Optimization of Var-Voltage Regulation Control Strategy for Grid-Connected Inverter of Photovoltaic Power

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Abstract. With the continuous increase of installed capacity of large photovoltaic power stations, the light intensity and temperature changes of photovoltaic power generation units themselves will cause grid-connected voltage fluctuation or even beyond the limit, so large photovoltaic power stations must participate in voltage regulation control. To solve this problem, the voltage distribution characteristics of the photovoltaic power station are firstly analyzed quantitatively, and the analysis shows the voltages at the photovoltaic inverter buses are relevant with the impedance of the collecting lines, the voltage at the PCC point, the location of the photovoltaic unit, and the output power of the photovoltaic unit. Furthermore, our work proposes the reactive power distribution strategy and voltage control strategy of photovoltaic power station based on particle swarm algorithm, and the correctness and feasibility of the proposed control strategy are verified by simulation, so as to ensure the rationality of the voltage control target of each photovoltaic inverters while taking into account the voltage of each photovoltaic unit.

1. Introduction
With the continuous reduction of system costs and the continuous improvement of power generation efficiency, the construction of photovoltaic power plants can make large-scale and effective use of solar energy. [1-2]. Different from small-capacity photovoltaic grid-connected power generation systems, many photovoltaic power plants are built in desert areas with abundant sunlight resources, which are far away from load centers, where the load is relatively scattered, so the regional power grid has long transmission lines and the power grid is relatively weak[3-4]. The light intensity and temperature changes of the photovoltaic power generation system itself will cause the grid-connected voltage to fluctuate or violate, so the photovoltaic power station must participate in voltage regulation and control[5].

The generation of photovoltaic units in the photovoltaic power station is collected to the junction point through the collecting circuit, because the system has multiple feeder nodes, when the photovoltaic system is connected to the grid, the direction of the line flow changes. When the power is transmitted through the transmission line, the beginning of the voltage distribution along the line is higher than the end. Therefore, at the end of the feeder, the voltage rise is the largest.[6] In view of the backward construction of reactive power compensation devices of large-scale photovoltaic power stations in China or the lack of reactive power compensation requirements, it is of great practical
significance to study reactive power and voltage control strategies suitable for large-scale photovoltaic power stations.

In this paper, the voltage distribution characteristics of photovoltaic power stations are quantitatively analyzed to study the influence factors of reactive power output of photovoltaic power units on the voltage of photovoltaic power stations. On this basis, the optimal solution of the minimum internal loss in photovoltaic power station is obtained by particle swarm optimization for grid-connected inverter reactive power and voltage control. It is verified by experimental simulation, which provides a new idea for researching the reactive power and voltage control strategy of grid-connected inverter suitable for photovoltaic power plants.

2. Voltage Distribution Characteristics Of Units In photovoltaic Power Station
For the convenience of research, an equivalent model of photovoltaic power station is established, as shown in Figure 1.

In the figure, the parameters of the i-th photovoltaic unit are:
- \( P_i \) and \( Q_i \): Active and reactive power;
- \( Z_i \): Impedance of the transmission line with the previous photovoltaic unit;
- \( Z_{Ti} \): Equivalent impedance of step-up transformer;
- \( U_{iL} \) and \( U_{iH} \): Step-up transformer low voltage side and high voltage side voltage;
- \( U_{POIL} \) and \( U_{POIH} \): Main transformer low voltage side and high voltage side voltage;
- \( U \): Power voltage.

Take the grid voltage \( U \) as the reference voltage, ignoring the transverse component of the voltage drop and the admittance parameters in the line, the formula for the parallel dot voltage \( U_{POIH} \) of the photovoltaic power station can be derived as follows: (the following processes are all calculated in per unit).

\[
U_{POIH} \approx U + \frac{\left( \sum P_i - \Delta P \right) R_g + \left( \sum Q_i + Q_c - \Delta Q \right) X_g}{U}
\]

Where:
- \( \sum P_i \) and \( \sum Q_i \): Total active power and reactive power output of photovoltaic power station;
- \( Q_c \): Reactive power output by the reactive power compensation device;
- \( \Delta P \) and \( \Delta Q \): The active and reactive power losses of active and reactive power caused by the main transformer, photovoltaic unit step-up transformer, and collection line impedance respectively;
- \( Z_g = R_g + jX_g \) is the impedance of transmission lines.

According to Equation (1), \( U, \sum P_i, \sum Q_i, \Delta P, \Delta Q, Z_g, Q_c \) will have an impact on the junction voltage of the photovoltaic power station. Because of the transmission line impedance can not be changed, when the power grid disturbances affect and node voltage, can adjust the reactive power of the photovoltaic power station output \( \sum Q_i \) and reactive power compensation device output reactive power \( Q_c \) to stabilize parallel dot voltage, thus reducing the system internal loss.
Due to the same structure of the collector lines, take string 1 as an example for analysis. The voltage \( U_{iL} \) at the \( i \)-th photovoltaic unit is established in equation (2).

\[
\begin{align*}
U_{iL} &= \frac{P_i R_{Ti} + Q_i X_{Ti}}{U_{ih}} + U_{il} \\
U_{il} &= \frac{\left(\sum_{k=1}^{3} k_i R_k\right) + \left(\sum_{k=1}^{3} k_i Q_k\right) X_i}{U_{(i-1)H}} + U_{\text{POI}}
\end{align*}
\] (2)

Where: \( Z_{Ti} = R_{Ti} + jX_{Ti} \); \( Z_i = R_i + jX_i \).

