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Active and reactive power coordination control strategy of overvoltage for distributed PV integrated grid

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Abstract: Aiming at the voltage rise due to the photovoltaic generation system (PVGS) at the point of common coupling (PCC), the cause is analysed with power transmission theory. Here, the principle and strategies of voltage regulation based on active and reactive power in PVGS are proposed. In this control strategy, the voltage of PCC is tracked by PV system in real time. When the voltage of PCC is normal, inverter will output in the way of maximum power point tracking (MPPT).When the voltage of PCC exceeds the upper limit, the inverter will regulate the voltage using the remaining capacity preferentially. If the remaining capacity is insufficient, the inverter will adjust active output and dynamically calculate the active and reactive best out values. In this way, the voltage of PCC is adjusted in an appropriate range to achieve the active output minimisation and reactive output optimisation of inverter. The experimental results validate the effectiveness of the proposed control scheme for voltage regulation.

1 Introduction

With the intensification of the energy crisis and environmental pollution, the countries of the world have accelerated the development and utilisation of new energy. Photovoltaic (photovoltaic, PV) power generation is a clean and non-polluting renewable energy. In recent years, the installed capacity of PVGS is increasing, and it is developing from large-scale centralised to large-scale distributed construction. At present, PV showing 'large-scale distributed development and low voltage access, local consumption' and 'focus on the development of large-scale, high-pressure, high voltage and long distance transmission access in two ways coexist pattern' [1]. But because the output of photovoltaic power generation is random, accessed to distribution network will affect the power flow distribution, and flow direction. However, with the PV penetration to improve the effect of photovoltaic system, the grid voltage increases significantly. The problem that how to improve the voltage limit caused by photovoltaic grid connection is one of the most important problems to be solved for the realisation of distributed PV one of the most important problems to be solved for the realisation of distributed PV friendly access [2]. At present, in view of the research of the voltage limit caused by the increase of photovoltaic permeability, it is proposed that voltage regulation is carried out by means of transformers on load voltage regulation or combined with switching capacitor bank [3]. But scene that it is commonly used to solve voltage limit is limited, and the position of the fixed installation of the transformer and capacitor group is not pertinent. In addition, the voltage regulation of the transformer has a certain frequency in the actual distribution network, and the adjustment process cannot be adjusted continuously and smoothly. It is proposed that the voltage regulation of the installation of energy storage devices, static var generators (static reactive compensators, SVC) at the point of connection [4]. But the increase in hardware investment will increase investment, and the utilisation of compensation devices is low.

Research on voltage regulation strategy of PV grid-connected generation system, in the literature [5, 6], using a single inverter control means that the absorption of reactive power, reactive power regulation, the premise of this method is the residual capacity of the inverter is large enough, but the lack of capacity remaining in the inverter will not be able to adjust to the normal range of voltage regulation. In the literature [7, 8], it proposes to reduce the voltage limit by reducing the output active power of the inverter. Although this method can effectively solve the problem of dot voltage limit, it increases the photovoltaic discard rate. In the literature [9], the residual capacity of multiple photovoltaic inverter in power grid by pressure regulates power in the photovoltaic power, establishing communication between and in accordance with the target voltage control algorithm, the reactive power of each inverter needs to send, to send to each instruction type inverter implementation. Although this method reduces the hardware investment, saving cost, for the centralised control mode, the control between inverter and instruction to control conflicts, communication interruption caused by inverter control problems; on the other hand, when the PV output is relatively large with decreasing the residual capacity of the inverter, prone to reactive power surge capacity shortage, unable to effectively solve the problem of limit voltage.

