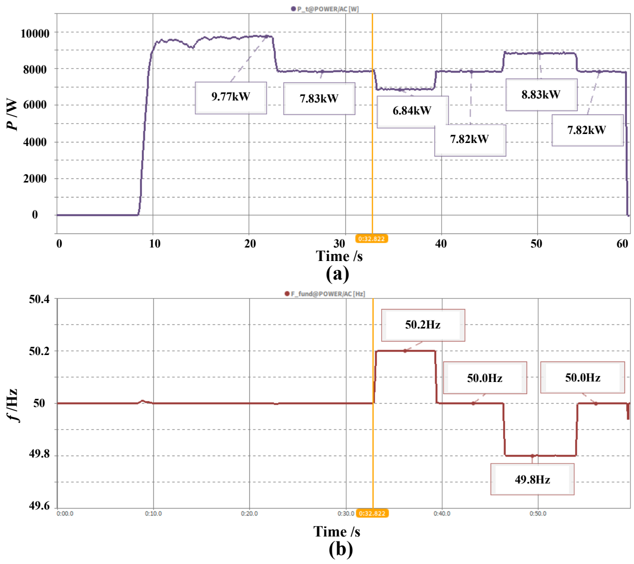

Fig. 6. Primary frequency regulation experimental waveform

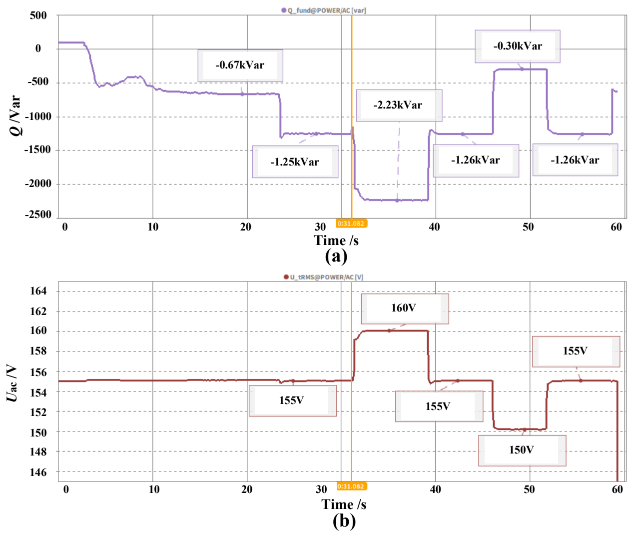

Fig. 7. Primary voltage regulation experimental wave-form

In summary, the experimental results show that the active reserve control strategy proposed in this paper can perform primary frequency regulation and primary voltage regulation according to the expected target, provide active support for the power grid, and can achieve rapid mode switching.

4.2 Simulation Verification Of Constant Voltage Power Monitoring Method

In order to improve the accuracy of reserve power control and reduce the impact of sudden changes in the external environment on the system, a constant power voltage monitoring method is proposed in the previous section. This section simulates and verifies it to test whether the system can monitor the rapid change of external light intensity in time. The simulation results are shown in Fig.8. The upper and lower figures in the figure are the change curves of active power and light intensity respectively. It can be seen from the figure that MPPT is started after the start of the photovoltaic system and enters the active reserve mode at about 0.5s.The light intensity decreases abruptly at 1s.The system captures the information of the sudden change of the external environment within 0.05s, and quickly enters the MPPT mode. After the system is stable, it will work again at the new active reserve working point to provide active support for the power grid.

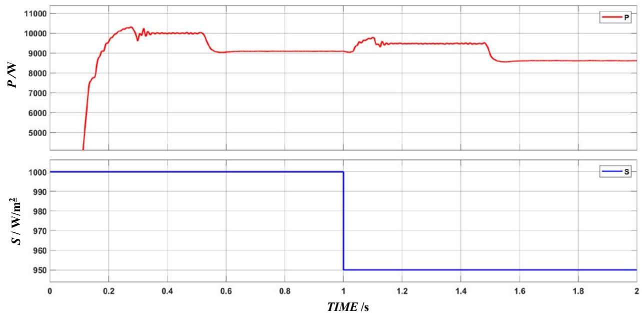

Fig. 8. Simulation waveform of primary voltage regula-tion reactive power and grid voltage

The simulation verifies the accuracy of the theory and proves that the proposed power voltage monitoring method can improve the accuracy of the system active reserve power control.

5 Conclusion

Photovoltaic power station should have the ability of frequency regulation and voltage regulation. Aiming at the photovoltaic system without energy storage, this paper proposes an active reserve grid support control strategy based on a single-stage three-level grid-connected inverter. Under this strategy, the inverter can quickly switch between the traditional MPPT mode and the active reserve mode. In the active reserve mode, the system has primary frequency regulation and primary voltage regulation capabilities to actively support the grid. In addition, aiming at the problem that the active reserve power control is not accurate when the external conditions of the system change abruptly, this paper proposes a constant power voltage monitoring method to ensure the accuracy of the reserve power control. Finally, the effectiveness and feasibility of the proposed control strategy are verified by experiments, which has certain engineering practical significance.

6 References

[1] Y. Yun, H. Wang, C. Shi and K. Huang, "PV-VSG Control Strategy Suitable for Insufficient Active Reserve," in *2023 IEEE 6th International Conference on Information Systems and Computer Aided Education (ICISCAE)*, 2023, pp. 264-269. DOI: 10.1109/ICISCAE59047.2023.10392659.

[2] Y. Zhu, H. Wen and G. Chu, "Active Power Control for Grid-connected Photovoltaic System: A Review," in *2020 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia)*, 2020, pp. 1506-1511. DOI: 10.1109/ICPSAsia48933.2020.9208459.

[3] E. I. Batzelis, A. Junyent-Ferre and B. C. Pal, "MPP Estimation of PV Systems keeping Power Reserves under Fast Irradiance Changes," in *2020 IEEE Power & Energy Society General Meeting (PESGM)*, 2020, pp. 1-5, DOI: 10.1109/PESGM41954.2020.9281698.

[4] Y. Zhu and H. Wen, "Sensorless Active Power Reserve Control for PV System with Low-Complexity MPP Estimation," in *2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia)*, 2020, pp. 3204-3209, DOI: 10.1109/IPEMC-ECCEAsia48364.2020.9367753.

[5] X. Li, R. You, M. Li, J. Zhou and W. Yu, "A Control Strategy of Photovoltaic Grid-connec*ted Inverter Based on Active Power Reserve," in 2021 6th International Conference on Power and Renewable Energy (ICPRE)*, 2021, pp. 499-503, DOI: 10.1109/ICPRE52634.2021.9635184.

[6] D. Singh and K. Seethalekshmi, "A Review on Various Virtual Inertia Techniques for Distributed Generation," in *2020 International Conference on Electrical and Electronics Engineering (ICE3)*, Gorakhpur, India, 2020, pp. 631-638, DOI: 10.1109/ICE348803.2020.9122959.