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To cite this article: Guang Liu et al 2020 J. Phys.: Conf. Ser. 1585 012004

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Improved Reactive Power Control of Voltage Fluctuation Caused by Photovoltaic Concentrated Integration

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Abstract. In the past few years, the number of large-scale photovoltaic (PV) power station is increasing quickly. Due to the power fluctuation of PV station, the voltage in the power grid with large-scale PV stations integrated may fluctuate irregularly. It may cause transformer tap or shunt capacitor switching frequently. To smooth the voltage fluctuation, a typical solution is to install energy storage system which needs high investment. The alternative way is to use reactive power to regulate the voltage. This paper introduces the ability of reactive power control to mitigate the above voltage fluctuation problem. An improved $\Delta Q(\Delta P)$ control is proposed. Comparing with the common Q(U) droop control, the results of an actual PV station case verifies its good performance.

1. Introduction

Typical integrated schemes of photovoltaic (PV) generation in China includes building integrated photovoltaic (BIPV), rooftop PV and PV power stations. Among them, in northwest China, where sunlight is strong, PV power stations have been used on a large scale. With the increasing penetration of the PV power station, the related adverse effects to the power system becomes more severe [1]. One of them is the voltage fluctuations due to fluctuations in the output power of PV generation. The root reason is that, the PV output power is largely affected by the randomness of weather conditions. When solar irradiation changes suddenly in a cloudy day, the voltage fluctuations will be more serious [2] and may cause transformer tap or shunt capacitor switching frequently.

To solve that problem, some solutions have been proposed [3]. One of the basis of them is the power prediction of PV station. The smaller the prediction error, the smaller the effect of the power fluctuations on the grid voltage. An ultra-short-term predication method based on ground-based cloud images and neural network is proposed in [4]. It can forecast PV power in next serval hours reliably with minute-level time resolution. According to the prediction value, an effective solution is utilizing energy storage system (ESS) [5]. To reduce the operation loss and prolong the lifetime of ESS, the optimal scheduling strategy for PV station and ESS is proposed in [6]. However, most PV stations do not choose to install ESS due to its large investments and maintenance needs. By contrast, improved reactive power control is a more practical solution [7]. In order to suppress the voltage fluctuation, this paper compares two reactive power-voltage droop control methods, namely Q(U) droop control and

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 $\Delta Q(\Delta P)$ control. The oscillation problem of Q(U) control is proposed and explained. The performance of the Q(U) and $\Delta Q(\Delta P)$ control method are tested by a case of actual 40MW grid-connected PV station. The results show $\Delta Q(\Delta P)$ control has a better performance on smoothing voltage fluctuation.

2. Voltage Fluctuation Caused by PV Generation

According to Chinese grid code for power quality, voltage fluctuation refers to a series of changes or continuous changes in the voltage RMS value. The two main indicators are the relative voltage d and the rate of occurrence r. The relative voltage d is defined as equation (1).

$$d = \frac{\Delta U}{U_N} \times 100\% \tag{1}$$

1

Where ΔU is the difference between two adjacent extreme values on the voltage rms curve, and U_N is the system nominal voltage.

Figure 1 shows the simplified grid-connected PV station diagram, where U_{S1} , U_{S2} , U_{PV} represent the voltage of grid, low voltage side of the transformer and PV station terminal.



The relationship between the bus voltage U_{S2} and U_{PV} can be described as equation (2) and (3).

$$\dot{U}_{S2} = \dot{U}_{PV} + \left(\frac{P_{PV} + jQ_{PV}}{\dot{U}_{PV}}\right)^* (R_{PV} + jX_{PV})$$
(2)

$$U_{PV} = \sqrt{\frac{U_{S2}^{2} + 2(P_{PV}R_{PV} + Q_{PV}X_{PV}) + \sqrt{U_{S2}^{4} + 4U_{S2}^{2}(P_{PV}R_{PV} + Q_{PV}X_{PV}) - 4(P_{PV}X_{PV} - Q_{PV}R_{PV})^{2}}{2}}$$
(3)

