Coordinated control method of active and reactive power for voltage regulation in distribution systems with high-penetration PV

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Abstract. Owing to the intermittent and randomness of solar radiation, high-penetration photovoltaic (PV) energy injected into power distribution systems will inevitably change the magnitude and direction of the power flow, thus causing problems such as voltage violation of the point of common coupling (PCC) and further having a hazardous influence on consumers’ electricity quality. And the communication construction of China’s distribution systems is now relatively weak, difficultly integrating multiple voltage regulation equipment. To improve consumers’ voltage quality at the PCC, a coordinated control method based on active and reactive power of local inverter is proposed. This method can realize the economic regulation of the voltage at the PCC through reactive compensation and active reduction, which can maximum assure the voltage magnitude at the PCC within limits (including upper and lower limits) and maximize the utilization capacity of PV inverter. Based on Matlab/Simulink, simulation results in different scenarios show the effectiveness of the proposed method.

1. Introduction

By the end of 2018, the installed capacity of PV generation in China has reached 170 million kW, which accounts for 24% of China’s renewable energy. The integration of PV systems into distribution systems generally adopts unity power factor mode[1]. However, owing to the intermittent and randomness of solar radiation, the active power output of PV systems will change inevitably[2]. When the distribution system connected to PV system is weak, high-penetration PV will cause voltage fluctuation. In severe case, the voltage magnitude of some nodes in the distribution system can violate the limits[3], which will threaten the normal operation of AC grid. Thus how to solve the problem of voltage violation (including upper and lower limits) at the PCC has become a hot research topic.

In view of the voltage violation at the PCC, study in [4] has studied the access capacity of distributed PV under different PV access scenarios, but does not consider the reactive voltage regulation capability of distributed generators. Some scholars have proposed using the reactive power compensation device (SVG) or energy storage device to regulate voltage[5-6], but in actual power grid, these methods will greatly increase the construction cost and the overall utilization rate of the voltage regulator is low. Study in [7] has pointed out that if the penetration rate of PV power in AC grid exceeds 30%, adjusting the reactive power output of PV systems can avoid the voltage violation. For the voltage regulation of the distribution system with high-penetration PV, there are three main types: centralized control, distributed control and local control. For centralized voltage control, study in [8]
has calculated the power flow to regulate the voltage of distribution systems, but this method needs a larger number of computing resources, causing the heavy communication burden. For distributed voltage control, study in [9] has proposed a voltage control method based on the power coordinated control of multiple inverters. But the communication construction in China’s distribution systems is now relatively weak, difficulty meeting the requirements in short term. For local voltage control, the German Institute of Electrical Engineers has proposed four reactive power control methods to regulate voltage [10]: Q method (fixed reactive power), cosφ method (fixed power factor), cosφ (P) method and Q(U) method. In addition to these four types of voltage control, some studies have proposed to regulate the voltage by utilizing the residual capacity of PV inverter[11-12]. However, these methods have the problem of excessive active reduction and reactive voltage support of the PV inverter is not fully utilized, especially when the voltage magnitude lowers the lower limit. Therefore, under the guarantee that the voltage magnitude at the PCC is within limits, how to optimize active and reactive power output of the PV inverter to realize the economic voltage regulation in the distribution system needs further study.

In this paper, the voltage characteristics at the PCC are analyzed in Section 2 and a coordinated control method based on active and reactive power of local inverter is proposed in Section 3. When the voltage magnitude at the PCC violates the limits, the residual capacity of the PV inverter is preferentially used for the reactive power output to regulate the voltage. If the residual capacity is insufficient, calculate the optimal output value of active and reactive power to regulate the voltage. Section 4 presents the related simulations and results and Section 5 summarizes the study.

2. Voltage characteristics at the PCC

High-penetration PV power injected into power distribution systems will change the magnitude and direction of the power flow inevitably, thus causing problems such as voltage fluctuation and violation of the PCC. To give a brief description on how PV power feed-in can affect the voltage, an equivalent circuit of a PV system connected to its PCC is shown in Figure 1, where $U_s$, $U_o$ are the variable voltage at the PCC and the constant bus voltage of low voltage distribution system respectively, $P_{pv}$, $Q_{pv}$ are the active power output and reactive power output of PV system respectively, $P_L$, $Q_L$ are the active power and reactive power output of the local load respectively, $R$, $X$ are the resistance and reactance of the low-voltage line respectively.