Based on the power transmission theory of power system, this paper analyses the causes of PCC voltage rise caused by grid connected photovoltaic power-generation system. A practical method of voltage regulation in photovoltaic system's coordinated control strategy of active and reactive power of inverter is proposed. When the PCC voltage is the upper limit, it gives priority to the use of inverter residual capacity by pressure regulating power inverter, if inverter's residual capacity is insufficient, system can ensure that the PCC voltage is regulated to meet the requirements of the premise, achieving the maximum power output of inverter and the calculation of active power and reactive power optimal output value. This strategy does not require additional hardware input, has well dynamic characteristics, can work steadily in load fluctuation, and has well adaptability.

1.1 Analysis of the principle of voltage rise

After the PV power is connected to the distribution network, the magnitude and direction of the tidal current may be changed, which makes the line voltage of the distribution network change. Fig. 1 is a simplified structure diagram of the PV grid connected system. The photovoltaic power supply is given priority to the load, and the remaining energy is after a section of line. By 10/0. 4 kV boost transformer into large power grid. In Fig. 1, U_0 is said the low-voltage-side bus voltage, the amplitude and phase remain unchanged; U_S is said photovoltaic power supply voltage of PCC; P_{PV}, Q_{PV} are active power from photovoltaic power and reactive power; P_L and Q_L are active power load and reactive power of

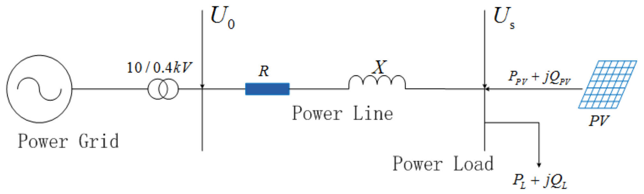

Fig. 1 *Simplified structure of PV grid-connected system*

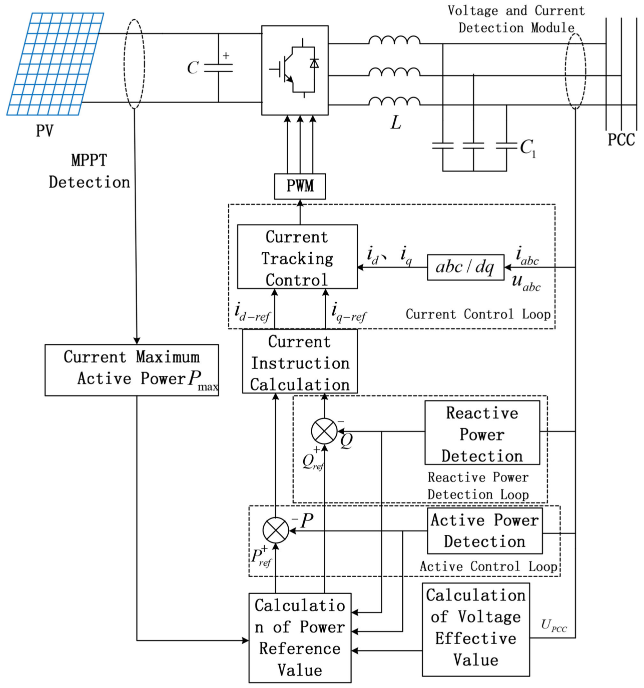

Fig. 2 *Schematic of inverter power control*

users load; R and X are the line resistance and reactance value, respectively.

After the photovoltaic power supply is connected, the PCC voltage U_s is:

$$U_s = U_0 + \frac{(P_{PV} - P_L - P_s)R + (Q_{PV} - Q_L - Q_S)X}{U_0} + j\frac{(P_{PV} - P_L - P_s)X - (Q_{PV} - Q_L - Q_s)R}{U_0} \tag{1}$$

In the formula, P_S and Q_S**,** respectively, indicate the active and reactive power loss of the line.

Usually, the line loss is much less than that of PCC power. P_S and Q_S are negligible in formula (1). Besides, the longitudinal component of voltage is far less than its transverse component. The longitudinal component of voltage is also negligible in formula (1). After simplification, the PCC voltage U_s is as follows:

$$U_s = U_0 + \frac{(P_{PV} - P_L)R + (Q_{PV} - Q_L)X}{U_0} \tag{2}$$

The user load is usually a resistive load, that is, the active P_L and the reactive Q_L are positive. According to the formula (2), we know that the voltage of the load side is less than the system voltage when the P_{PV} and Q_{PV} are all 0.

