Active Power Reserve Photovoltaic Virtual Synchronization Control Technology*

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Abstract: The photovoltaic virtual synchronous generator (PV-VSG) solves the problem of lack of inertia in the PV power-generation system. The existing PV plants without energy storage are required to participate in the power grid’s frequency modulation (FM), but existing PV-VSGs with energy storage have high requirements for coordinated control. Therefore, the active power reserve PV-VSG (APR-PV-VSG) is studied. Based on the different methods to obtain the maximum power point (MPP), the peer-to-peer and master-slave APR-PV-VSG strategies are proposed. The PV inverters are deviated from the MPP to reserve active power, which is used as the virtual inertia and primary FM power. These methods equip the PV power station with FM capability. The effectiveness of the proposed control strategies is verified by simulation results.

Keywords: Active power reserve photovoltaic virtual synchronous generator (APR-PV-VSG), peer-to-peer model, master-slave model, frequency regulation

1 Introduction

Photovoltaic (PV) power generation has been developed rapidly in recent years[1-2]. However, large-scale PV plants reduce the equivalent moment of inertia of the power system and weaken the primary frequency-response capability[3-4]. Therefore, the virtual synchronous generator (VSG), which simulates the external characteristics of synchronous generators, is gradually being developed[5-7]. Since PV systems are susceptible to environmental influences, some researchers have studied the photovoltaic virtual synchronous generator (PV-VSG), which applies VSG technology to traditional PV power-generation systems, and make them participate in the grid frequency regulation. There are two ways to implement PV-VSG technology: energy-storage systems (ESSs) and active power reserve. ESSs are usually equipped on the DC or AC side of PV systems, and can effectively provide frequency modulation (FM) of the power output in a short time by controlling the charging and discharging of ESSs. The implementation of this type of PV-VSG needs to be equipped with energy storage, but the cost of energy storage equipment remains high. The active power reserve is achieved by shifting the operating point from the MPP, and the reserved active power is used as the power output of the rotational inertia and primary frequency regulation. In Ref. [8], the PV system maintains some of the power up/down capability by reducing the output. However, the reserve power is not used efficiently and energy is wasted. Ref. [9] proposes predictive PV inverter control methods, which provide a fast frequency response, but the prediction accuracy requires further research.

In this letter, according to different methods of acquiring the maximum power point (MPP) of PV power stations, the peer-to-peer and the master-slave control strategies of the active power reserve PV-VSG (APR-PV-VSG) are proposed, where the reserve power is used as the inertia power and primary FM power. The two strategies are compared. Finally, the simulation results are provided to verify the effectiveness of the proposed control strategies.

2 Topology and basic control

The PV-VSG adopts the main circuit topology of the traditional centralized PV inverter, which is shown...
in Fig. 1. \( C_1 \) and \( C_2 \) are the DC-side capacitors. Ignoring the parasitic resistance of the filter inductor and capacitor, the bridge-side inductor \( L_1 \), filter capacitor \( C_f \), and grid-side inductor \( L_2 \) form the LCL filter.

Fig. 1 Main circuit topology of PV-VSG

Considering the transformation of traditional PV power stations, PV-VSG adopts the current-source control mode. The basic control is as follows

\[
P_{\text{ref}} = \frac{J\omega_{\text{ref}} \tau s}{\tau s + 1} (\omega_{\text{ref}} - \omega_g) + k_i (\omega_{\text{ref}} - \omega_g)
\]

(1)

\[
Q_{\text{ref}} = Q_0 + \frac{1}{n} (u_{\text{ref}} - u_d)
\]

(2)

where \( k_i \) is the primary frequency coefficient, \( \tau \) is the lead lag time constant, \( \omega_g \) is the grid angular velocity, \( P_{\text{ref}} \) is the active power output, \( J \) is the virtual inertia, \( \omega_{\text{ref}} \) is the rated rotor angular velocity, \( s \) is the Laplace operator, \( u_{\text{ref}} \) is the voltage reference value, \( Q_{\text{ref}} \) is the reactive power output, \( Q_0 \) is the upper reactive power command, \( n \) is the reactive power droop coefficient, and \( u_d \) is the \( d \)-axis component of the output voltage.

3 Peer-to-peer control strategy

In the peer-to-peer control strategy, MPPT is carried out separately by each inverter. Then, the spare active power is reserved in a certain proportion and the FM is performed near the power point after spare power is reserved. During this period, the FM power could not exceed the reserve power. Owing to the change of light, the above actions are repeated at intervals. The peer-to-peer PV-VSG control must be switched between the MPPT and FM states. The given active power is the key to this switch, and it is realized by the judgement logic shown in Fig. 2.