![Figure 1. Equivalent circuit of a PV system connected to its PCC.](image)

When the PV power generation system is connected to its PCC, the voltage at the PCC ($U_s$) can be expressed by equation (1):

$$U_s = U_o + \frac{(P_{pv} - P_L - P)^R + (Q_{pv} - Q_L - Q)X}{U_o} + j\frac{(P_{pv} - P_L - P)X - (Q_{pv} - Q_L - Q)R}{U_o}$$

(1)

with $P_s$ the active power loss and $Q_s$ the reactive power loss of the line.

Generally, the power loss of line is much smaller than the output power of PV system, thus $P_L$ and $Q_L$ in equation (1) can be neglected. Moreover, the horizontal component of the voltage drop is much smaller than its vertical component. Therefore, the simplified voltage at the PCC ($U_s$) can be calculated with the following equation:
According to equation (2), when the PV power generation system is connected to AC grid, the voltage at the PCC will be raised to some extent. Typically, the PV system is connected to AC grid adopting unity power factor mode. When the active power output of the PV power generation system is large and the local load is small, the voltage at the PCC to be greater than the bus voltage or even exceed the upper limit. Similarly, when the active power output is small and the local load is large, the voltage at the PCC is lower than the bus voltage or even lower the lower limit. These conditions are not allowed by AC grid, thus some necessary measures should be taken to guarantee that the voltage at the PCC is within limits.

In addition, three main factors, which affect the voltage at the PCC, can be found from equation (2) obviously: the impedance parameter of the line, the local load and the output of PV system. Among them, the impedance parameter of the low-voltage line depends on the installation position, which is generally fixed; the local load depends on the user’s demand and is an uncontrollable factor; the output of PV system is controllable. Its active power output can be dynamically adjusted from zero to the maximum value. Similarly, the reactive power output can be adjusted by the residual capacity of PV inverter. Therefore, when the voltage at the PCC violates the voltage limits, the voltage regulation can be performed by adjusting the output of PV inverter.

3. Coordinated control method

At present, most inverters adopt double close-loop decoupling control method, which can independently control the active power and the reactive power. As shown in Figure 2, a PV inverter control system used in this paper is given.

![Figure 2. PV inverter control system.](image)

This PV inverter control system mainly includes the double closed-loop control of voltage and current and the coordinated control of active and reactive power. In the double closed-loop control of voltage and current, the current loop controls the current output of PV inverter to follow the current instruction \((i_{dref}, i_{qref})\), so as to generate the active power and the reactive power by feeding in AC grid;
the voltage loop maintains the stability of the bus voltage \( V_{dc} \) at the DC side, and provides the active current instruction \( l_{dref} \) for the current loop. In the coordinated control of active and reactive power, the reference value of active and reactive power output is given by detecting the current output of PV system and the maximum active power output \( P_{max} \), which guarantees that the voltage at the PCC is within limits.

When the active power output of PV system changes, the reactive power output, which can make the voltage at the PCC within limits, is first calculated under the assumption of sufficient capacity of PV inverter. Then, the reference value of active and reactive power output is reasonably selected according to different voltage regulation states of PV inverter. Using the equivalent circuit of Figure 1, the equation for adjusting the voltage at the PCC to the upper limit can be obtained, which is expressed as:

\[
U_{\text{max}} = U_o + \frac{(P_{\text{max}} - P) R + (Q_{\text{pv}} - Q) X}{U_o}
\]

(3)

Where:

- \( U_{\text{max}} \) is the upper limit of the voltage at the PCC.
- \( P_{\text{max}} \) is the active power output of PV inverter by MPPT.
- \( Q_{\text{pv}} \) is the reactive power output adjusting the voltage at the PCC to the upper limit.

Since the local load cannot be predicted and its specific value is unknown, put the equation (3) into the equation (2), \( Q_{\text{pv}} \) can be calculated by equation (4):

\[
Q_{\text{pv}} = \frac{U_o (U_{\text{max}} - U_o) - (P_{\text{max}} - P) R}{X} + Q_{\text{pv}}
\]

(4)

Similarly, the reactive power output \( Q_{\text{pv}} \) adjusting the voltage at the PCC to the lower limit \( U_{\text{min}} \) can be calculated by equation (5):

\[
Q_{\text{pv}} = \frac{U_o (U_{\text{min}} - U_o) - (P_{\text{max}} - P) R}{X} + Q_{\text{pv}}
\]