The PCC voltage is at this time:

$$U_s = U_0 - \frac{P_L R + Q_L X}{U_0} \tag{3}$$

After photovoltaic power is connected to the grid, photovoltaic power is output according to the maximum power point tracking (Maximum Power Point Tracking, MPPT) and the unit power factor is generated, that is, the active power is output according to the maximum power and reactive power. The power Q_{PV} is 0, and the PCC voltage is at this time:

$$U_0 = U_0 + \frac{(P_{PV} - P_L)R - Q_L X}{U_0} \tag{4}$$

The analysis (4) shows that the photovoltaic power and the dot voltage are raised after the power grid is connected to the power grid.

When the active power output of the photovoltaic power is increased, then the $(P_{PV} - P_L)R - Q_L X < 0$, the node voltage will be greater than the system voltage. When the PV power reaches a certain limit, the voltage will be higher than the upper limit. If we do not take measures to adjust the voltage, we will threaten the power users. The analysis (4) shows the factors that affect the load voltage U_s are mainly as follows: load power, photovoltaic power supply, and line impedance. The line impedance values R and X are related to the installation position of the photovoltaic power supply. They are fixed values; the load power depends on the power consumption. The power consumption and the photovoltaic power are uncontrollable of the user. However, the active and reactive power of photovoltaic power supply is controllable, and the magnitude of active power output can be quantitatively regulated between zero and maximum active output value, which can absorb or generate reactive power according to the need of the inverter's residual capacity. Therefore, when the voltage limit occurs, it can be controlled by controlling the active and reactive power output of the inverter.

2 Coordinated control method of active and reactive power

2.1 Principle of inverter power control

Fig. 2 is a block diagram of active power and reactive power coordinated control based on PQ control for photovoltaic grid connected system. It mainly includes active power control loop, reactive power control loop, and current control loop. U_s is said the effective value of voltage and network; P_{ref}, Q_{ref}, respectively, indicate the reference values of active and reactive power of the system; P_{max} indicates the maximum active power value of PV at the next moment; P and Q, respectively, represent active and reactive power generated by PV at the moment; u_{abc} and i_{abc}, respectively, represent the voltage of photovoltaic network the instantaneous value and the instantaneous current of photovoltaic power injection system; i_d and i_q, respectively, represent abc/dq system after coordinate transformation of active and reactive current; i_{d-ref} and i_{q-ref}, respectively, indicate the reference value of active and reactive current, respectively.

After the inverter is connected to the grid, the instantaneous value of voltage and current U_{abc} and i_{abc} are detected and transmitted to the voltage effective value calculation module and the active and reactive power detection module in real time. These modules transfer the corresponding data to the power reference value calculation module. At the same time, the MPPT detection module calculates the maximum active value P_{max} that can be output at the next moment of the PV. It is transmitted to the power reference value calculation module. The calculation of the power reference value is the core content of this study. Its function is to judge the PCC point voltage condition. According to the current inverter working condition, the active and reactive power and reactive power reference value P_{ref}, Q_{ref} are calculated using the active and reactive power coordinated control strategy of the inverter; then, the active power control loop, reactive power control loop, and active current reference value and reactive current reference value of i_{d-ref}, i_{q-ref} passed to the current control loop, the current tracking control of grid-connected inverter output to change quickly and accurately tracking P_{ref}, Q_{ref}. The adjustment period of P_{ref} and Q_{ref} is consistent with the sampling period of voltage and current of PCC point, thus realising fast and dynamic regulation of dot voltage.