The partial derivative relationship between the voltage and active power is as follows. The voltage variation ΔU_{PV} is related to system voltage U_{S2} , line impedance, the out active and reactive power of the PV station and their variation.

$$\frac{\partial U_{PV}}{\partial P_{PV}} = \frac{\sqrt{2}}{4} \begin{bmatrix} U_{S2}^{2} + 2(P_{PV}R_{PV} + Q_{PV}X_{PV}) \\ + \sqrt{U_{S2}^{4} + 4U_{S2}^{2}(P_{PV}R_{PV} + Q_{PV}X_{PV}) - 4(P_{PV}X_{PV} - Q_{PV}R_{PV})^{2}} \end{bmatrix}^{-\frac{1}{2}} \\ \times \begin{cases} 2R_{PV} + \frac{1}{2} \left[(U_{S2}^{4} + 4U_{S2}^{2}(P_{PV}R_{PV} + Q_{PV}X_{PV}) - 4(P_{PV}X_{PV} - Q_{PV}R_{PV})^{2} \right]^{-\frac{1}{2}} \\ \times \left[4U_{S2}^{2}R_{PV} - 8(P_{PV}X_{PV} - Q_{PV}R_{PV})X_{PV} \right] \end{cases}$$
(4)

3. Reactive Power Control to Smooth Voltage Fluctuation

3.1. Reactive power-voltage (Q(U)) droop control

The reactive power-voltage Q(U) droop control is one of the common voltage control method [8]. Its idea is adjusting the reactive power output of PV generation according to the interest voltage magnitude, which can be described as (5).

$$Q_{PV} = \begin{cases} Q_{\max} & U_{PV} \leq U_{low} \\ Q_{\max} - \frac{2Q_{\max}}{U_{up} - U_{low}} (U_{PV} - U_{low}) & U_{low} < U_{PV} < U_{up} \\ -Q_{\max} & U_{PV} \geq U_{up} \end{cases}$$
(5)

CEEPE 2020 IOP Publishing 1585 (2020) 012004 doi:10.1088/1742-6596/1585/1/012004

Journal of Physics: Conference Series

As shown in figure 2, with the gradual rise of voltage magnitude U_{PV} , the inductive reactive power absorbed by PV increases until its maximum value. In contrast, when voltage magnitude decreases, the PV station absorbs capacitive reactive power. However, the final voltage magnitude cannot be determined directly according to figure 2. The voltage and reactive power absorbed by the PV generation will affect each other until an equilibrium state is reached. The process can be explained by the red line in figure 3. The voltage magnitude changes with different reactive power output of PV under different active power output conditions (two black solid lines named U(P, Q) curves). At the beginning, the voltage is at operated point 1. Then reactive power absorption can be determined and voltage change to operated point 2. Finally, it will converge to the intersection of Q(U) droop curve and U(P, Q) curve. When the active power changes from P₁ to P₂, the voltage change without and with Q(U) droop control are ΔU_1 and ΔU_2 , respectively. It can be seen that ΔU_2 is smaller than ΔU_1 . In actual, if the slope of Q(U) droop curve becomes larger, the difference between ΔU_1 and ΔU_2 will also be larger. The control process may oscillate if the slope is too large [9], as shown in figure 4. Thus Q(U) droop control can't eliminate voltage fluctuation completely.



3.2. Reactive power-active power deviation $(\Delta O(\Delta P))$ droop control

To improve the disadvantage of oscillation in Q(U) droop control caused by the interaction of voltage and reactive power. The $\Delta O(\Delta P)$ droop control is proposed in this subsection. According to equation (3), the change of P_{PV} can be taken as the independent variable to make the control system more stable. Considering the typical grid-connected PV system in figure 1, the relationship between the voltage variation ΔU_{PV} , P_{PV} and Q_{PV} can be expressed in equation (4) and equation (6).