(5)

Therefore, the voltage regulation of PV inverter can be divided into five states, as follow:

1) State 1: \( Q_{\text{pv}} > 0 \), \( Q_{\text{pv}} < 0 \) and the rated capacity of PV inverter \( (S_{\text{pv}}) \) is sufficient. It indicates that the PV inverter needs to provide inductive reactive power (from a generator’s point of view) to adjust the voltage at the PCC to the upper limit. Or it needs to provide capacitive reactive power to adjust the voltage at the PCC to the lower limit when the PV system is in MPPT mode. And the voltage at the PCC will not violate the limits, even if the reactive power output is 0. So the reference value of active and reactive power can be calculated by equation (6):

\[
\begin{cases}
P_{\text{ref}} = P_{\text{max}} \\
Q_{\text{ref}} = 0
\end{cases}
\]

(6)

with \( P_{\text{ref}} \) the reference value of the active power and \( Q_{\text{ref}} \) the reference value of the reactive power.

2) State 2: \( Q_{\text{pv}} < 0 \) and the rated capacity of PV inverter is sufficient. It means that the PV inverter needs to provide capacitive reactive power to adjust the voltage at the PCC to the upper limit when the PV system is in MPPT mode. So the reference value of active and reactive power can be calculated by equation (7):
\[
\begin{align*}
P_{\text{ref}} &= P_{\text{max}} \\
Q_{\text{ref}} &= Q'_{\text{pmax}}
\end{align*}
\]

(7)

3) State 3: \(Q'_{\text{pmax}} < 0\) and the rated capacity of PV inverter is insufficient. It indicates that the output of PV inverter will exceed the rated capacity of PV inverter if the active power output is \(P_{\text{max}}\) and the reactive power output is \(Q'_{\text{pmax}}\). To adjust the voltage at the PCC to the upper limit and meet the requirement of the rated capacity of PV inverter, the active power output needs to be reduced and the reactive power output needs to be increased, which should be the optimal output of active and reactive power. Thus the reference value of active and reactive power can be calculated by equation (8):

\[
\begin{align*}
U_z &= U_a + \frac{(P_{\text{ref}} - P_z)R + (Q_{\text{ref}} - Q_z)X}{U_a} \\
\text{max} &= U_a + \frac{(P_{\text{ref}} - P_z)R + (Q_{\text{ref}} - Q_z)X}{U_a} \\
P_{\text{ref}}^2 + Q_{\text{ref}}^2 &= S_N^2
\end{align*}
\]

(8)

Two solutions of \(P_{\text{ref}}\) and \(Q_{\text{ref}}\) can be obtained by solving equation (8). Among them, the solution with larger \(P_{\text{ref}}\) is the optimal output of active and reactive power.

4) State 4: \(Q'_{\text{pmin}} > 0\) and the rated capacity of PV inverter is sufficient. It shows that the PV inverter needs to provide inductive reactive power to support the voltage at the PCC when the PV system is in MPPT mode. Hence the reference value of active and reactive power can be calculated by equation (9):

\[
\begin{align*}
P_{\text{ref}} &= P_{\text{max}} \\
Q_{\text{ref}} &= Q'_{\text{pmin}}
\end{align*}
\]

(9)

5) State 5: \(Q'_{\text{pmin}} > 0\) and the rated capacity of PV inverter is insufficient. It shows that the output of PV inverter will exceed the rated capacity of PV inverter if the active power output is \(P_{\text{max}}\) and the reactive power output is \(Q'_{\text{pmin}}\). To maximize the utilization capacity of PV inverter and to provide the voltage support, the reference value of active and reactive power should follow equation (10):

\[
\begin{align*}
P_{\text{ref}} &= P_{\text{max}} \\
Q_{\text{ref}} &= \sqrt{S_N^2 - P_{\text{ref}}^2}
\end{align*}
\]

(10)

4. Simulations and results

To verify the effectiveness of the coordinated control method of active and reactive power in low voltage AC grid, a PV grid-connected simulation model, whose structure is shown in Figure 1, is built by simulation tool Matlab/Simulink. The PV generator and user load are both located at the end of the feeder. The simulation parameters are shown in Table 1 and scenarios are as follows:

Table 1. Simulation parameters of the PV grid-connected simulation model.

