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Research on Distributed Photovoltaic Grid-connected Voltage Cooperative Control Strategy Considering Local Load

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Abstract The remaining capacity of the photovoltaic inverter has achieved good results in solving the problem of the voltage limit of the grid-connected point of the distributed photovoltaic power generation system. But at present, in order to increase the reactive power capacity of the inverter, related research mainly focuses on limiting the power output of the inverter, without considering the impact on the penetration rate of the distributed photovoltaic power generation system. This paper clarifies the mechanism of the voltage limit of the grid-connected point of the distributed photovoltaic power generation system, and proposes a coordinated control strategy for the voltage of the distributed photovoltaic grid-connected point that takes into account the local load. Use back-to-back converters to control the local load reactive power of photovoltaic power generation, and change the output power of photovoltaic power generation by controlling the working status of the grid-connected inverter. Set up the brake control link. When the limit is exceeded, the local load reactive power control will be given priority to adjust the grid-connected point voltage, thereby avoiding the impact on the photovoltaic power generation capacity of the distribution network. Finally, experiments based on Matlab/Simulink simulation platform verify the feasibility and effectiveness of the proposed control strategy.

Keywords: *PV, grid inverter, local load, voltage limit, brake control*

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1. Introduction

As a large number of distributed photovoltaic power generation systems are connected to the grid, the proportion of photovoltaic power generation capacity in the total system capacity is increasing, and the impact on the power system is gradually increasing. Photovoltaic power generation systems usually need grid-connected inverters to achieve grid-connected operation through low-voltage or medium-voltage distribution networks [1]. Among them, the problem of over-limit voltage at the grid connection point is an important factor affecting the safety and stability of the power grid [2,3]. On the one hand, distributed photovoltaic power generation units do not have the dynamic reactive power support capabilities of traditional generator sets; on the other hand, the grid-connected photovoltaic voltage level will also be affected by changes in the grid's operating status. In recent years, research on the problem of voltage over-limit of the grid-connected point of distributed photovoltaic power generation systems has shown that when the voltage exceeds the limit, providing dynamic reactive power support to the system can effectively improve the degree of voltage over-limit of the grid-connected point and improve the parallelism of distributed photovoltaic power generation systems. The security and stability of the network [4,5,6]. The current research on the problem of photovoltaic grid-connected point voltage exceeding the limit mainly focuses on two aspects: the grid-connected voltage control strategy based on reactive voltage regulating equipment [7] and the grid-connected voltage control strategy based on photovoltaic grid-connected inverters [8,9,10].

Based on the grid-connected voltage control strategy of reactive voltage regulating equipment, some scholars have proposed to divide the time scale and dynamic response performance of various reactive voltage regulating devices, and consider the reactive power replacement between reactive voltage regulating devices. Ensure the system's better dynamic voltage support capability [11]. Although this method can have a strong dynamic support ability in the process of meeting the reactive power demand of the system, the use of fast reactive power compensation devices (such as static var compensator, static var generator) increases the cost of the system, and The voltage regulating capacity of slow-speed voltage regulating equipment (such as on-load regulating transformers, capacitor banks) cannot meet the rapid reactive power requirements of the system. Based on the grid-connected voltage control strategy of the photovoltaic grid-connected inverter, the research mainly focuses on using the remaining capacity of the grid-connected inverter to provide a certain amount of reactive power to the system for voltage regulation. The photovoltaic grid-connected inverter has the ability of fast reactive power compensation, and the utilization of its remaining capacity can reduce the input cost of system reactive power compensation equipment [12]. However, the current research on voltage control of grid-connected inverters does not provide countermeasures when the inverter is insufficiently reactive. In response to this shortcoming, limiting the inverter's output active power can increase the inverter's reactive capacity when the inverter's reactive capacity is limited [13,14]. The above research gives the countermeasures when the reactive power sufficiency of photovoltaic grid-connected inverters is insufficient, but the impact on the penetration rate of distributed photovoltaic power generation systems is not considered, and it is impossible to reduce waste as much as possible on the basis of ensuring reactive power demand. Most of the research is aimed at the distribution network [15], and there are still few researches on the control of photovoltaic grid-connected active output limitation.