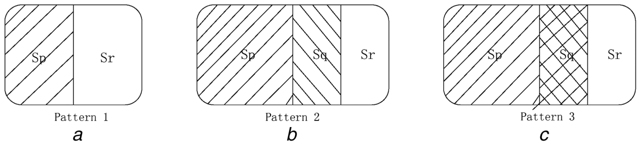

Fig. 3 *Schematic diagram of inverter operating status and capacity utilisation*

2.2 Coordinated control strategy for active and reactive power of inverters

In grid-connected photovoltaic system, inverter voltage regulation of active power and reactive power coordination control function in priority order is divided into the following: the PV point voltage is limited to the state, give priority to ensure the quality of power supply is safe and reliable; the inverter output active power maximisation, improve the efficiency of photovoltaic power generation; the reactive power output of the inverter as small as possible, reduce the network loss.

According to the capacity utilisation of the inverter and the different voltage regulation level, the voltage regulation state of the inverter is divided into three operating conditions, as shown in Fig. 3. Among them, S_P is said the active power occupation capacity; S_P is reactive power; S_r is inverter occupancy capacity; S_r is residual capacity; S is said active power cut capacity, but also increase the capacity of reactive power; I is said working next time without pressure, in order to achieve the control function of the active power inverter and, according to the MPPT output, reactive power output is 0, the capacity utilisation in Fig. 3*a* is shown; of case said the next time PCC voltage will be the upper limit, according to the function of the order of priority strategy. Given priority to the use of part of the residual capacity of the inverter without pressure regulating power, active power in the process of adjusting the pressure according to the output of MPPT, inverter capacity utilisation in Fig. 3*b* is shown; III said that next time PCC operating voltage will be the upper limit and the residual capacity of the inverter using separate reactive power regulation cannot be normal range of PCC to reduce voltage, inverter power output, excess capacity for non-pressure regulating power, inverter capacity utilisation (*c*) as shown in Fig. 3.

When the load power changes or the output of PV active power changes, we need to predict the voltage regulation of the inverter at the next time, and then calculate the reference value of active and reactive output. According to the priority order of the coordinated control function of active and reactive power, it is necessary to filter the working conditions of the inverter at the next time stage step by step. In Fig. 1, a current PCC voltage is U_S, the active power output of PPV, the reactive power output of Q_{PV}, active power P_L, reactive power is Q_L; next time with the same load, MPPT can work according to the PV output maximum active power is $P_{\max}$, the PCC voltage is adjusted to the upper limit value of $U_{\max}$ for inverter of reactive voltage is Q'_{PV}. When the PV power is output at MPPT next time, and the voltage of the switching point is adjusted to the upper limit $U_{\max}$, the calculation formula of the residual capacity and reactive power of the inverter is as follows:

$$U_{\max} = U_0 - \frac{(P_L - P_{\max})R + (Q_L - Q'_{\mathrm{PV}})X}{U_0} \tag{5}$$

As the load power cannot be measured, its specific data are unknowable, and it can be combined by formula (2) and (5) to get the next time of reactive voltage regulation which is as follows:

$$Q'_{\mathrm{PV}} = \frac{U_0(U_{\max} - U_s) - (P_{\max} - P_{\mathrm{PV}})R}{X} + Q_{\mathrm{PV}} \tag{6}$$

(i) mode I: if the formula (6) calculates the result $Q'_{\mathrm{PV}} > 0$, it indicates that when the active power of PV power is output by MPPT at the next time, in order to adjust the PCC voltage to the upper limit $U_{\max}$, the inverter needs to release reactive power. According to formula (2), the magnitude of PCC voltage U_S is directly proportional to the output of reactive power of inverter, so even if the reactive power voltage $Q'_{\mathrm{PV}} = 0$, the PCC voltage will not exceed the limit. In conclusion, when the residual capacity of inverter does not need no pressure regulating power, namely Q'_{PV}, S_q satisfies formula (7), at next time, the inverter will work in the mode I. The inverter capacity utilisation in Fig. 3*a* shows, the mode of the inverter active power and reactive power output as the reference value:

$$\begin{cases} P_{\mathrm{ref}} = P_{\max}, Q_{\mathrm{ref}} = 0 \\ Q'_{\mathrm{PV}} > 0, S_q^2 = Q_{\mathrm{PV}}^2 \end{cases} \tag{7}$$