$$\frac{\partial U_{PV}}{\partial Q_{PV}} = \frac{\sqrt{2}}{4} \begin{bmatrix} U_{S2}^{2} + 2(P_{PV}R_{PV} + Q_{PV}X_{PV}) \\ +\sqrt{U_{S2}^{4} + 4U_{S2}^{2}(P_{PV}R_{PV} + Q_{PV}X_{PV}) - 4(P_{PV}X_{PV} - Q_{PV}R_{PV})^{2}} \end{bmatrix}^{-\frac{1}{2}} \\ \times \begin{cases} 2X_{PV} + \frac{1}{2} \left[(U_{S2}^{4} + 4U_{S2}^{2}(P_{PV}R_{PV} + Q_{PV}X_{PV}) - 4(P_{PV}X_{PV} - Q_{PV}R_{PV})^{2} \right]^{-\frac{1}{2}} \\ \times \left[4U_{S2}^{2}X_{PV} + 8(P_{PV}X_{PV} - Q_{PV}R_{PV})R_{PV} \right] \end{cases}$$
(6)

Equation (4) and equation (6) can be linearized near the operating point. The control target is to make the voltage fluctuation equals 0 ($\Delta U_{PV}=0$), as equation (7). Thus the relationship between the variation

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1585 (2020) 012004 doi:10.1088/1742-6596/1585/1/012004

of the PV station active power and reactive power can be obtained as equation (8), which is the control curve of the improved $\Delta Q(\Delta P)$ droop control.

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$$\Delta U_{PV} = \frac{\partial U_{PV}}{\partial P_{PV}} \Delta P_{PV} + \frac{\partial U_{PV}}{\partial Q_{PV}} \Delta Q_{PV} = 0$$
⁽⁷⁾

$$\Delta Q_{PV} = -\frac{\frac{\partial U_{PV}}{\partial P_{PV}}}{\frac{\partial U_{PV}}{\partial Q_{PV}}} \Delta P_{PV}$$
(8)

4. Simulated verification

A practical centralized PV station connected to the 35kV system is selected as the case. The system configuration is the same as figure 1. The line impedance is 0.13+j0.388 per unit, with a 5km length. The rated power of the PV station is 40MW. It is assumed that the voltage of the 35kV bus remains unchanged, which is 1.08pu. And the reactive power is provided by SVG with \pm 7Mvar capacity. The irradiation curve of one day in May 2019 published on NREL website is selected for simulating PV power fluctuation, as shown in figure 5.



The voltage magnitude curve can be obtained by calculating the power flow every minute. In the following three cases, that is, without control, with Q(U) control and with $\Delta Q(\Delta P)$ control, the simulation results of voltage fluctuation are shown in figure 6-8.



From figure 6-8, it can be seen that Q(U) method partly relieves the fluctuation of U_{PV} , while the $\Delta Q(\Delta P)$ method almost completely eliminate the voltage fluctuation problem. The slight fluctuations of voltage magnitude are caused by errors in the linearization process described in section 3. Due to

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1585 (2020) 012004 doi:10.1088/1742-6596/1585/1/012004

the limit of the maximum reactive power output, $\Delta Q(\Delta P)$ method may encounter the over voltage problem as shown in figure 8. This problem can be solved by providing sufficient reactive power output of PV station, which can be realized by utilizing the reactive power output capacity of PV inverters [7].When Q is sufficient, the voltage nearly keeps constant as shown in figure 9.



5. Conclusion

This paper introduces the ability of reactive power control to smooth the irregular voltage fluctuation problem caused by the power fluctuation of PV station. The typical structure of grid-connected PV station is discussed and the analytical voltage magnitude expression of grid connection point of PV station is given. The control effect of common Q(U) droop control is analysed and the oscillation of this control process is explained. The improved $\Delta Q(\Delta P)$ control is proposed, and the simulation results shows that the voltage fluctuation can be nearly eliminated using this method.

6. Acknowledgement

This study is supported by State Grid Xinjiang Bortala Power Supply Company technology project "Analysis of Power Quality Issues in Photovoltaic Generation Central Integration Area".

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