Aiming at the deficiencies of the above research, this paper proposes a distributed photovoltaic grid-connected voltage coordinated control strategy that takes into account the local load, which can quickly and effectively solve the problem of grid-connected voltage over-limit and maximize the capacity of photovoltaic power consumption. From the perspective of power system power transmission theory, this paper clarifies the mechanism of voltage over-limit of the grid-connected point of distributed photovoltaic power generation system; back-to-back converters control the reactive power of the local load of the distributed photovoltaic power The working status of the grid-connected inverter is changed, the output power of the distributed photovoltaic power generation is changed, the braking control link is set, and the photovoltaic grid-connected voltage coordinated control strategy is formed; and it is tested and verified in the Matlab/Simulink simulation platform.

2. Analysis of the Mechanism of voltage Over-limit at the Grid Connection Point

The flow of power in the traditional distribution network is from the bus to the load. When the distributed photovoltaic power generation system is connected to the distribution network, if the output of the photovoltaic power generation system is greater than the load of the access point, the excess power will be returned to the distribution network The voltage at the point of common coupling (PCC) of the photovoltaic power generation system suddenly rises. The equivalent circuit of the distributed photovoltaic power generation system connected to the distribution network is shown in Figure 1.

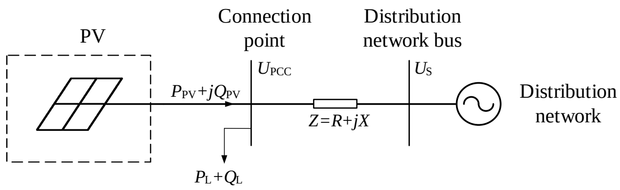

Figure 1. Grid-connected equivalent circuit of distributed photovoltaic power generation system

In Figure 1, P_{PV} and Q_{PV} are the active power and reactive power delivered by the distributed photovoltaic power generation system to the grid connection point respectively; P_L and Q_L are the active power and reactive power of the local load of the photovoltaic grid connection point respectively; U_{PCC} is the grid connection point voltage; Z is the equivalent impedance between the grid connection point and the distribution network bus, where R is the resistance component, X is the reactance component; U_S is the distribution network bus voltage.

When the distributed photovoltaic power generation system is not connected to the distribution network, the grid-connected point voltage U'_{PCC} is:

$$U'_{PCC} = U_S - \frac{P_L R + Q_L X}{U'_{PCC}} \tag{1}$$

When the distributed photovoltaic power generation system is connected to the distribution network, the grid connection point voltage U_{PCC} is:

$$U_{PCC} = U_S + \frac{(P_{PV} - P_L)R + (Q_{PV} - Q_L)X}{U_{PCC}}. \tag{2}$$

Then the voltage change of the grid connection point before and after the distributed photovoltaic power generation system is connected is ΔU:

$$\begin{aligned}\Delta U &= U_{PCC} - U'_{PCC} \\ &= \frac{P_{PV}R + P_{PV}X}{U'_{PCC}} + (P_L R - Q_L X)\left(\frac{1}{U'_{PCC}} - \frac{1}{U_{PCC}}\right).\end{aligned} \tag{3}$$

When the grid connection point voltage exceeds the limit, the output of the photovoltaic power generation system is much greater than the local load power of the grid connection point, then the second term in the above formula is much smaller than the first term and can be ignored, and the voltage change at the grid connection point is obtained as:

$$\Delta U \approx \frac{P_{PV}R + Q_{PV}X}{U'_{PCC}}. \tag{4}$$

It can be seen from formula (4) that the grid connection point voltage is affected by factors such as the impedance parameters of the transmission line, the voltage of the distribution network, the local load power and the output power of photovoltaic power generation. The initial investment cost of improving the impedance parameters of transmission lines is huge [1], and its economy is poor; directly reducing the output of photovoltaic power generation is also contrary to the economy. Therefore, adopting the coordinated control strategy of adjusting the local load power of the photovoltaic grid-connected and changing the working state of the grid-connected inverter can effectively reduce the occurrence of voltage over-limit phenomenon at the grid-connected point and maximize the consumption of photovoltaic power generation by the distribution network ability.

