Reactive Power Control of Grid-Connected Photovoltaic Power Generation

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Abstract. In order to solve the problem of grid-connected point voltage exceeding the limit caused by large-scale photovoltaic power stations connected to the grid, and to increase the penetration rate of photovoltaics in the grid, photovoltaic power stations should have more flexible reactive voltage regulation capabilities to provide reactive power support to the grid. To this end, this paper establishes an equivalent aggregation model for large-scale photovoltaic power plants. Under the premise that the photovoltaic power station is not equipped with reactive power compensation devices and the inverter reactive power output is zero, it is analyzed that due to the existence of line and transformer impedance, photovoltaic access reduces the grid the problem of voltage stability. Based on the above reasons, this paper proposes a three-layer reactive power control strategy for photovoltaic power plants from the perspective of the cooperation between the reactive power compensation device and the grid-connected inverter. This strategy coordinates the reactive power output between the reactive power compensation device and the photovoltaic power generation unit and between the inverters of a single photovoltaic power generation unit. Under this control strategy, the photovoltaic power plant can regulate the grid voltage more effectively, and the active and reactive power losses of the grid are minimized on the premise that the grid voltage is maintained within the required range. Combined with the photovoltaic array power reduction operation strategy, the stable operation of the power grid is ensured under the premise of a certain reactive power output capacity of the photovoltaic power station. Finally, an example is used to verify the correctness and effectiveness of the strategy.

1. Introduction
In recent years, with the continuous reduction of photovoltaic system costs and the maturity of photovoltaic grid-connected technologies, large-scale photovoltaic power generation has become more and more popular in the international community. Large-scale photovoltaic power plants are generally built in remote areas with abundant solar energy resources. Compared with small and medium-sized photovoltaic systems, solar energy can be used more intensively, and it is easy to control and manage parallel inverters [1]. However, as the proportion of photovoltaic power generation in the power grid continues to increase, photovoltaic power needs to be transmitted to the load center over a long distance, and the photovoltaic system has an adverse effect on the voltage stability of the grid. Literature [2] uses constant power control for photovoltaic systems to solve the problem of grid voltage over-limit caused by photovoltaic access, but it can only achieve one-way output reduction operation. The literature [3] uses energy storage devices to suppress the influence of the fluctuation of the active power output of the photovoltaic system on the voltage stability of the grid, but additional energy storage devices and
complex control technologies are required. Literature [4] uses static reactive power compensator to dynamically supply reactive power to improve the voltage stability of photovoltaic power station, but large-capacity reactive power compensation device will increase system cost.

The inverter connected to the photovoltaic system and the grid can realize the decoupling of active and reactive power through control [5]. The photovoltaic power station should make full use of the inverter's reactive power regulation capability to provide voltage support for the grid. With the maturity of photovoltaic grid-connected technology, standard inverters in photovoltaic power plants will gradually be replaced by smart inverters [6], as shown in Figure 1. Under the control of the smart inverter, even if the photovoltaic active power output is at the rated capacity, the inverter can still be connected to the grid with a power factor of 0.9, which greatly improves the reactive power control capability of the photovoltaic power station. The analysis of literature [7] shows that when the penetration rate of photovoltaic power generation in the grid is greater than 30%, its voltage regulation capability can completely replace the voltage regulation capacitor in photovoltaic power plants.

The difference between distributed photovoltaic power generation system and photovoltaic power plant reactive power voltage control is that the former is only for reactive power control of a single inverter, while the latter not only needs to coordinate reactive power control between multiple inverters, but also needs to consider reactive power compensation. Coordinated control between the device and the inverter. This paper analyzes the influence of transmission line parameters on the grid-connected voltage stability of photovoltaic power plants, adopts a three-layer reactive power control strategy to provide reactive voltage support to the grid, and uses reduced power control for photovoltaic arrays when necessary. Finally, simulations verify the correctness and reliability of the reactive power control and voltage support methods in this paper.

2. Analysis of the stability of photovoltaic grid connection

2.1. Distributed photovoltaic power generation structure

A photovoltaic power station is composed of several photovoltaic power generation units in parallel.

