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Voltage prevention and emergency coordinated control strategy for photovoltaic power plants considering reactive power allocation

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ABSTRACT

This paper proposes a voltage prevention and emergency control strategy that consists of coordinately arranging multiple reactive power sources in order to handle the point of common coupling (PCC) voltage fluctuation and stability in large-scale PV power plants. When a disturbance occurs at the PCC, dynamic reactive power compensation devices are coordinated preferentially to support the PCC voltage. After the disturbance is cleared, the reactive power in dynamic and fast devices is transferred into static and slow devices so that the static VAR generation (SVG) can maintain a large power margin for coping with the next disturbance. Moreover, the reactive power output of the individual inverter in PV power plants is coordinately allocated using a model to optimize the in-station voltage distribution. Finally, the effectiveness of the proposed control strategy is verified by an example simulation of a practical large-scale PV power plant.

1. Introduction

With the cost of PV power plants continuously decreasing worldwide because of falling component average selling prices, the construction of large-scale PV power plants is appreciated by governments. Compared with small and medium-scale PV systems, large-scale PV power plants utilize solar energy resources more effectively [1,2]. However, since the random fluctuation of the output power and the lack of reactive power support at the PCC usually cause a large variable range of the PCC voltage [3–5], the large PV power plants are commonly forced to equip themselves with voltage and reactive power control systems.

Under the current technical conditions, an inverter can realize decoupling control of active and reactive power, so reactive power can be adjusted dynamically [6]. PV enterprises usually make the inverters operate in unity power factor mode to maximize economic benefit. If the reactive power output of the inverters can be fully utilized, the cost of dynamic reactive power compensation devices can be greatly reduced [7].

Several control methods for inverters and PV power plants have been presented. In Ref. [8], a simplified reactive power control strategy for single-phase grid-tied PV inverters was proposed, and a 1-kVA single-phase PV inverter was built to verify the performance of the strategy. In Ref. [9], a new high-efficiency transformerless topology was proposed for grid-tied PV systems with reactive power control, and the proposed topology could inject reactive power into the utility grid without any additional current distortion or leakage current. The above research provides a theoretical and practical basis for inverters to participate in reactive power and voltage control of PV power plants. In Ref. [10], a reactive power flow control pursuing the active integration of PV systems in LV distribution networks was proposed. In Ref. [11], two new reactive power control methods that exploit the networked approach were presented. The above research solves the overvoltage issue in distribution networks using reactive power control for PV systems. The authors in Refs. [12–14] proposed control solutions to enhance the fault ride-through capability for PV power plants. In Ref. [15], a novel DVS capability as a function of PV inverters that uses both active and reactive power injection to improve the short-term voltage stability was proposed. However, the above researchers did not consider the coordination of different reactive power sources in a PV power plant.

This paper proposes a voltage prevention and emergency control strategy for PV power plants by coordinately arranging multiple reactive power sources. The reactive power in the dynamic and fast devices is transferred into the static and slow devices so that the strategy maximizes the ability of SVG reactive power. Moreover, the reactive power optimization problem is transformed into a nonlinear programming model with constraints. After solving the model, the reactive power output of every inverter is obtained, and the optimal allocation of reactive power among the inverters is realized.

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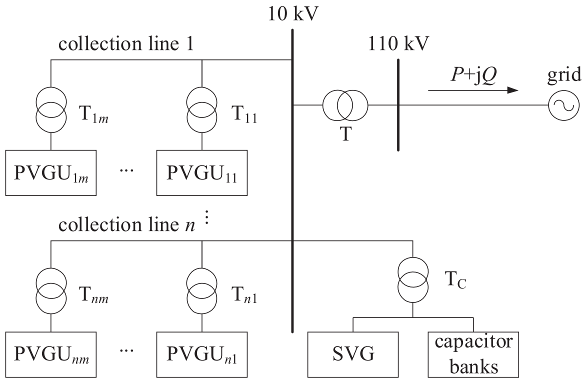

Fig. 1. Topology of a large-scale PV power plant.

2. Voltage characteristics of a PV power plant

A large-scale PV power plant is composed of PV generation units (PVGUs). Since PV arrays occupy a large land area, the distance among PVGUs is far, and the impedance of collection lines cannot be ignored. The voltage distribution characteristics provide a theoretical basis for formulating a reactive power allocation scheme.