3. Analysis of Cooperative Control Strategy

In this paper, back-to-back converters are used to control the local load reactive power of distributed photovoltaic power generation systems to adjust the grid-connected point voltage; by controlling the working status of the distributed photovoltaic power generation system grid-connected inverters, the output power of distributed photovoltaic power generation is changed , And set up a braking link to form a coordinated control strategy for grid-connected point voltage. This control strategy makes the control mode and operation mode of the system not be affected by the access of distributed photovoltaic power generation system. The grid-connected topology of distributed photovoltaic power generation system with local load is shown in Figure 2.

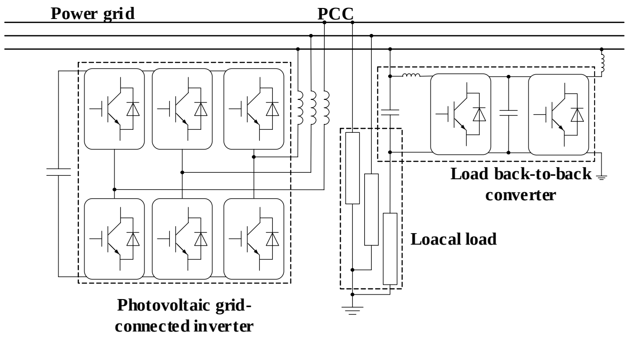

Figure 2. Grid-connected topology of distributed photovoltaic power generation system with local load

3.1. Local Load Reactive Power Control

In the actual distribution network, the power load that allows wide voltage range input can be defined as non-critical load [16], such as household appliances such as water heaters and lights. Select non-critical loads in the local load of the distributed photovoltaic power generation system and use back-to-back converters to control them to adjust U_{PCC}. The back-to-back converter system consists of two voltage source PWM converters connected in a back-to-back manner by means of intermediate DC energy storage capacitors. One converter works in rectification state, and the other The converter works in the inverter state and realizes the power exchange between the AC systems on both sides together. The circuit structure of the back-to-back converter in series with the local load is shown in Figure 3. Among them, the DC energy storage capacitor C acts to provide DC voltage support and reduce the DC side harmonics; the AC side inductance L acts on the converter and the AC grid to achieve energy exchange and filter out the harmonics in the current; C_f and L_f The low-pass filter acts to filter out high-frequency signals. U_{NC} and I_{NC} are the voltage across the local load and the current flowing through the local load, respectively.

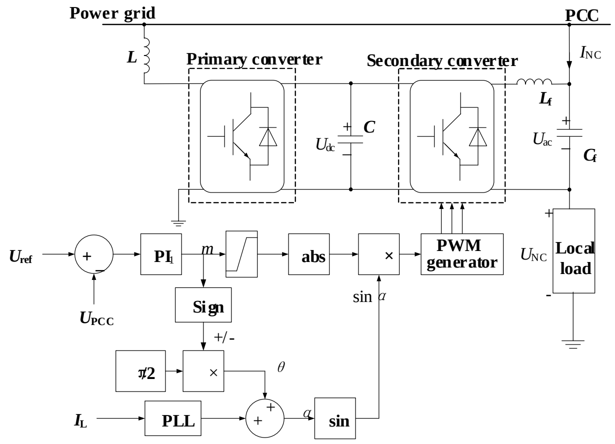

Figure 3. Control block diagram of local load back-to-back converter

As a rectifier, the primary converter uses the unit power factor voltage stabilization control loop [17] used by ordinary rectifiers to convert the AC voltage of the distribution network into a stable DC voltage $\boldsymbol{U}_{dc}$ and realize the input of the secondary converter Unit power factor control on the side. The secondary converter acts as an inverter, and realizes real-time control of the amplitude and phase of the AC side voltage $\boldsymbol{U}_{ac}$ according to the difference between the U_{PCC} and the grid-connected point voltage setting U_{ref} (U_{PCC} deviation value), thereby realizing no local load Flexible control of work power makes U_{PCC} stable within the allowable range. The vector relationship of each voltage in Figure 3 can be expressed as:

$$\mathbf{U}_L = \mathbf{U}_{ac} + \mathbf{U}_{NC} \tag{5}$$

$\boldsymbol{U}_{NC}$ is the grid-connected point voltage U'_{PCC} before the back-to-back converter participates in regulation, and $\boldsymbol{U}_L$ is the grid-connected point voltage after the back-to-back converter participates in regulation. The back-to-back converter participates in the control of the reactive power of the local load, so the $\boldsymbol{U}_{ac}$ generated by it is orthogonal to the I_{NC}. The phase difference θ of $\boldsymbol{U}_{ac}$ leading the $\boldsymbol{I}_{NC}$ needs to be controlled to -90°/90°, as shown in Figure 4. Among them, λ is the impedance angle of the local load.

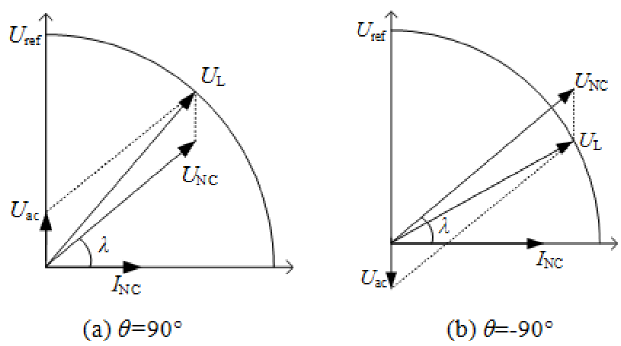

Figure 4. Local load voltage control phasor relationship

Acording to formula (5) and Figure 4, we can see that in order to adjust the voltage level of U_{PCC} to U_{ref} in real time, the U_{PCC} is monitored in real time through the measuring device, and then the amplitude of $\boldsymbol{U}_{ac}$ is dynamically changed according to the deviation of U_{PCC}, and the amplitude of $\boldsymbol{U}_{ac}$ should be deviated from U_{PCC}. The absolute value of is proportional, and the angle of phase difference θ (-90° or 90°) is switched according to the positive or negative of the U_{PCC} deviation value.

Therefore, the control of $\boldsymbol{U}_{ac}$ amplitude and phase difference θ is studied, and the corresponding control loop is designed, as shown in Figure 3. Taking the voltage stabilization control model in [17] as a reference, as a regulator that can take into account both transient performance and steady-state performance, PI regulator can be used to control the Uac amplitude. The difference between UPCC and Uref is sent to the PI regulator, the value of θ depends on the sign of the output value m of the PI regulator; the post-limiting link of the PI regulator is used to limit the size of m; abs is the absolute value function; The phase locked loop PLL is used to determine the phase angle of I_{NC}, and α is the sum of the phase angle of I_{NC} and θ.

3.2. Distributed Photovoltaic Grid-connected Inverter Control

Although the above-mentioned local load reactive power control has good flexibility for solving the U_{PCC} over-limit problem and can respond quickly, usually the number of non-critical loads in the local load and its adjustable reactive power capacity are limited. Therefore, it is necessary to limit the output of photovoltaic power generation by changing the working state of the photovoltaic grid-connected inverter, and further control U_{PCC}, as shown in Figure 5. In order to avoid reducing the utilization rate of distributed photovoltaic power generation, and to ensure that the local load reactive power control is preferentially adopted when the U_{PCC} exceeds the limit so as to obtain greater economic efficiency, a brake control link is designed in the inverter control loop of Figure 5. When the U_{PCC} deviation value is relatively small relative to the upper limit of the grid-connected point voltage, the local load reactive power control adjustment U_{PCC} takes priority, which can avoid the reduction in the output of the photovoltaic power generation system and affect the distribution network's ability to absorb distributed photovoltaic power generation.