When $Q'_{\mathrm{PV}} = 0$, the PCC voltage U_S is:

$$U_s = U_{\max} - \left(\frac{(P_{\max} - P_{\mathrm{PV}})R}{U_0} + XQ_{\mathrm{PV}}\right) \tag{8}$$

(ii) Mode II: if the formula (6) results of Q'_{PV} is less than or equal to 0, the next time that the active power output of photovoltaic power by MPPT, for the PCC voltage adjustment to the upper limit of $U_{\max}$ needs to absorb reactive power of Buck inverter. If the reactive power voltage inverter for photovoltaic maximum power output capacity and the capacity for does not exceed the allowable value of the inverter capacity, namely S_P and S_q meet the formula (9), at next time, the inverter will work in the mode II, the inverter capacity utilisation as shown in Fig. 3*b*, the condition the inverter output active and reactive power reference value as shown in (9). In the formula, the S_q represents the maximum allowable value of the inverter.

$$\begin{cases} Q'_{\mathrm{PV}} < 0 \\ S_{\mathrm{q}}^2 = Q_{\mathrm{PV}}^2 \\ S_p^2 = P_{\max}^2 \\ S_p^2 + S_q^2 \le S_{\max}^2 \\ P_{\mathrm{ref}} = P_{\max} \\ Q_{\mathrm{ref}} = Q'_{\mathrm{PV}} \end{cases} \tag{9}$$

(iii) model III: if the mode II of S_P, the S_q does not meet the inverter capacity constraints that photovoltaic power active power output by MPPT, the reactive power output of Q'_{PV} inverter will exceed the maximum capacity, the residual capacity of the inverter using separate reactive power regulation to PCC voltage to normal range. By formula (2), the size of the U_s and PCC voltage inverter output active power is proportional to the size, in order to make the PCC voltage is adjusted to the normal range, the need to reduce the inverter output active power, excess capacity to absorb reactive power, namely, the next time will be working mode III inverter, inverter capacity utilisation in Fig. 3*c* shown in.

According to the inverter active and control function of priority to ensure the coordination work, and network voltage limit, and the maximum power output of inverter, reactive power output of the minimum, this will be the next time limit voltage value is set to the reference value, the inverter capacity to maximise the utilisation of the active and reactive output reference value calculation formula (10) shown:

$$\begin{cases} U_s = U_0 - \dfrac{(P_L - P_{\mathrm{PV}})R + (Q_L - Q_{\mathrm{PV}})X}{U_0} \\ U_{\max} = U_0 - \dfrac{(P_L - P_{\mathrm{ref}})R + (Q_L - Q_{\mathrm{ref}})X}{U_0} \\ S_P^2 = P_{\mathrm{ref}}^2 \\ S_{\mathrm{p}}^2 = Q_{\mathrm{ref}}^2 \\ S_p^2 + S_q^2 = S_{\max}^2 \end{cases} \tag{10}$$

There are two solutions for the solution of (10) P_{ref} and Q_{ref}, and the reference value solution curve of the active and reactive power output is shown in Fig. 4.

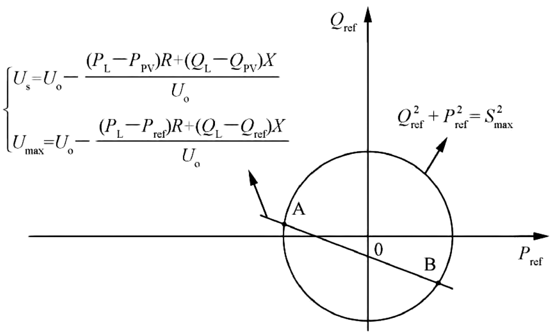

Fig. 4 *Curve for solving active and reactive power output reference value of inverter*

