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# Voltage prevention and emergency coordinated control strategy for photovoltaic power plants considering reactive power allocation

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ABSTRACT

This paper proposes a voltage prevention and emergency control strategy that consists of coordinately arranging multiple reactive power sources in order to handle the point of common coupling (PCC) voltage fluctuation and stability in large-scale PV power plants. When a disturbance occurs at the PCC, dynamic reactive power compensation devices are coordinated preferentially to support the PCC voltage. After the disturbance is cleared, the reactive power in dynamic and fast devices is transferred into static and slow devices so that the static VAR generation (SVG) can maintain a large power margin for coping with the next disturbance. Moreover, the reactive power output of the individual inverter in PV power plants is coordinately allocated using a model to optimize the in-station voltage distribution. Finally, the effectiveness of the proposed control strategy is verified by an example simulation of a practical large-scale PV power plant.

## 1. Introduction

With the cost of PV power plants continuously decreasing worldwide because of falling component average selling prices, the construction of large-scale PV power plants is appreciated by governments. Compared with small and medium-scale PV systems, large-scale PV power plants utilize solar energy resources more effectively [1,2]. However, since the random fluctuation of the output power and the lack of reactive power support at the PCC usually cause a large variable range of the PCC voltage [3–5], the large PV power plants are commonly forced to equip themselves with voltage and reactive power control systems.

Under the current technical conditions, an inverter can realize decoupling control of active and reactive power, so reactive power can be adjusted dynamically [6]. PV enterprises usually make the inverters operate in unity power factor mode to maximize economic benefit. If the reactive power output of the inverters can be fully utilized, the cost of dynamic reactive power compensation devices can be greatly reduced [7].

Several control methods for inverters and PV power plants have been presented. In Ref. [8], a simplified reactive power control strategy for single-phase grid-tied PV inverters was proposed, and a 1-kVA single-phase PV inverter was built to verify the performance of the strategy. In Ref. [9], a new high-efficiency transformerless topology was proposed for grid-tied PV systems with reactive power control, and the proposed topology could inject reactive power into the utility grid without any additional current distortion or leakage current. The above research provides a theoretical and practical basis for inverters to participate in reactive power and voltage control of PV power plants. In Ref. [10], a reactive power flow control pursuing the active integration of PV systems in LV distribution networks was proposed. In Ref. [11], two new reactive power control methods that exploit the networked approach were presented. The above research solves the overvoltage issue in distribution networks using reactive power control for PV systems. The authors in Refs. [12–14] proposed control solutions to enhance the fault ride-through capability for PV power plants. In Ref. [15], a novel DVS capability as a function of PV inverters that uses both active and reactive power injection to improve the short-term voltage stability was proposed. However, the above researchers did not consider the coordination of different reactive power sources in a PV power plant.

This paper proposes a voltage prevention and emergency control strategy for PV power plants by coordinately arranging multiple reactive power sources. The reactive power in the dynamic and fast devices is transferred into the static and slow devices so that the strategy maximizes the ability of SVG reactive power. Moreover, the reactive power optimization problem is transformed into a nonlinear programming model with constraints. After solving the model, the reactive power output of every inverter is obtained, and the optimal allocation of reactive power among the inverters is realized.

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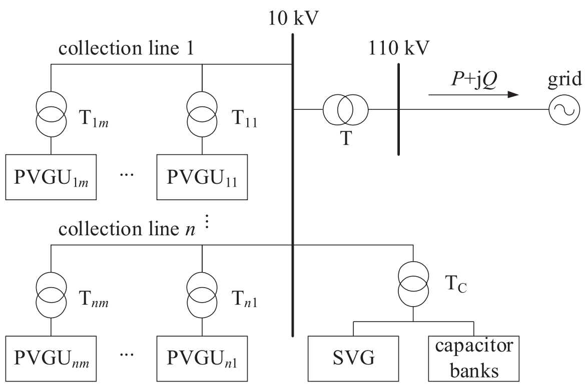


**Fig. 1.** Topology of a large-scale PV power plant.

## 2. Voltage characteristics of a PV power plant

A large-scale PV power plant is composed of PV generation units (PVGUs). Since PV arrays occupy a large land area, the distance among PVGUs is far, and the impedance of collection lines cannot be ignored. The voltage distribution characteristics provide a theoretical basis for formulating a reactive power allocation scheme.

### 2.1. Topology of a PV power plant

The common topology of a large-scale PV power plant is shown in Fig. 1. There are $n$ collection lines in the PV power plant, and every collection line has $m$ PVGUs.

A PVGU is composed of PV arrays, an inverter, and a grid-tied controller. The electric power is fed into collection lines through local transformers and then transmitted outwards through the main transformer [16]. The SVG and the capacitor banks are connected to the 10 kV bus through the transformer $T_C$. The 10 kV bus is the PCC, and it is also the voltage control point. In Fig. 1, $T_{nm}$ is the local transformer configured for the PVGUs, and $T_C$ is the transformer configured for the reactive power compensation devices. T is the main transformer of the PV power plant, and $P + jQ$ is the external transmission power of the PV power plant.