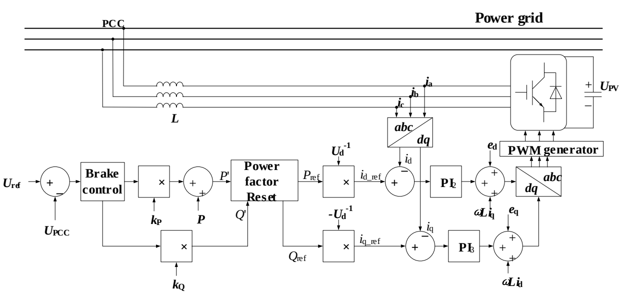

Figure 5. Local load voltage control phasor relationship

The braking link is mainly composed of Schmitt circuits with output in the same direction. When the U_{PCC} exceeds the limit, different threshold voltages are used during the voltage rise and fall. The forward threshold voltage U_{T1} is greater than the reverse threshold voltage U_{T2}. When the U_{PCC} deviation value is less than U_{T1}, the grid-connected inverter control is in the braking range, and the local load reactive power control takes priority, and the local load absorbs reactive power to effectively stabilize the U_{PCC}. If the U_{PCC} deviation value still reaches U_{T1} under the influence of the local load reactive power control participating in the adjustment, it indicates that the U_{PCC} cannot be effectively adjusted by relying solely on the local load reactive power control. At this time, the grid-connected inverter control takes effect, limiting the distributed photovoltaic power generation system The output power stabilizes U_{PCC}. When the U_{PCC} deviation value is less than U_{T2}, the grid-connected inverter control re-enters the braking range, and only the local load reactive power control regulation takes effect.

When the distributed photovoltaic power generation system is connected to the grid through the converter, the grid-connected inverter usually works in the state of unit power factor inverter, and the given value of the grid-connected inverter output reactive power is zero [1]. When the grid connection point voltage exceeds the limit and the output of the distributed photovoltaic power generation system needs to be limited, the given value of reactive power can be adjusted to change the working mode of the inverter to achieve the purpose of effectively adjusting the U_{PCC}. If the power factor range of the grid-connected inverter is:

$$n \le \cos\varphi \le 1. \tag{6}$$

Suppose that the active power output limit is performed when U_{PCC} reaches U_P, and the inverter outputs the maximum reactive power when U_{PCC} reaches U_Q. Taking into account the droop characteristics of the power factor, the power factor of the grid-connected inverter varies with U_{PCC} as shown in Figure 6.

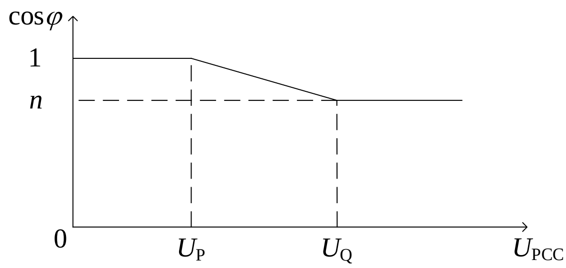

Figure 6. Power factor change curve

Assuming that the output active power of the grid-connected inverter is P and the apparent capacity is S, the maximum value Q_m of the reactive power that can be output is:

$$\begin{cases} Q \le \sqrt{S^2 - P^2} \\ Q_m = \sqrt{S^2 - P_m^2} \end{cases}. \tag{7}$$

In the formula, Pm is the maximum active power output by the distributed photovoltaic power generation system according to the maximum power tracking. Therefore, the reference value for the grid-connected inverter to absorb reactive power varies with voltage as follows:

$$Q=\begin{cases}0 & U_{\mathrm{PCC}}<U_{\mathrm{P}}\\ Q_{\mathrm{m}}\left(U_{\mathrm{PCC}}-U_{\mathrm{P}}\right)\left(U_{\mathrm{Q}}-U_{\mathrm{P}}\right)^{-1} & U_{\mathrm{P}}\le U_{\mathrm{PCC}}\le U_{\mathrm{Q}}\\ Q_{\mathrm{m}} & U_{\mathrm{PCC}}>U_{\mathrm{Q}}\end{cases}. \quad (8)$$

The control loop of the distributed photovoltaic grid-connected inverter is shown in Figure 5, which adopts the dual closed-loop control method of power and current. Calculate the reference value of reactive power absorption according to the real-time U_{PCC} limit value and voltage-power droop characteristics. At the same time, the U_{PCC} limit value is multiplied by the adjustment coefficient and added to the real-time power of the photovoltaic output to obtain the grid-connected inverter control The set value of the output power in the process:

$$\begin{cases}P^{'}=P+k_{\mathrm{P}}\left(U_{\mathrm{ref}}-U_{\mathrm{PCC}}\right)\\ Q^{'}=k_{\mathrm{Q}}\left(U_{\mathrm{ref}}-U_{\mathrm{PCC}}\right)\end{cases} \quad (9)$$

In the formula, kP and kQ are the control coefficients of active power and reactive power respectively.