From equation (2), it can be seen that the voltage at the bus of the photovoltaic unit does not only depend on the impedance of the collection line, but also depends on the parallel dot voltage of the photovoltaic power station, the position of the photovoltaic unit in the collection line, its own power injection, and the power injection of other photovoltaic units.

Further derivation is easy to obtain. The voltage at the photovoltaic unit at the beginning end of the collection line is the lowest, which is close to the grid-connection point voltage of the photovoltaic power station. The voltage at the outlet of the photovoltaic unit at the end of the collection line is the highest, and the voltage violation is most likely to occur. The impedance of the collector line has an uplifting effect on the voltage, and the voltages at photovoltaic units gradually increase from the beginning towards the end of the collector line.

In order to further verify the above analysis, a simulation model of the internal network of PSCAD photovoltaic power station was established for experiment. The simulation model is shown in Figure 2. There are 32 photovoltaic units in the photovoltaic power station, composed of three photovoltaic strings, and the parallel dot voltage level is 35kV. The distance between string 1 and the grid connection point is the shortest, string 2 the second, and string 3 the farthest from the grid connection point. Each string has 11, 10, and 11 photovoltaic units respectively. The serial number of each string unit is arranged from 1 to 11 (or 10) from nearest to farthest.

**Figure 2.** PSCAD model of the internal network simulation of photovoltaic power station

Set the reactive power output of each unit as 0, observe and record the voltage of each unit inside the photovoltaic power station, as shown in Figure 3.
The terminal voltages of the units increase with the increase of the line impedance. The terminal voltage of the unit 1 is the lowest, which is close to the voltage of the grid connection point, and the unit voltage at the end of the collector line may exceed the safe operating range.

Take string 1 as an example, let the power injection of each unit be -200KVar, -100KVar, 0, 100KVar and 200KVar, where positive means power injection and negative means power absorption. Observe and record the voltage of each unit in string 1, as shown in Figure 4.

The unit voltage rises with the increase of the reactive power generated by the photovoltaic, and the photovoltaic reactive output has a regulating effect on the unit voltage. Through the above scenario analysis, it can be concluded that in this scenario, the bus voltage of the photovoltaic unit close to the grid connection point is the lowest, and the bus voltage of the photovoltaic unit far from the grid connection point is the highest, and the bus voltage of the photovoltaic unit gradually increases along the collection line. In this scenario, if the reactive power increases, the bus voltage of the photovoltaic unit will rise, and the bus voltage will also rise.

The above simulation experiment shows that the bus voltage of the photovoltaic unit is relevant with the impedance of the collection line, the voltage of the grid-connected point of the photovoltaic unit, the location of the photovoltaic unit in the electrical line, and its own output power. The parallel dot voltage of the photovoltaic unit is related to the impedance of the transmission line, the grid voltage, the active and reactive power injection of the photovoltaic power station, the reactive power injection of the reactive power compensation device, and the active and reactive power loss.
3. Reactive Power Regulation Allocation Strategy For Photovoltaic Inverter

Photovoltaic units due to the different distances from the photovoltaic power station and outlets, especially the area of large photovoltaic power stations can exceed 10 square kilometers, If the total reactive power reference amount required by the photovoltaic power station is evenly distributed to each photovoltaic unit, The line loss caused by the photovoltaic unit far away from the junction point will be much higher than that caused by the photovoltaic unit near the junction point.

Therefore, this paper proposes a reactive power optimal allocation scheme based on particle swarm optimization. By setting the objective function in the particle swarm optimization algorithm and searching for the optimal solution through iteration, to realize the optimal distribution of reactive power in the photovoltaic power station and effectively reduce reactive power line loss.

The reactive power optimal allocation strategy adopted in this paper is shown in the figure below:

As Figure 5 shown, the control strategy first obtains the difference between the reference voltage of the photovoltaic power station and the real-time detection voltage, calculates the difference through the PI controller to obtain the reactive power reference quantity required for the photovoltaic power station, and then search the optimal solution by particle swarm optimization algorithm and allocate it to the photovoltaic inverter to realize the adjustment of grid voltage.