2.1. Topology of a PV power plant

The common topology of a large-scale PV power plant is shown in Fig. 1. There are n collection lines in the PV power plant, and every collection line has m PVGUs.

A PVGU is composed of PV arrays, an inverter, and a grid-tied controller. The electric power is fed into collection lines through local transformers and then transmitted outwards through the main transformer [16]. The SVG and the capacitor banks are connected to the 10 kV bus through the transformer T_C. The 10 kV bus is the PCC, and it is also the voltage control point. In Fig. 1, T_{nm} is the local transformer configured for the PVGUs, and T_C is the transformer configured for the reactive power compensation devices. T is the main transformer of the PV power plant, and $P + jQ$ is the external transmission power of the PV power plant.

2.2. Voltage distribution characteristics of a PV power plant

An equivalent model of a large-scale PV power plant is shown in Fig. 2, where $P_i + jQ_i$ is the output power of the ith PVGU, jQ_C is the reactive power output of the reactive power compensation devices, Z_i is the collection line impedance between the ith and $i - 1$th PVGU, Z_{Ti} is the equivalent impedance of the ith local transformer, U_{iL} and U_{iH} are the low and high side voltages of the ith local transformer, respectively, U_{PCC} is the low side voltage of the main transformer, and U is the grid voltage.

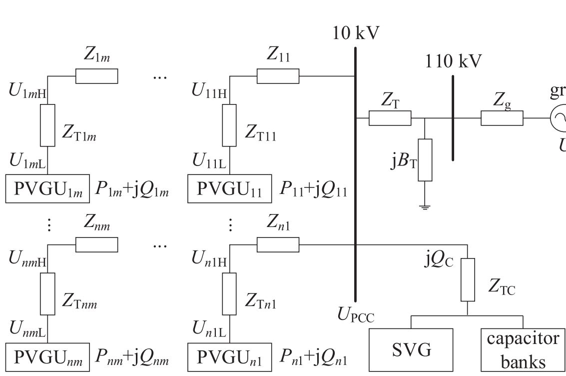

Fig. 2. Equivalent model of a large-scale PV power plant.

2.2.1. PCC voltage of a PV power plant

Taking grid voltage U as the benchmark, the PCC voltage of a PV power plant can be approximated as

$$U_{PCC} \approx U + \frac{(\sum P_i - \Delta P)R_g + (\sum Q_i + Q_C - \Delta Q)X_g}{U} \tag{1}$$

where ΔP and ΔQ are the active and reactive power losses of the main transformer, local transformers and collection lines. $Z_g = R_g + jX_g$ is defined as the Thevenin equivalent impedance of the external grid as seen from the PV power plant terminal.

The PCC voltage is related to grid voltage, the output power of the PVGUs, the output power of the reactive power compensation devices, the Thevenin equivalent impedance of the external grid and all kinds of losses. When the PCC voltage fluctuates, reactive power ΣQ_i and Q_C can be adjusted to support it.

2.2.2. Terminal voltage of the PVGUs

Due to the same collection line structure, take the first collection line as an example. The ith PVGU port voltage U_{iL} is

$$\begin{cases} U_{iL} = \frac{P_i R_{Ti} + Q_i X_{Ti}}{U_{iH}} + U_{iH} \\ U_{iH} = \frac{\left(\sum_{k=i}^{1m} P_k\right) R_i + \left(\sum_{k=i}^{1m} Q_k\right) X_i}{U_{(i-1)H}} + U_{(i-1)H} \\ U_{11H} \approx U_{PCC} \end{cases} \tag{2}$$

where $Z_{Ti} = R_{Ti} + jX_{Ti}$ and $Z_i = R_i + jX_i$.

The PVGU terminal voltage is related to the PCC voltage, the location of PVGUs at the collection lines, the impedance of the collection lines and the output power of the PVGUs.

Taking a 10 × 10 PV power plant as an example, the simulation model consists of 10 collection lines. Every collection line consists of 10 PVGUs, and the 1th PVGU is the closest to the PCC. The PCC voltage of the PV power plant is shown in Fig. 3. It shows that the PCC voltage is positively correlated with the active and reactive power, where the reactive power is dominant.