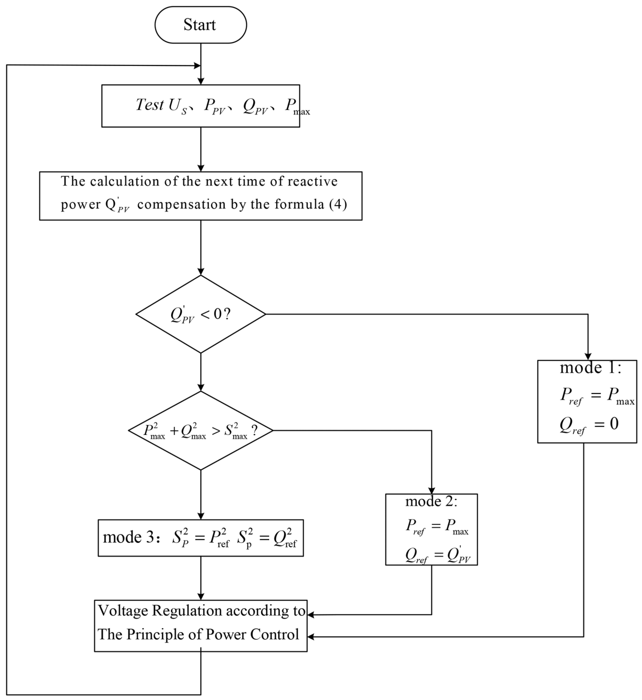

Fig. 5 *Flowchart of active and reactive power coordination control strategy for inverter*

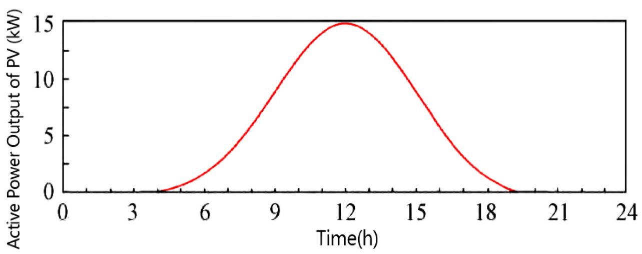

Fig. 6 *Active power output curve of PV in one day*

2.3 Flow chart of active and reactive power coordinated control of inverters

The flow chart of the coordinated control of the active and reactive power of the inverter is shown in Fig. 5. First, the PCC voltage U_S, the active PPV, reactive Q_{PV}, and the maximum active P_{max} of PV MPPT at the next moment are detected. Calculate the next time reactive voltage Q'_{PV} size, and determine the positive and negative, if $Q'_{PV} > 0$ that work in the condition of the inverter, according to (7) calculation of active power and reactive power output reference value; if $Q'_{PV} \leq 0$, and P_{max} and Q'_{PV} in the total capacity of the inverter capacity within the scope of that work in inverter according to the formula (9) the calculation of active power and reactive power output reference value; if Q'_{PV} is less than 0, but the total capacity of P_{max} and Q'_{PV} exceeded the maximum capacity of the inverter, the inverter operates in that condition III, according to (10) calculation of active power and reactive power output reference value. Finally, the inverter power control module is used to adjust the output of the grid connected inverter to track the changes of P_{ref} and Q_{ref} quickly and accurately, and achieve the dynamic regulation of the voltage of the grid.