Particle swarm optimization (PSO) is a kind of random searching algorithm based on swarm intelligence, which makes particles converge to the global optimal solution gradually by sharing location and fitness information between particles. Each particle in the group on behalf of the feasible region of a feasible solution, the position of each particle next is determine by its current position and update speed, speed, and inertia particles its optimal position ($P_{best}$), the global optimal position ($G_{best}$) affect the renewal speed of particles, which generates the next generation of particles, so the update until the convergence to the global optimal solution. Set the number of particles in the particle swarm to be $N$, and the particle dimension to be $D$ dimension. The ith particle $X_i = (X_{i,1}, X_{i,2}, \cdots, X_{i,D})$ has the $J$TH dimension velocity component $v_{i,j}$ and position component $X_{i,j}$, which are respectively expressed as:
\[
\begin{align*}
\begin{cases}
    v_{i,j}(t + 1) = \omega v_{i,j}(t) + c_1 r_1 (P_{besti,j} - v_{i,j}(t)) \\
    + c_2 r_2 (G_{besti,j} - v_{i,j}(t)) \\
    x_{i,j}(t + 1) = x_{i,j}(t) + v_{i,j}(t + 1)
\end{cases}
\end{align*}
\] (3)

Where: \( i = 1, 2, \cdots, N \); \( j = 1, 2, \cdots, D \); \( \omega \) is the inertia weight, \( \omega \in [0, 1] \); \( c_1, c_2 \) is the learning factor, \( c_1, c_2 \in [0, 2] \); \( r_1, r_2 \) are random Numbers on the interval \([0, 1]\).

In this paper, to balance the voltage at the terminals of each photovoltaic unit in the station by means of reactive power regulation, the objective function is set to obtain the minimum value of voltage variance \( S^2 \) at the terminals of each photovoltaic unit, as shown below:

\[
F = \min (S^2)
\] (4)

Where:

\[
S^2 = \frac{1}{k}((\bar{u} - u_1)^2 + (\bar{u} - u_2)^2 + \cdots + (\bar{u} - u_k)^2)
\] (5)

\( \bar{u} \) is the average terminal voltage of each photovoltaic unit. \( u_k \) is the terminal voltage of the KTH pv unit.

Set the power flow constraint conditions as follows:

\[
0 \leq Q_{fs} \leq Q_{max}
\] (6)

Where, \( Q_{fs} \) is the reactive power injected into the corresponding node, and \( Q_{max} \) is the maximum reactive power that can be injected into node \( K \). When the reactive power is out of bounds in the optimization process, it is calculated according to the corresponding upper or lower bounds.

The operating voltage constraint is:

\[
V_{kmin} \leq V_k \leq V_{kmax}
\] (7)

Where, \( V_{kmin} \) and \( V_{kmax} \) are respectively the minimum and maximum operating voltages on node \( K \).

To simplify the research, particle swarm optimization was carried out on the group-string 1 photovoltaic unit. Algorithm parameters were set as follows: the number of iterations was 400; the number of particle swarm is 40, the inertia weight is \( \omega = 0.6 \); \( c_1 = c_2 = 0.6 \).

Set the above parameters and use the particle swarm algorithm to find the minimum value of the terminal voltage variance of each photovoltaic unit in the site and the corresponding reactive power output of each unit at this time, as shown in the Table 1:

**Table 1. Reactive Power Output of Each Unit Corresponding to The Optimal Value Of PSO.**

| The unit number | 1   | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    |
|-----------------|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Reactive output (KVar) | 10.06 | 16.76 | 9.57  | 20.30 | 21.94 | 25.54 | 9.44  | 2.49  | 21.88 | 6.98  | 2.18  |

In the PSCAD model, the reactive power output of the string 1 photovoltaic unit is distributed according to the above table. The comparison diagram of the terminal voltage of each unit is as follows:
Figure 6. Comparison chart of terminal voltage of string 1 before and after reactive power optimization

As shown in the Figure 6, the reactive power output of string 1 photovoltaic unit when the minimum variance of the terminal voltage of each photovoltaic unit in the station is obtained by the particle swarm algorithm can reduce the voltage difference between the terminals of each photovoltaic unit, thereby reducing the interior Active power loss.

4. Conclusion

By studying the reactive power and voltage control strategies of grid-connected inverters in photovoltaic power stations, the conclusions are as follows:

1. The unit voltage rises with the increase of reactive power of photovoltaic unit, and photovoltaic reactive output has a regulating effect on the unit voltage. The voltage of the bus of the photovoltaic unit close to the junction point is the lowest, while that of the bus of the photovoltaic unit far from the junction point is the highest, and the voltage of the bus of the photovoltaic unit gradually increases along the collector line. When the reactive power increases, the bus voltage of the photovoltaic unit rises, and the bus voltage of the dot rises.

2. The optimal solution obtained by using the particle swarm optimization algorithm can optimize the reactive power distribution of the photovoltaic unit in series 1, which can reduce the extra active power loss inside the photovoltaic power station.

Next step:

1. Use complex network structure and increase the number of units to make the system parameters fit the actual photovoltaic power station. Apply particle swarm optimization algorithm to the whole station to balance the voltage at the end of photovoltaic power units and reduce network loss.

2. Apply particle swarm optimization algorithm among multiple photovoltaic power stations to study the effect of particle swarm optimization algorithm among multiple photovoltaic power stations.

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