Determine the power factor according to the power factor range:

$$\cos\varphi=\begin{cases}\cos\varphi & n\le\cos\varphi\le 1\\ n & 0\le\cos\varphi\le n\end{cases}. \quad (10)$$

From this, the current reference value on the d-q coordinate axis can be obtained, so as to realize the adjustment of U_{PCC}.

4. Case Analysis

In order to verify the feasibility and effectiveness of the proposed control strategy, this paper builds a model of distributed photovoltaic power generation system with local load connected to the distribution network in the Matlab/Simulink simulation platform. The distribution network structure is shown in Figure 7. The line voltage level is 380V, and the highest voltage allowed by the distribution network is 1.05UN, and U_N is the rated voltage. In the calculation example, the voltage setting value U_{ref} of the grid connection point is U_N. Set 65kW constant power loads on the line to replace users. The photovoltaic grid-connected control part is built as shown in Figure 7, and the control parameters are shown in Table 1.

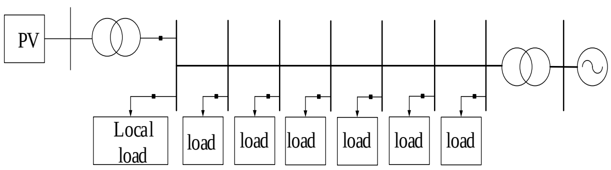

Figure 7. Example of distribution network topology

The output power of the distributed photovoltaic power generation system is shown in Figure 8. Between 10s and 90s, the output of the distributed photovoltaic power generation system increases sharply. The simulation results of the voltage level of the grid-connected point without adopting the control strategy are shown in Figure 9. The photovoltaic power output is low in 0-10s, and U'PCC remains near UN; in 10s-40s, due to the increase in photovoltaic output, The U'PCC increased, but the voltage remained within the normal range; after 40s, U'PCC exceeded the limit (1.05pu).

Table 1. Font Sizes for Papers

Local load Reactive power control	Filter inductor L	2mH
	DC side capacitor C	6800uF
	Low pass filter inductor L_f	1uH
	Low-pass filter capacitor C_f	10uF
	DC side voltageU_{dc}	200V
	Non-critical loadimpedance Z_{NC}	10+j5.7735
PV grid-connected Inverter control	Grid-connected inverter capacity	40kVA
	Power factor range$n$	0.9
	Forward threshold voltageU_{T1}	0.03UN
	Reverse threshold voltageU_{T2}	0.01UN
	Operating voltageU_P	1.025UN
	Operating voltageU_Q	1.045UN
	Active power control factor k_P	8
	Reactive power control factor k_Q	5

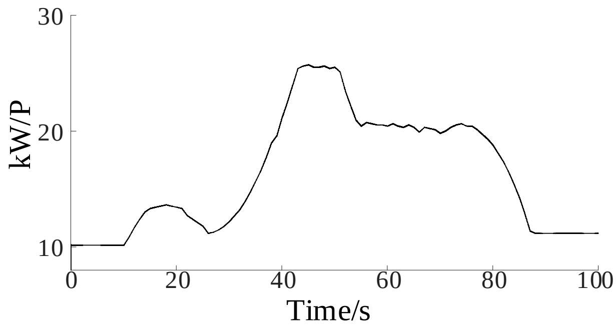

Figure 8. Distributed photovoltaic output power

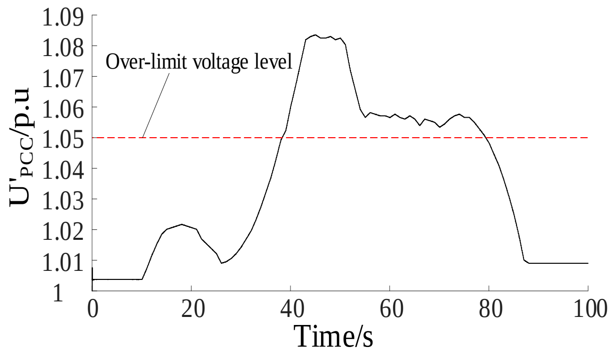

Figure 9. No control strategy is adopted for photovoltaic grid-connected point voltage