The terminal voltage distribution of the PVGUs is shown in Fig. 4. With the increase in active power, the PVGU terminal voltage increases. For one of the collection lines, the 1th PVGU port voltage is the minimum and close to the PCC voltage. The port voltage increases gradually along the direction of the collection lines. When the active power output of the PV power plant is large, a voltage over-limit is likely to occur at the end of the collection lines.

2.3. Reactive power capacity of the PV inverter

The reactive power capacity of a PV inverter is limited by its apparent power. If the active power output of the inverter increases, the reactive power capacity will be reduced accordingly. Since the inverter can work at 1.1 times the apparent power in a short time, the relationship between the active power output and the reactive power output of the ith inverter is

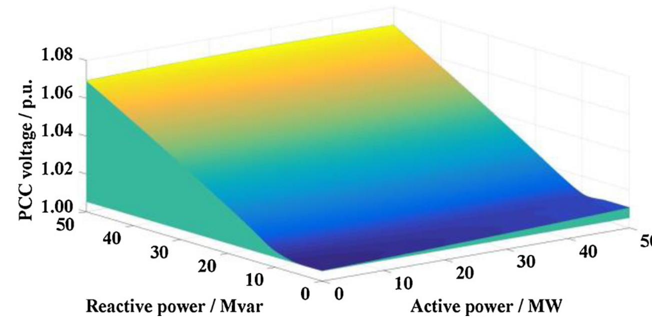

Fig. 3. PCC voltage of a PV power plant.

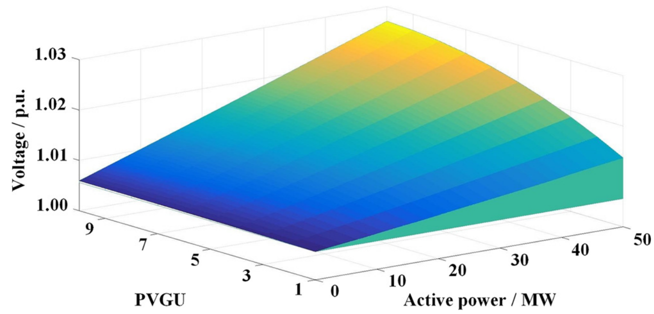

Fig. 4. Terminal voltage distribution of the PVGUs.

$$P_i^2 + Q_i^2 \le (1.1S_i)^2 \tag{3}$$

The reactive power output range of the *i*th inverter is

$$-\sqrt{(1.1S_i)^2 - P_i^2} \le Q_i \le \sqrt{(1.1S_i)^2 - P_i^2} \tag{4}$$

When $P_i = 1$ p.u. and the PV inverter needs output reactive power in a short time, according to formula (4), $Q_{i\max} = 0.458$ p.u. It can be seen that Q_i still retains a certain reactive power margin.

When $P_i = 1$ p.u. and the PV inverter needs output reactive power in a long time, the reactive power output range of the *i*th inverter is

$$-\sqrt{S_i^2 - P_i^2} \le Q_i \le \sqrt{S_i^2 - P_i^2} \tag{5}$$

To ensure that Q_i retains a certain reactive power margin, it is necessary to limit the size of P_i. P_i is usually reduced to 0.9 p.u., according to formula (5), and $Q_{i\max} = 0.436$ p.u.

2.4. Output characteristics of the SVG and capacitor banks

The basic principle of SVG is to regulate the amplitude and phase of the bridge circuit AC side voltage to output the required reactive current, thus achieving the reactive power compensation effect. When the fundamental component of the inverter output voltage is less than the system voltage, the SVG absorbs the reactive power from the system. When the fundamental component of the inverter output voltage is greater than the system voltage, the SVG outputs reactive power to the system. When the fundamental component of the inverter output voltage is equal to the system voltage, the SVG works in a zero reactive power state. Therefore, the reactive power provided by the SVG can be continuously adjusted from positive to negative. The SVG has the advantages of fast response, good reactive power compensation, wide operation range, less harmonic content and less space occupation, but its investment and operation costs are relatively high.