In the actual photovoltaic power station, the photovoltaic array occupies a large area, and the distance between each photovoltaic power generation unit is relatively long. It is necessary to collect the generated energy through \( n \) circuit collection lines and then connect it to the grid connection point. Each collection line connects \( m \) photovoltaic power generation units in parallel unit. Among them, \( Z_{ij} \) \((i=1,2,3,\ldots, n, j=1,2,3,\ldots,m)\) is the impedance of the collector circuit, \( Z_T \) is the impedance of the step-up transformer of the photovoltaic power station, and \( Z_G \) is the impedance of the grid.

![Fig.1 Schematic diagram of PVGU](image)

Considering factors such as the large area of the photovoltaic array, the rated power of each photovoltaic power generation unit is generally \( P=1\text{MW} \). When the rated power of a single grid-connected inverter is \( P_1=500\text{kW} \), the total number of grid-connected inverters required is \( k \) for
2.2. Stability analysis

Fig. 2 shows the equivalent structure of a photovoltaic power station integrated into the power grid, where $R_{p}$ and $X_{p}$ are the equivalent resistance and reactance of the collecting circuit and transformer in the photovoltaic power station; $R_{g}$ and $X_{g}$ are the equivalent resistance and reactance of the grid respectively; $P$ and $Q$ are respectively inject the active and reactive power of the grid into the photovoltaic power station; $I$ is the current injected into the grid by the photovoltaic power station; $U_{pv}$ is the grid-connected point voltage of the photovoltaic power station; $U$ is the grid voltage.

\[
k = \frac{P}{P_{1}} = 2 \quad (1)
\]

Figure 2 The equivalent impedance $Z_{l-p}$ and $Z_{T-p}$ of the collector circuit and transformer are respectively.

\[
Z_{l-p} = \frac{m(m+1)(2m+1)Z}{6m^{2}n} \quad (2)
\]

\[
Z_{T-p} = \frac{1}{mn}Z_{l} + Z_{T} \quad (3)
\]

The active power and reactive power injected into the grid by the photovoltaic power station are respectively $P$ and $Q$, where:

\[
Q = \sum_{i=1}^{m+n} Q_{pi} + \sum_{i=1}^{n} Q_{i} - \sum_{i=1}^{n} Q_{g} - Q_{1} \quad (4)
\]

\[
\sum_{i=1}^{m+n} Q_{i} + \sum_{i=1}^{n} Q_{g} + Q_{1} = (nmI_{pv})^{2}X_{p} \quad (5)
\]

Reactive voltage control is adopted. When the photovoltaic power station is in a steady state, $U_{pv}$ remains stable. When the reactive power $Q'$ injected into the grid by the photovoltaic power station is

\[
Q' = \frac{U_{pv}^{*}U - U^{2} - PR_{g}}{X_{g}} \quad (6)
\]

It can be seen from formula (6) that when the photovoltaic active power output is a certain value, the required reactive power support is inversely proportional to the line reactance. In order to increase the reactive voltage regulation capability of the photovoltaic system, a static synchronous compensator can be connected in series on the line. From equations (4) to (6), it can be seen that in order to maintain a constant voltage at the grid connection point, the reactive power generated by the photovoltaic power station is

\[
\sum_{i=1}^{m+n} Q'_{pi} + \sum_{i=1}^{n} Q'_{i} = n^{2}m^{2}\frac{Q'^{2} + P^{2}}{U^{2}}X_{p} + Q' \quad (7)
\]
### 3. Photovoltaic grid-connected reactive power control

According to formula (6) and formula (7), the reference value of reactive power output of photovoltaic power plant can be obtained to maintain constant voltage at the grid-connected point, but the given value of reactive power depends on the line impedance. In this paper, an improved $Q(U)$ reactive power control strategy based on the voltage amplitude of the grid connection point is adopted. Its expression is that $Q_{\text{max}}$ is the maximum value of the sum of reactive power of the photovoltaic power plant inverter and reactive power compensation device.

$$Q = \begin{cases} Q_{\text{max}} & U < U_1 \\ \frac{Q_{\text{max}}}{U_1 - U_2} (U - U_1) + Q_{\text{max}} & U_1 \leq U \leq U_2 \\ 0 & U_2 < U \leq U_3 \\ \frac{Q_{\text{max}}}{U_3 - U_4} (U - U_4) & U_3 < U \leq U_4 \\ -Q_{\text{max}} & U > U_4 \end{cases}$$

(8)