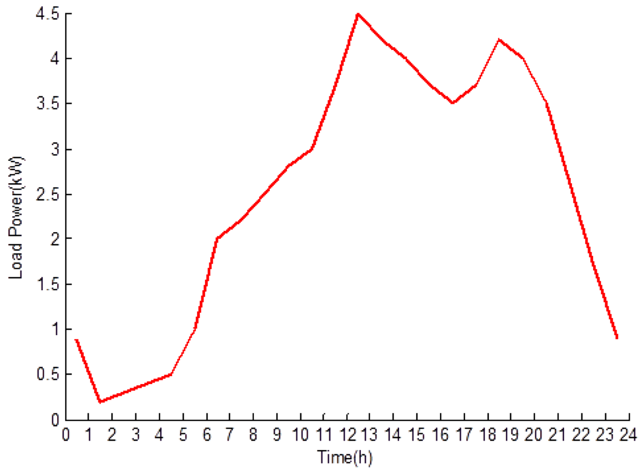

Fig. 7 *Load power information in different periods of day*

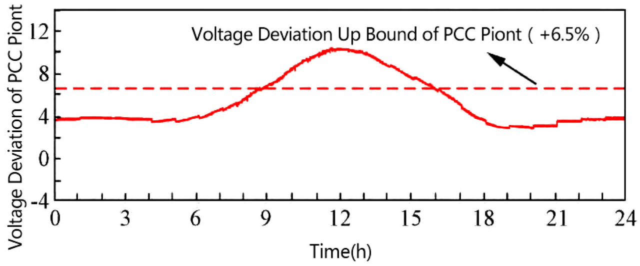

Fig. 8 *PCC voltage deviation without control strategies of inverter*

3 Simulation analysis

Taking Fig. 1 system as an example, a simulation model of a single photovoltaic grid connected system is established in Matlab/Simulink. The system before U_0 is replaced by the 0.4 kV equivalent power supply in Fig. 1, to ensure that the normal voltage side U_0 of the power supply system is maintained at 0.4 kV, and the line impedance is $0.9048 + j0.3144\ \Omega$. In accordance with the provisions of the GB/T12325-2008, 4 kV three-phase power supply system allows the voltage deviation of 7%, in order to increase the safety margin, the upper limit of voltage is set to +6.5%. The maximum active power output curve of a day is shown as shown in Fig. 6. The maximum capacity of the inverter is $S_{max} = 17$ kW. In the hour, the load power in each time period of PCC is counted, as shown in Fig. 7.

The PCC voltage deviation under different control strategies of the inverter is simulated. Fig. 8 is the dynamic process of the PCC voltage deviation in one day without any control, traditional reactive power control, active and reactive power control. Fig. 9 is the power output curve of PV system under coordinated control strategy of active power and reactive power. Fig. 10 is the capacity curve of PV system in active power and reactive power coordinated control strategy in one day. Fig. 11.

From Fig. 8, it can be seen that during the period of 9:00 to 16:00, if the inverter is under any control strategy, due to the large output of photovoltaic power, the PCC voltage will appear the upper limit, and the voltage deviation will exceed +6.5%. Fig. 9 analysis showed that the voltage is limited by the residual capacity of the inverter reactive power regulation strategy, can shorten the time and reduce the voltage limit, but 11:00–14:00 there will still be more voltage limit, because the time is the peak power output of PV output time of day the inverter and the limited capacity of the effective utilisation of capacity of power and pressure is reduced,

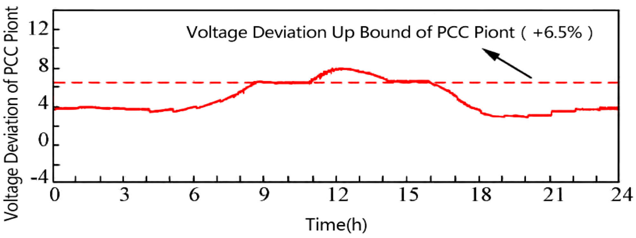

Fig. 9 *PCC voltage deviation with reactive control strategies of inverter*

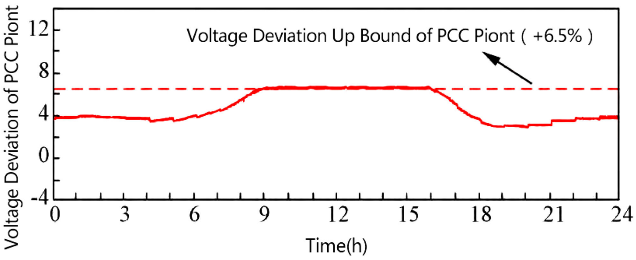

Fig. 10 *PCC voltage deviation with active and reactive power coordination control strategy of inverter*