The capacitor banks can only provide inductive reactive power step by step. When the system has excess reactive power, it can only be adjusted by removing the capacitor banks. The reactive power provided by the capacitor banks is proportional to the square of the node voltage. When the node voltage drops, the reactive power is reduced, and the capacitor banks can not be start and cut off frequently to respond quickly to the dynamic changes of system's reactive power demand. Therefore, it is difficult to realize the dynamic compensation of reactive power. However, the capacitor banks are still the main device for the static compensation of reactive power because of their low cost, convenient maintenance, and flexible installation.

3. Voltage prevention and emergency coordinated control strategy

3.1. Overall framework

The aim of the control strategy is to realize reactive power coordinated control among the SVG, inverters and capacitor banks in the large-scale PV power plant. The strategy ensures that the voltage operates at the optimum level under normal conditions. When a disturbance occurs at the PCC, dynamic reactive power compensation devices are coordinated preferentially to support the PCC voltage. When the disturbance is cleared, by the orderly replacement of dynamic (or fast) and static (or slow) reactive power, the SVG can maintain a large reactive power margin to cope with the next possible disturbance.

After calculating the total reactive power response of the inverters, according to the sensitivity information and the PVGU terminal voltage, the minimum in-station PVGU terminal voltage variance is optimized. Thereby, the reactive power output of every inverter is determined, and the in-station voltage distribution is optimized.

This paper presents a voltage prevention and emergency coordinated control strategy, as shown in Fig. 5. The strategy consists of state measurement and calculation, voltage emergency and preventive coordinated control, and in-station reactive power optimization allocation processes.

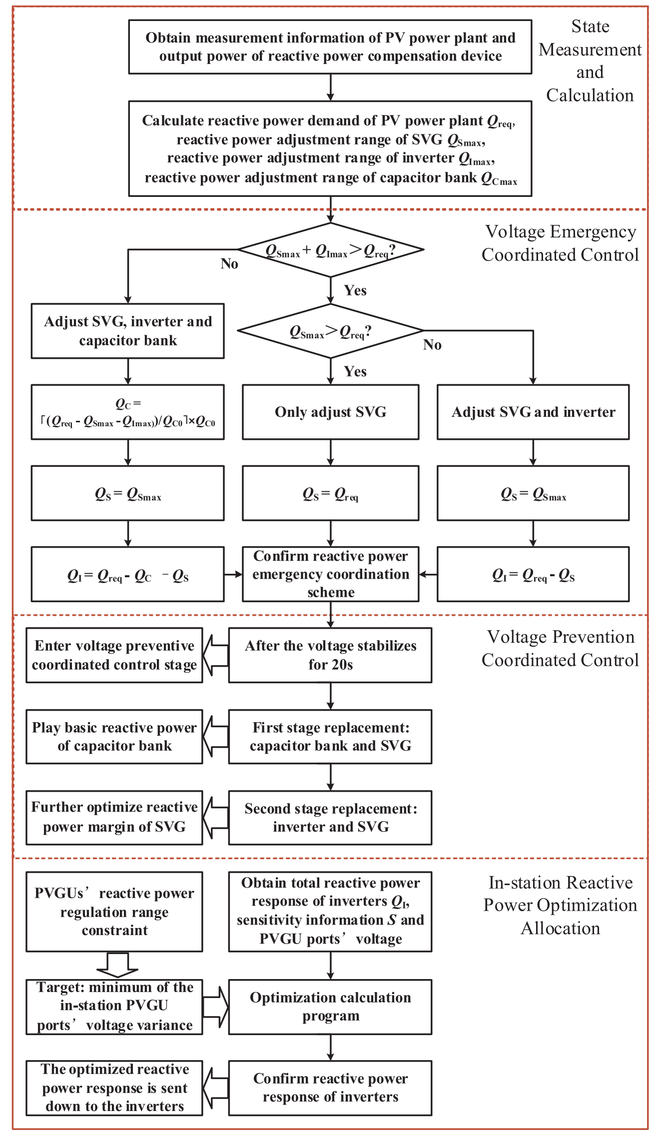

Fig. 5. Overall framework of the control strategy.