#### 3.1. First

In order to reduce the reactive power transmission in the collection circuit of the photovoltaic power station, reduce power loss and improve the reliability of inverter operation. Priority is given to reactive power compensation devices in reactive power control. Generally, SVG is installed on the low-voltage side of the main transformer for centralized compensation. When $Q_{\text{SVG,min}} \leq Q \leq Q_{\text{SVG,max}},$ $Q^*$ is completely borne by the reactive power compensation device. When the active power output of each photovoltaic unit is at its maximum, the inverter's reactive power output capability is weak. In order to reduce the negative impact of photovoltaic access on the stability of the grid, the capacity of SVG should be determined under the extreme condition of the active output of each photovoltaic unit at the rated state, and the

$$Q^*_r = Q_t + Q_x + Q_g$$

(9)

#### 3.2. Second

When the reactive power compensation device is fully generated, the remaining reactive power is allocated to each photovoltaic power generation unit. Reactive power distribution is carried out among the photovoltaic power generation units. Since the reactive power output of each photovoltaic power generation unit has different effects on the grid-connected point voltage, the principle of the second-level reactive power distribution strategy is: the total reactive power issued by each photovoltaic unit under certain premises, the grid-connected point voltage can be adjusted to the maximum efficiency. Its reactive power distribution uses a sensitivity method based on weighting coefficients to allocate reactive power to each photovoltaic power generation unit. Power flow equation for steady state operation of power system.

$$\begin{align*}
P_t &= U_i \sum_{j=1}^{n} Y_{ij} \cos(\theta_j - \delta_i + \delta_j) \\
Q_t &= -U_i \sum_{j=1}^{n} Y_{ij} \sin(\theta_j - \delta_i + \delta_j)
\end{align*}$$

(10)

#### 3.3. Third

Restricted by the capacity of grid-connected inverters, photovoltaic power generation units are generally composed of several photovoltaic power generation units. Therefore, reactive power is distributed among the inverters. The reactive power given value of a single photovoltaic power
generation unit is obtained from the second layer of reactive power distribution. In order to ensure that each inverter has the same reactive power margin, it can prevent the reactive power output of a certain inverter from exceeding the limit and causing Chain reaction of other inverters. The principle is.

\[
Q_{pv/n}^* = \frac{Q_{pv, i}, Q_{pv, n, max}}{\sum_{i=1}^{n} Q_{pv, i, n, max}}
\]

(11)

4. Simulation Analysis
This paper uses MATLAB/Simulink to establish a simulation model for grid-connected operation of photovoltaic power plants as shown in Fig3. The total installed capacity of the photovoltaic power station is 50MW and consists of 50 photovoltaic power generation units. A single 1MW photovoltaic power generation unit is operated in parallel by two 500kW inverters, and is boosted to 10kV through a 0.29/10kV transformer to connect to a 110kV booster station.

Fig.3 Simulation model

Fig.4 plots the voltage variation of the grid connection point under different control strategies. It can be seen from Figure 10 that when the photovoltaic power plant does not adopt the reactive voltage support strategy, as the photovoltaic active power output increases, the reactive power absorbed by the photovoltaic power plant from the grid increases, and the grid-connected point voltage first rises and then drops. When the active output is 50MW, the grid-connected point voltage is 0.898 (pu); when the photovoltaic power station adopts the reactive voltage support strategy, the grid-connected point voltage is restricted to 0.981~1.014 (pu), which greatly improves the stability of the grid-connected voltage run.

Fig.4 Simulation model
5. Conclusion
When the photovoltaic power station is not equipped with a reactive power compensation device and the reactive power output of the grid-connected inverter is zero, with the increase of the photovoltaic active power output, the grid-connected point voltage will first rise and then drop; in the constant voltage control mode, To increase the reactive voltage regulation capability of photovoltaic power stations, static synchronous compensators can be connected in series on the line to adjust the line impedance. The adoption of a three-layer reactive power control strategy for photovoltaic power plants can give full play to the reactive power and voltage support capabilities of the power plant, reduce internal power loss in the power plant, improve the power plant's voltage regulation capability, and ensure the reliability of all devices. Constrained by the voltage regulation capability of photovoltaic power plants, power reduction control methods should be adopted for photovoltaic arrays when necessary to ensure the stable operation of the power grid.

Acknowledgement
Natural Science Foundation of Tibet Autonomous Region (XZ2019ZRG-52(Z))

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