| Parameter                  | Value |
|----------------------------|-------|
| Rated capacity of PV inverter \(S_N\) (kVA) | 40    |
| Voltage rating at the PCC \(U_c\) (V)       | 380   |
Voltage deviation at the PCC
\[ \Delta U \]
\[ \pm 7\% \]

Line impedance
\[ Z (\Omega) \]
0.300+j0.157

Simulation scenario 1 (the PV grid-connected system works in a relatively short time in fine weather): the PV system is connected to its PCC, the ambient temperature is constantly 25°C and the user load is constantly 0. The light intensity of PV system changes stepwise with time, 600 W/m² at 0s, 800 W/m² at 0.5s, 900 W/m² at 1s. Figure 3 shows the comparison of the voltage at the PCC and the output of PV inverter between the no-control method and the coordinated control method. And the comparison of the utilization capacity of PV inverter at different periods is shown in Figure 4.

![No-control method](image1)
![Coordinated control method](image2)

Figure 3. Comparison of the voltage at the PCC and the output of PV inverter under scenario 1.

![Comparison of utilization capacity](image3)

Figure 4. Comparison of the utilization capacity of PV inverter under scenario 1.

From the comparison of Figure 3, the voltage magnitude at the PCC exceeds the upper limit (+1.07 pu) during 0.5 s to 1.4 s, the active power output of PV inverter is constantly in MPPT mode and the reactive power output is constantly 0 with the no-control method. By adopting the coordinated control method, the voltage magnitude at the PCC is adjusted to the upper limit during 0.5 s to 1.4 s. During the period from 0.5 s to 1 s, the PV inverter provides capacitive reactive power to adjust the voltage at the PCC without reducing the active power output. And the optimal output of active and reactive power is performed with active reduction during 1 s to 1.4 s. According to Figure 4, compared with the no-control method, the capacity utilization rate of PV inverter using the coordinated control method is increased by approximately 4% in period 2 (0.5-1s), which indicates that the coordinated control method has certain advantage in capacity utilization.
Simulation scenario 2 (the PV grid-connected system works in a relatively short time in rainy weather): the PV system is connected to its PCC, the ambient temperature is constantly 25 °C and the light intensity is constantly 100 W/m². The user load changes stepwise with time, 0 kVA at 0 s, 43+j10 kVA at 0.5 s, 48+j11 kVA at 1 s. Figure 5 shows the comparison of the voltage at the PCC and the output of PV inverter between the no-control method and the coordinated control method. And the comparison of the utilization capacity of PV inverter at different periods is shown in Figure 6.

![Figure 5](image1.png)
(a) No-control method

![Figure 5](image2.png)
(b) Coordinated control method

Figure 5. Comparison of the voltage at the PCC and the output of PV inverter under scenario 2.

![Figure 6](image3.png)

Figure 6. Comparison of the utilization capacity of PV inverter under scenario 2.

From the comparison of Figure 5, the voltage magnitude at the PCC lowers the lower limit (0.93 pu) during 0.5 s to 1.4 s, the active power output of PV inverter is constantly in MPPT mode and the reactive power output is constantly 0 with the no-control method. By adopting the coordinated control method, the PV inverter provides inductive reactive power to support the voltage at the PCC to the lower limit during 0.5 s to 1.4 s, which makes full use of the residual capacity of PV inverter and provides the voltage support. According to Figure 6, compared with the no-control method, the capacity utilization rate of PV inverter using the coordinated control method is increased by approximately 6% in period 2 (0.5-1s) and 26% in period 3 (1-1.4s). In some cases, the capacity utilization rate of PV inverter using the coordinated control method can reach 100%.

5. Conclusions

In this paper, the voltage characteristics at the PCC about the PV grid-connected system were analyzed and the active and reactive power coordinated control method, preferentially using the residual capacity of PV inverter for voltage regulation, was proposed.

To verify the effectiveness of the coordinated control method of active and reactive power, comparison results of the no-control method and the coordinated control method were presented under different scenarios. When the voltage at the PCC exceeded the upper limit with the no-control method, the coordinated control method can guarantee the voltage magnitude at the PCC within limits and the
optimal output of PV inverter. When the voltage at the PCC lowered the lower limit with the no-control method, but the coordinated control method can provide voltage support and make full use of the residual capacity of PV inverter.

Although the coordinated control method of active and reactive power can maximumly assure the voltage magnitude at the PCC within limits and maximize the utilization capacity of PV inverter, it has not considered that the coordinated control of multi-node PV systems in the distribution system and will be extended in the future.

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