### 2.2. Voltage distribution characteristics of a PV power plant

An equivalent model of a large-scale PV power plant is shown in Fig. 2, where $P_i + jQ_i$ is the output power of the $i$th PVGU, $jQ_C$ is the reactive power output of the reactive power compensation devices, $Z_i$ is the collection line impedance between the $i$th and $i - 1$th PVGU, $Z_{Ti}$ is the equivalent impedance of the $i$th local transformer, $U_{iL}$ and $U_{iH}$ are the low and high side voltages of the $i$th local transformer, respectively, $U_{PCC}$ is the low side voltage of the main transformer, and $U$ is the grid voltage.

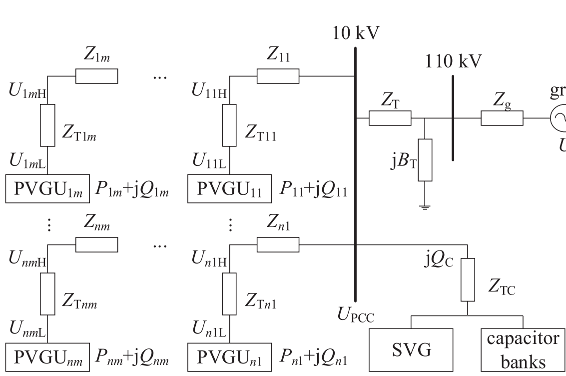


**Fig. 2.** Equivalent model of a large-scale PV power plant.

#### 2.2.1. PCC voltage of a PV power plant

Taking grid voltage $U$ as the benchmark, the PCC voltage of a PV power plant can be approximated as

$$U_{PCC} \approx U + \frac{(\sum P_i - \Delta P)R_g + (\sum Q_i + Q_C - \Delta Q)X_g}{U} \tag{1}$$

where $\Delta P$ and $\Delta Q$ are the active and reactive power losses of the main transformer, local transformers and collection lines. $Z_g = R_g + jX_g$ is defined as the Thevenin equivalent impedance of the external grid as seen from the PV power plant terminal.

The PCC voltage is related to grid voltage, the output power of the PVGUs, the output power of the reactive power compensation devices, the Thevenin equivalent impedance of the external grid and all kinds of losses. When the PCC voltage fluctuates, reactive power $\Sigma Q_i$ and $Q_C$ can be adjusted to support it.

#### 2.2.2. Terminal voltage of the PVGUs

Due to the same collection line structure, take the first collection line as an example. The $i$th PVGU port voltage $U_{iL}$ is

$$\begin{cases} U_{iL} = \frac{P_i R_{Ti} + Q_i X_{Ti}}{U_{iH}} + U_{iH} \\ U_{iH} = \frac{\left(\sum_{k=i}^{1m} P_k\right) R_i + \left(\sum_{k=i}^{1m} Q_k\right) X_i}{U_{(i-1)H}} + U_{(i-1)H} \\ U_{11H} \approx U_{PCC} \end{cases} \tag{2}$$

where $Z_{Ti} = R_{Ti} + jX_{Ti}$ and $Z_i = R_i + jX_i$.

The PVGU terminal voltage is related to the PCC voltage, the location of PVGUs at the collection lines, the impedance of the collection lines and the output power of the PVGUs.

Taking a 10 × 10 PV power plant as an example, the simulation model consists of 10 collection lines. Every collection line consists of 10 PVGUs, and the 1th PVGU is the closest to the PCC. The PCC voltage of the PV power plant is shown in Fig. 3. It shows that the PCC voltage is positively correlated with the active and reactive power, where the reactive power is dominant.

The terminal voltage distribution of the PVGUs is shown in Fig. 4. With the increase in active power, the PVGU terminal voltage increases. For one of the collection lines, the 1th PVGU port voltage is the minimum and close to the PCC voltage. The port voltage increases gradually along the direction of the collection lines. When the active power output of the PV power plant is large, a voltage over-limit is likely to occur at the end of the collection lines.

### 2.3. Reactive power capacity of the PV inverter

The reactive power capacity of a PV inverter is limited by its apparent power. If the active power output of the inverter increases, the reactive power capacity will be reduced accordingly. Since the inverter can work at 1.1 times the apparent power in a short time, the relationship between the active power output and the reactive power output of the $i$th inverter is

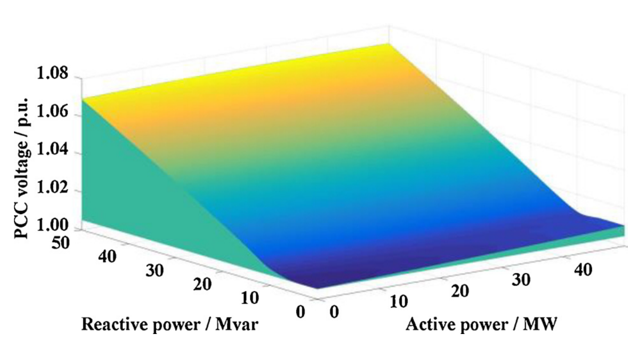


**Fig. 3.** PCC voltage of a PV power plant.