3.2. State measurement and calculation

On the short time scale, the light intensity received by a large-scale PV power plant does not mutate, external grid operation mode does not change much, and the line parameters (including transformer parameters) are fixed. Therefore, the PV power plant reactive power demand can be estimated by measuring the voltage at present. The PV power plant reactive power demand Q_{req} is

$$Q_{req} = \delta(Q, P, U)(U_{PCCref} - U_{PCCmeas}) \tag{6}$$

where U_{PCCref} is the PCC voltage control reference value. $U_{PCCmeas}$ is the PCC voltage measured value at present. $\delta(Q,P,U)$ is the regulation characteristic coefficient considering the influence of Q, P and U on U_{PCC}, which is obtained by off-line simulation. $\delta(Q,P,U)$ is approximately a constant under the certain conditions of the Q, P and U. The dimension of $\delta(Q,P,U)$ is (reactive power) × (voltage)$^{-1}$.

The reactive power compensation device is limited by its own capacity. By obtaining the real-time output operation status, the reactive power regulation range of the SVG Q_{Smax}, the inverter Q_{Imax}, and the capacitor bank Q_{Cmax} can be calculated. The reactive power and voltage control system coordinates multiple reactive power sources through the above information.

3.3. Voltage emergency coordinated control

Voltage emergency coordinated control refers to the consideration of the output characteristics of the multiple reactive power sources and the strategy coordinate reactive power for every device, in order to realize emergency control of the transient voltage stability.

1) When the SVG reactive power margin is sufficient and only the SVG assumes the reactive power demand, the reactive power response of the SVG is

$$Q_S = Q_{req} \tag{7}$$

2) When the SVG reactive power margin is insufficient, but the sum of the SVG and inverter reactive power margin can satisfy the reactive power demand of the PV power plant, the SVG and the inverters jointly assume the reactive power demand. The SVG outputs maximum reactive power.

$$Q_S = Q_{Smax}$$

The remaining reactive power demand is assumed by the inverters. The total reactive power response of the inverters is

$$Q_I = Q_{req} - Q_S \tag{9}$$

3) When the sum of the SVG and inverter reactive power margin is insufficient, the SVG, inverters and capacitor banks jointly assume the reactive power demand. By determining the number of capacitor banks used, their reactive power can be calculated.

$$Q_C = \lceil (Q_{req} - Q_{Smax} - Q_{Imax})/Q_{C0} \rceil \times Q_{C0} \tag{10}$$

where $\lceil (Q_{req} - Q_{Smax} - Q_{Imax})/Q_{C0} \rceil$ is the number of capacitor banks used. Since the capacitor banks can only be used in groups, the calculated number should be rounded up. The remaining reactive power is adjusted by the inverters. Q_{C0} is the capacity of one capacitor bank.

The SVG outputs maximum reactive power, and the remaining reactive power is adjusted by the inverters. The total reactive power response of the inverters is

$$Q_I = Q_{req} - Q_C - Q_S \tag{11}$$

3.4. Voltage preventive coordinated control

Voltage preventive coordinated control refers to the preventive state after the disturbance is cleared. The SVG maintains the optimal reactive power margin by replacing the reactive power among the multiple reactive power sources in order to realize preventive control of the transient voltage stability.

After the voltage stabilizes for 20 s, the strategy enters the voltage preventive coordinated control process. Considering the output characteristics of a reactive power compensation device, the first stage replacement is operated between static reactive power (capacitor bank) and dynamic reactive power (SVG), whereas the second stage replacement is operated between slow reactive power (inverter) and fast reactive power (SVG).

Taking the middle position of the SVG output as the optimal operation point, at the optimal operation point, the SVG has the largest positive and negative reactive power adjustment range. The forward deviation of the SVG from the optimum operating point before the first stage replacement is Q_{Sd1}. Checking that the PCC voltage is not exceeded, find the capacitor bank that satisfies Eq. (12).

$$\begin{cases} \max\{nQ_{C0}\} \le Q_{Sd1} \\ \text{s.t.} \quad n \le n_C \\ \quad U_{mea} + nQ_{C0}S_C \le U_{up} \end{cases} \tag{12}$$

where n is the number of capacitor banks to be entered, and n_C is the number of capacitor banks that have the potential to be entered. U_{mea} is the real-time measurement of the PCC voltage. U_{up} is the PCC voltage upper-limit, and S_C is the sensitivity of the capacitor banks to the PCC voltage.

If there are n capacitor banks that can be entered, then they must be entered. Under the action of the voltage closed-loop control, the reactive power output of the SVG is reduced, and the reactive power margin of the SVG is increased. The first stage replacement process ends.