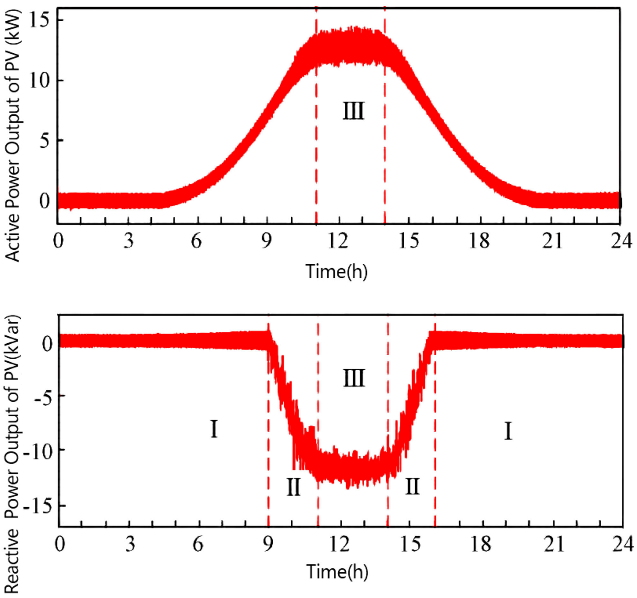

Fig. 11 *Power output curve of PV system under coordination control of active and reactive power*

even if all the remaining capacity for inverter reactive voltage cannot be transferred to within the normal range of PCC voltage. From Fig. 9, we can see that the PCC voltage can be effectively controlled in the normal range using the active and reactive coordination control strategy proposed here to adjust the voltage.

Fig. 8 analysis to Fig. 12 indicates that in the inverter active power and reactive power coordination control strategy, the morning of the 9:00 and 16 in the afternoon, before the period of time after the 00 point voltage is limited, according to the inverter mode I work, the active power output by MPPT, the reactive power output is zero at 9:00–11:00 and in the afternoon 14:00–16:00 during the inverter according to mode II, voltage limit, reactive voltage will call PCC voltage stability at the maximum allowable

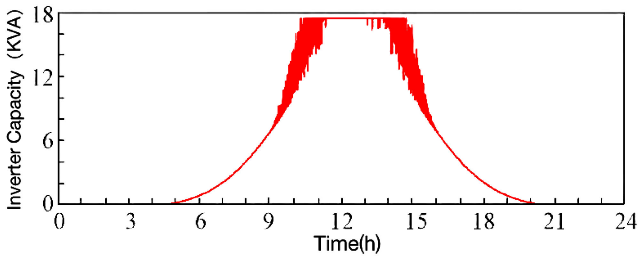

Fig. 12 *Capacity utilisation curve of inverter under coordination control of active and reactive power*

value of the minimum active power output, according to MPPT; 11:00–14:00 during the work according to the mode III of the inverter. In the process of adjusting the pressure, the PCC inverter capacity and voltage stability will always be in the maximum boundary value, so as to ensure the maximum power output of inverter, reactive power output of the minimum.

4 Conclusion

Here, through the analysis of photovoltaic systems and network voltage characteristics, it illustrates influence network voltage deviation factor, and propose a practical voltage regulation method for photovoltaic system that inverter active power and reactive power coordination control strategy. The simulation results show that this method overcomes the traditional inverter voltage and reactive power control strategy shortcomings of limited capacity, and can guarantee the network voltage and meet the requirements of the premise, to achieve maximum utilisation of inverter active power and reactive power optimal output, improve the power efficiency and utilisation rate of photovoltaic system.

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