The Control Strategy for the Adaptive Reactive Voltage of Low and Medium Voltage Distribution Network with High Photovoltaic Penetration

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Abstract. The high permeability of photovoltaic power generation systems in medium and low voltage distribution networks brings challenges such as reverse power flow and voltage rise. Voltage violation becomes an important factor of restricting the massive access of distributed photovoltaics. In this paper, the reactive voltage control problem caused by the high-permeability photovoltaic access to the distribution network is studied. Based on the inverter reactive voltage control strategy, a distributed photovoltaic cosφ (U, P) control model is proposed, and based on the grid-connected point voltage and the actual active output of photovoltaics, a distributed photovoltaic in-situ adaptive reactive voltage control strategy is proposed. After simulation verification, this control strategy can automatically adjust photovoltaic output make full use of the voltage support capability of distributed photovoltaics at various locations and periods, effectively make up for the shortcomings of traditional voltage regulation capabilities, and improve reactive voltage control capabilities.

1. Introduction
Distributed energy has the advantages of low cost, simple control, environmental protection and clean, etc. It has been widely used in the middle and low voltage distribution network to solve the problems of environmental pollution and fossil fuel consumption [1]. In the research of renewable energy, photovoltaic power generation has always occupied a very important position. However, the installation of a large number of photovoltaic systems in the distribution network has also brought a series of challenges [1-2]: photovoltaic grid-connected power causes current flow, which increases system losses and at the same time easily causes the node voltage to exceed the limit and voltage fluctuations. Therefore, how to effectively reduce voltage fluctuations, solve the problem of voltage limit violations, and improve photovoltaic utilization is the focus of this paper.

Many scholars have carried out detailed analysis on the influence of the location and capacity of distributed power sources on grid voltage fluctuations [3-5]. Among them, the literature [3] conducted a more detailed analysis of the influence of different capacities and positions of a single distributed power supply on the voltage. Literature [4] separately studied the changes of the system voltage when...
the active power, reactive power and load of photovoltaic power generation grid-connected systems change. At present, the distribution network mainly relies on transformer taps and capacitors to adjust the voltage level, which is difficult to meet the voltage control requirements after a large number of distributed photovoltaics are connected. In response to this problem, domestic and foreign researchers have proposed methods such as the configuration of energy storage, new reactive power compensation devices, and reactive power optimization control of distributed power sources, to solve the impact of distributed photovoltaic access to the distribution network [6-13].

Based on the above-mentioned problems, this paper proposes an adaptive switching control strategy that includes constant cosφ, cosφ(U, P) and Q(U) three control modes. Considering the limited voltage regulation capability of distributed photovoltaics, a comprehensive voltage control strategy for active distribution networks that combines traditional voltage regulation methods such as transformer taps and reactive power compensation is proposed. Finally, this article analyzes the IEEE34 node example. The results show that the control strategy proposed in this article can effectively solve the impact of a large number of distributed photovoltaic access to the active distribution network, reduce the number of VQC device actions, and effectively protect the entire network Voltage level.

2. Analysis of reactive voltage control strategy of photovoltaic inverter

2.1. Photovoltaic inverter cosφ(P) control strategy

The specific curve of cosφ(P) control is shown in Figure 1.

Fig 1. The control strategy curve of cosφ(P)

The mathematical expression formula is shown in Equation (1).

$$\cos \phi = \begin{cases} 
1 & 0 < P < P_1 \\
1 - \frac{\cos \phi_{\min}}{P_y - P_1} (P - P_1) & P_1 \leq P \leq P_2 \\
\cos \phi_{\min} & P_2 \leq P \leq P_n 
\end{cases}$$

(1)

Where, P is the photovoltaic active power output value; cosφmin is the lower limit of power factor.

2.2. Photovoltaic inverter Q(U) control strategy

The output curve of the Q(U) control strategy is shown in Figure 2, where the reactive power generated by photovoltaics is positive, and the reactive power absorbed is negative.

According to the reactive power and voltage control strategy of the photovoltaic power supply in Figure 2, the principle of reactive power/voltage output can be adjusted, and the formula is as follows:

$$Q = \begin{cases} 
\frac{Q_{\max}}{U_i - U_i}(U_i - U_i) & U_i < U_i \\
\frac{Q_{\max}}{U_i - U_i}U_i & U_i < U_i < U_i \\
0 & U_i < U_i < U_i \\
\frac{Q_{\max}}{U_i - U_i}(U_i - U_i) & U_i < U_i < U_i \\
-\frac{Q_{\max}}{U_i - U_i}U_i & U_i < U_i 
\end{cases}$$

(2)
In formula (2), $U_i$ and $Q_i$ are the voltage and the reactive power output of photovoltaics at node $i$, $U_1$ and $U_5$ are the upper and lower limits of grid voltage operation, and $U_2$ and $U_4$ can be adjusted according to the actual demand of grid operation.