Since the capacitor bank can only be switched by groups and the number of switching times is limited during a period of time, the first stage replacement cannot reach the optimum. Therefore, it is necessary to use the second stage replacement to further optimize the SVG reactive power margin. When the first stage replacement is complete, the forward deviation from the optimum SVG operating point is Q_{Sd2}. The total reactive power increment response of the inverters ΔQ_I is

$$\Delta Q_I = Q_{Sd2} \tag{13}$$

After the inverter increases the reactive power, the reactive power output of the SVG is further reduced, and the reactive margin of the SVG is optimized. The second stage replacement process ends.

3.5. In-station reactive power optimization allocation

If the voltage at the end of the collection lines is too high, when the grid voltage fluctuates, the relay protection device will act. In this paper, the reactive power response of every PVGU is optimized. According to the in-station voltage distribution information, the reactive power output of every PVGU is adjusted in real time. While ensuring the reactive power response of the PV power plant, every PVGU terminal voltage difference is minimized to optimize the in-station voltage distribution.

According to sensitivity information, ignoring the effect of active power fluctuation on voltage, the ith PVGU terminal voltage may be approximately expressed as

$$U_i \approx U_I + \sum_{j=1}^{n} S_{ji} Q_j \tag{14}$$

where n is the number of in-station PVGUs, and U_i and U_I are, respectively, the ith PVGU terminal voltage after and before adjustment. S_{ji} is the voltage reactive power sensitivity of the jth PVGU to the ith PVGU, and Q_j is the reactive power response of the jth PVGU. With the minimum voltage variance for every PVGU terminal as the target, the objective function is

$$\min f = \sum_{i=1}^{n} \left(U_i - \frac{1}{n} \sum_{i=1}^{n} U_i \right)^2 \tag{15}$$

The constraint is

$$\begin{cases} \sum_{i=1}^{n} Q_i = Q_I \\ Q_{i\min} \le Q_i \le Q_{i\max} \end{cases} \quad (16)$$

where Q_i is the reactive power response of ith PVGU, and Q_I is the total reactive power response of the inverters. $Q_{i\min}$ and $Q_{i\max}$ are, respectively, the lower and upper limits of the reactive power regulation range of the ith PVGU that needs to be calculated according to the active power and apparent power of the current moment.

A global sequential quadratic programming method (SQP) is used to solve the nonlinear programming problems with constraints. Then, the reactive power reference value of every PVGU can be obtained.

4. Case study

4.1. PCC voltage analysis of a PV power plant

Taking an actual large-scale PV power plant as an example, the effect of the voltage preventive and emergency coordinated control strategy is analysed. The PV power plant consists of 100 PVGUs, and the total active power output of the PV power plant is 50 MW. The PVGU power is fed into 10 kV collection lines through 0.29/10 kV local transformers and then connected to the external grid through a 10/110 kV main transformer. The 10 kV PCC is equipped with one 5 Mvar SVG and eight 1.5 Mvar capacitor banks.

To compare the effect of different strategies, the following 3 control schemes are compared. Case 1: without any coordinated control strategy, i.e. only using the SVG voltage closed-loop control; case 2: only using the proposed emergency coordinated control strategy; case 3: the proposed preventive and emergency coordinated control strategies are all used. At the times of 5 s, 25 s and 65 s, the sudden increase of the loads at the PCC results in the fluctuation of PCC voltage. Fig. 6 is PCC voltage of the PV power plant. Figs. 7–9 are the reactive power outputs of the SVG, inverters and capacitor banks.

In case 1, when the first disturbance occurs, the SVG increases reactive power immediately, changing from approximately −3 Mvar to approximately 2 Mvar, to ensure the stability of the PCC voltage. During the second disturbance, due to the capacity limitation of the SVG, the reactive power output only increases to 5 Mvar, and the PCC voltage can only be recovered to approximately 0.985 p.u. When the third disturbance occurs, the SVG reactive power output cannot increase any more, and the PCC voltage falls to approximately 0.963 p.u.