The simulation result of U_{PCC} after adopting local load reactive power control is shown in Figure 10. When the output of photovoltaic power generation increases suddenly, U_{PCC} decreases to a certain extent. However, at 40s, U_{PCC} still has overrun. In order to verify the feasibility and effectiveness of the collaborative control strategy proposed in this paper, when the U_{PCC} deviation reaches the U_{T1} level, the distributed photovoltaic grid-connected inverter control is performed to change its working state to limit the output power of photovoltaic power generation; when the U_{PCC} deviation value When it drops to the U_{T2} level, exit the photovoltaic grid-connected inverter control, restore the maximum output of distributed photovoltaic power generation, and avoid the impact on the photovoltaic power generation capacity of the distribution network.

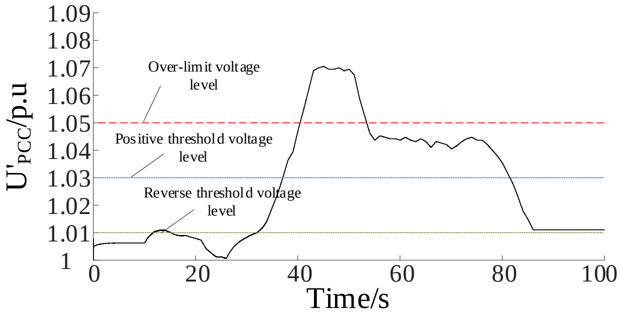

Figure 10. Local load reactive power control photovoltaic grid-connected point voltage

Under the same test environment, the simulation results of the grid-connected point voltage with the coordinated control strategy are shown in Figure 11. At 38s, when the local load reactive power control participates in the regulation, the U_{PCC} deviation value still reaches U_{T1}. At this time, the photovoltaic grid-connected inverter control takes effect and limits the photovoltaic power output. At 61s, the U_{PCC} deviation value is less than U_{T2}, and the grid-connected inverter control re-enters the braking range, and only the local load reactive power control regulation takes effect. At 73s, the U_{PCC} deviation value reaches UT1 again, and the grid-connected inverter control takes effect, stabilizing U_{PCC}. In the 100s test, U_{PCC} was always within the allowable range of normal operation, which verified the feasibility and effectiveness of the distributed photovoltaic grid-connected point voltage coordinated control strategy in this paper.

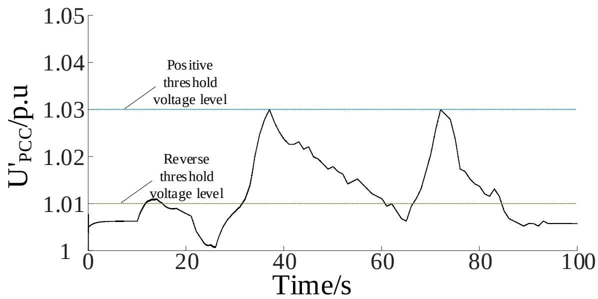

Figure 11. PV grid-connected point voltage

5. Conclusion

This paper clarifies the mechanism of the voltage limit of the grid-connected distributed photovoltaic power generation system, and proposes a distributed photovoltaic grid-connected voltage coordinated control strategy that takes into account the local load. Both the grid-connected photovoltaic local load and the grid-connected inverter can participate in the regulation of the grid-connected point voltage, and the reactive power of the local load can be controlled through the back-to-back converter; the photovoltaic power output can be restricted by controlling the working state of the photovoltaic grid-connected inverter. The use of a coordinated control strategy of braking control can quickly and effectively solve the problem of voltage over-limit at the grid connection point, and avoid the impact on the photovoltaic power generation capacity of the distribution network. Finally, simulation experiments verify the feasibility and effectiveness of the proposed control strategy.

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