3. Analysis of reactive voltage control strategy of photovoltaic inverter

The distributed photovoltaic $\cos \varphi (U, P)$ control strategy proposed in this paper is divided into two steps. First, according to the voltage level of the grid connection point, the distributed photovoltaic power factor is determined to lead or lag operation, and the value of $\cos \varphi_{\text{min}}$ is determined. For the $\cos \varphi_{\text{min}}$-$U$ curve in Figure 3-a, we can determine the value of $\cos \varphi_{\text{min}}$, which determines a certain curve in the subsequent $\cos \varphi$-$P$ curve cluster; then, the actual power factor $\cos \varphi$ of distributed photovoltaic operation is determined according to the actual active power output $P$ of distributed power supply. As shown in Figure 3-b, in the $\cos \varphi$-$P$ curve cluster, based on the $\cos \varphi_{\text{min}}$ determined in the previous step, select a certain curve and determine the value of $\cos \varphi$ based on the abscissa $P$. When the voltage is too high, as shown in the part below the abscissa axis in Figure 3-b, the power factor runs ahead, and the distributed photovoltaic absorbs reactive power. The power factor decreases with the increase of active power output, so as to increase the absorption value of reactive power and reduce the voltage uplift amplitude. When the voltage is too low, as shown in the part above the abscissa axis in Figure 3-b, the power factor lags behind and the distributed photovoltaic generates reactive power. The power factor increases with the increase of active power output, so as to reduce the output value of reactive power and avoid excessive reactive power compensation.

![Fig 3. The curves of improved $\cos \varphi (U, P)$ control strategy](image-url)

In Figure 3-a, $C_2$ is the minimum power factor value allowed by the photovoltaic inverter. The mathematical expression of $\cos \varphi_{\text{min}}(U)$ is shown in formula (3), and the mathematical expression of $\cos \varphi$ in Fig. 3-b is shown in formula (4). The two formulas jointly realize the complete $\cos \varphi (U, P)$ control strategy.

$$
\cos \varphi_{\text{min}} = \begin{cases}
C_2 & U_i < 0.95 \\
1 - \frac{1 - C_2}{U_2 - U_i} & 0.95 \leq U_i < 0.98 \\
1 & 0.98 \leq U_i \leq 1.02 \\
1 - \frac{1 - C_2}{U_4 - U_i} & 1.02 < U_i \leq 1.05 \\
C_2 & U_i > 1.05
\end{cases}
$$

(3)

$$
\cos \varphi_{\text{act}} = \begin{cases}
\cos \varphi_{\text{min}} & P \leq P_1 \\
\cos \varphi_{\text{min}} + \frac{1 - \cos \varphi_{\text{min}}(P - P_1)}{P_2 - P_1} & P_1 \leq P \leq P_2 \\
1 & P_2 < P \leq P_3 \\
1 - \frac{1 - \cos \varphi_{\text{act}}(P - P_1)}{P_2 - P_1} & P_2 \leq P \leq P_3 \\
\cos \varphi_{\text{act}} & P_3 \leq P
\end{cases}
$$

(4)
This control strategy realizes the joint control based on voltage and active power, effectively distinguishes the reactive power compensation range of different grid points, improves the voltage regulation effect of the system, and realizes the real-time rapid response of distributed photovoltaic reactive power output to weaken voltage fluctuation and reduce the voltage out-of-limit.

4. Example and analysis

This paper conducts simulation based on the improved IEEE 34-node distribution network system, as shown in Figure 4. The maximum active power output of the system is 3096.86kW, and the maximum active power load of the system is 3317.51kW.

| Node No | PV access | PV operation at unit power factor | PV operation under multi-model adaptive control |
|---------|-----------|----------------------------------|-----------------------------------------------|
| 13      |           | [0.958,1.009]                   | [0.958,1.022]                                 |
| 9       |           | [0.900,0.996]                   | [0.900,1.053]                                 |

Figure 5 shows the voltage fluctuation diagram of the low-voltage bus in the simulation example before and after the distributed photovoltaic access. It can be seen that the low-voltage bus also fluctuates significantly with the load or photovoltaic output. However, after the distributed photovoltaic adopts the multi-model adaptive voltage regulation control strategy, the voltage of the low-voltage bus has certain changes but is relatively stable.

Figure 6 shows the action curve of the transformer tap. It can be seen that the transformer tap has three different positions within 24h. After the distributed photovoltaic adopts the multi-model adaptive control strategy, there is no transformer tap action within 24 hours, which effectively reduces the number of actions.
5. Conclusion
By making full use of the reactive power support capacity of grid-connected photovoltaics, it can effectively make up for the shortcomings of traditional voltage regulation methods, enhance system voltage regulation capabilities, and reduce the investment cost of reactive power compensation devices, avoiding high investment in communication facilities caused by remote coordinated control. It is easy to promote and apply problems that are difficult to centrally control, and has a good practical application prospect.

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