In case 2, when the first disturbance occurs, only the SVG is involved in voltage regulation, so the situation is the same as case 1. When the second disturbance occurs, it is found that the SVG reactive power margin is insufficient. Therefore, the SVG and inverters jointly assume the reactive power demand. The SVG outputs maximum reactive power, and the remaining reactive power is assumed by the inverters to ensure the PCC voltage. When the third disturbance occurs,

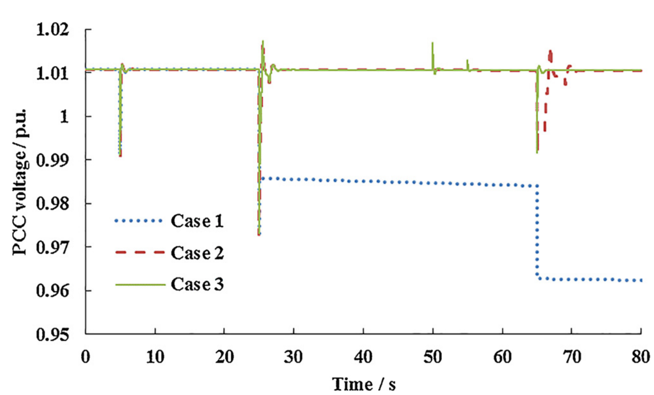

Fig. 6. PCC voltage of a PV power plant.

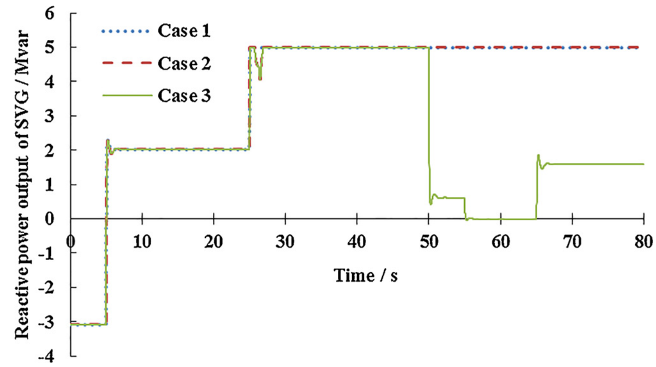

Fig. 7. Reactive power output of SVG.

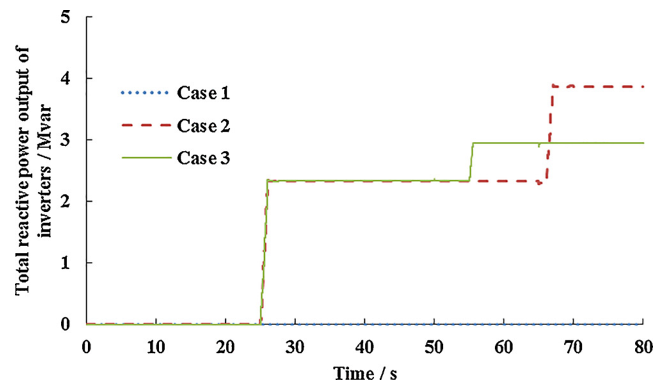

Fig. 8. Total reactive power output of the inverters.

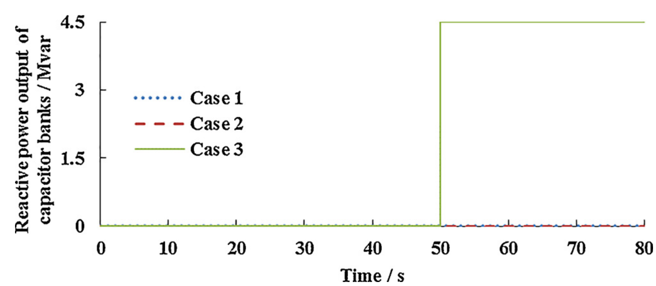

Fig. 9. Reactive power output of the capacitor banks.

the reactive power output of the SVG cannot increase and can only be increased by the inverters. The reactive power response of the inverters is not as fast as the SVG, so the PCC voltage returns to normal after a short time.

Compared with case 2, case 3 has a voltage preventive coordinated control process. After the voltage stabilizes for 20 s, the SVG reactive power margin is released through the first and second stage replacement. The specific replacement process is as follows: at 50 s, 3 capacitor banks are entered. At 55 s, the inverters increase reactive power output to fully release the SVG reactive power margin. The PCC voltage will fluctuate slightly during the replacement process. When the third disturbance occurs, the SVG reactive margin is sufficient to cope with the disturbance; thus, the PCC voltage is still able to return to a normal level quickly.

4.2. Terminal voltage analysis of the PVGUs

Take the 75 s instant as an example; Fig. 10 is a comparison of the PVGU reactive power output before and after optimization. In an average allocation, the reactive power output of every PVGU is 29.8 kvar. In the optimization allocation, the front 7 PVGUs output

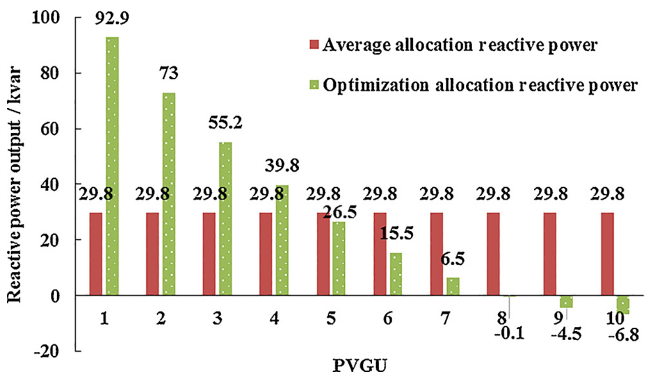

Fig. 10. Comparison of PVGU reactive power output under different allocation methods.

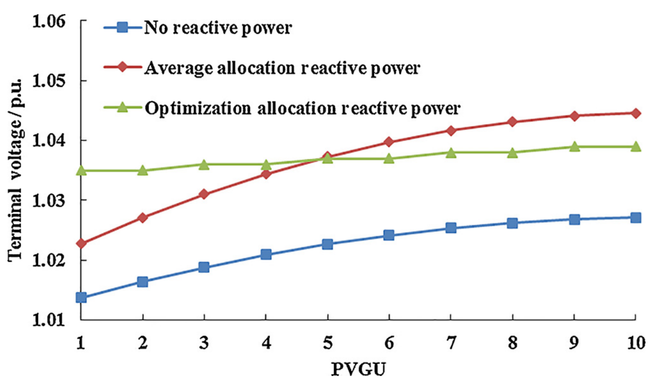

Fig. 11. Terminal voltage distribution of the PVGUs under different allocation methods.

inductive reactive power, and the back 3 PVGUs output capacitive reactive power, and the closer to the PCC, the more the inductive reactive power output. The total collection line reactive power output is 298 kvar, and the total output is unchanged before and after optimization.

Fig. 11 is the PVGU terminal voltage distribution under different allocation methods. When the PVGUs only output active power, the PVGU terminal voltage is relatively low, and the voltage at the end of the collection lines is only 1.0271 p.u. Under disturbance, the PVGUs output reactive power to support the PCC voltage. Comparing the traditional reactive power average allocation method and the proposed optimization allocation method: in average allocation, the voltage at the head and end of the collection lines differs greatly, and the maximum voltage is 1.04455 p.u. It is not conducive to setting protective devices. After optimization allocation, the PVGU terminal voltage at the head of the collection line is raised to 1.035 p.u., and the voltage at the end of the collection lines drops to 1.039 p.u. The in-station voltage is basically at the same level, and the maximum voltage is obviously decreased, which is beneficial to the stable operation of the PV power plant.

5. Conclusion

Based on an analysis of the voltage distribution of a large-scale PV power plant, this paper proposes a voltage preventive and emergency control strategy by coordinately arranging the multiple reactive power sources. The effectiveness of the strategy has been verified by simulation examples. The conclusions are as follows:

1) Under voltage prevention and emergency coordinated control, when a disturbance occurs at the PCC, the multiple reactive power sources are coordinated, and the reactive power output of the inverters is fully utilized to realize emergency control for transient voltage stability. When the disturbance is cleared by the orderly replacement of dynamic (or fast) and static (or low) reactive power, preventive control for transient voltage stability can be realized.
2) Taking the minimum of the in-station PVGU terminal voltage variance as the target. To ensure the success of the PV power plant reactive power response, the optimal allocation of PVGU reactive power is realized, the in-station voltage distribution of the PV power plant is optimized, and the maximum in-station voltage is reduced. Thus, the stable operation of the PV power plant is ensured.

Acknowledgement

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