In the MPPT state, the MPPT algorithm can use the classical perturbation-observation method to obtain the DC-side reference voltage \( u_{\text{mppt}} \). The output active power \( P_{\text{ref1}} \) is calculated as

\[
P_{\text{ref1}} = u_{\text{mppt}} (u_{\text{mppt}} - u_{\text{dc}}) G_{\text{dc}}(s)
\]

(3)

where \( u_{\text{dc}} \) is the DC-side voltage and \( G_{\text{dc}}(s) \) is the PI controller.

When the MPP is reached in the MPPT state, the operation state is switched to the frequency-regulation state according to the control requirements. To ensure that the PV-VSG runs stably to the right side of the PV curve\(^{[10]} \), the minimum voltage on the DC side needs to be limited. The MPP voltage is left with a certain margin as a warning value, and the output of a PI controller (maximum value is 0) is superimposed on the active power command of the frequency regulation. The power limit is

\[
P_{\text{limit}} = (u_{\text{dc}} - u_{\text{lit}}) G_{\text{lit}}(s)
\]

(4)

where \( u_{\text{lit}} \) is the warning voltage and \( G_{\text{lit}}(s) \) is the PI controller with a maximum output of 0.

The active power command in the frequency-regulation state is

\[
P_{\text{ref2}} = (1 - k) P_{\text{mpp}} + P_{\text{ref}} + P_{\text{limit}}
\]

(5)

where \( k \) is the reserve factor, which is generally set as 10\%, and \( P_{\text{mpp}} \) is the power at MPP.

To ensure rapidity and compensate for the hysteresis of the cutoff frequency of the filter link, a power loop is added and a PID controller is used.

\[
P_{\text{def}} = (P_{\text{ref}} - P_{\text{e}}) G_{\text{p}}(s)
\]

(6)

where \( P_{\text{ref}} \) is the specified value of the power loop, \( P_{\text{e}} \) is the output of power loop, \( P_{\text{e}} \) is the electromagnetic power, and \( G_{\text{p}}(s) \) is the PID controller. \( P_{\text{ref}} = P_{\text{ref}} \) when APR-PV-VSG is in the MPPT state, and \( P_{\text{ref}} = P_{\text{ref2}} \) when APR-PV-VSG is in the frequency-
The power calculation and current inner loop are the same as the traditional current-source VSG, and will not be discussed here.

4 Master-slave control strategy

According to the randomness principle, a certain number of PV inverters are selected as the master inverter. All the master inverters perform the MPPT algorithm, and the power and voltage of the MPP are transmitted to the slave inverters. The slave inverter averages the received MPP power and voltage of the master inverters. Then, it sets the reserve power and the primary frequency coefficient according to the average maximum power and voltage and performs FM near the reserve operating point. The control block diagram is shown in Fig. 3.

The average maximum power $P_{mpp,ave}$ is obtained through communication. The active output power command is

$$P^* = (1 - k) P_{mpp,ave} + P_{ref}$$  \hspace{1cm} (7)

where $k$ is the reserve power factor, and $(1-k)P_{mpp,ave}$ is the power of the reserve operating point of the slave inverter.

The search direction of DC-side voltage $U_{dc}$ is controlled by the difference between the active output power command $P^*$ and the instantaneous active power $P_e$. When $P^* > P_e$, $U_{dc}$ is moved toward MPP; when $P^* < P_e$, $U_{dc}$ is moved toward the open-circuit voltage. To operate the PV-VSG in the right half-plane of the $P-U$ curve, when the differential value of the DC-side power $P_{dc}$ to the voltage $U_{dc}$ is greater than 0, $U_{dc}$ is moved toward the open-circuit voltage. The DC-side voltage reference $u_{vppt}$ is obtained by the above method. The active power reference is

$$P^*_{ref} = (u_{vppt} - u_{dc}) G_{dc}(s)$$  \hspace{1cm} (8)

Since the current-source control is also used, in the master-slave control, the slave inverter is identical to that of the peer-to-peer control mode in reactive power control, current calculation, current loop, and pulse-width modulation (PWM).
5 Master-slave control strategy

The advantages and disadvantages of the two control strategies are shown in Tab. 1.

|                    | Peer-to-peer                                      | Master-slave                                   |
|--------------------|---------------------------------------------------|------------------------------------------------|
| **Advantages**     | Suitable for a wide range of applications, non-communication-based | State switching is not required                 |
| **Disadvantages**  | Need to switch between MPPT and FM states         | Only for flat areas, communication required     |

6 Simulation verification

In this letter, the simulated PV plant has a total capacity of 1 MVA, including inverters #1 and #2, each with a capacity of 500 kVA.

6.1 Peer-to-peer control verification

The simulation results of the peer-to-peer strategy are shown in Fig. 4. According to Fig. 4a, after starting PV-VSGs at time \( t_1 \), PV-VSGs reach MPP and operate after retaining a certain reserve power. The operating points of the two APR-PV-VSGs are different owing to the different irradiances. According to Fig. 4b, the grid frequency decreases. However, the grid frequency decreases more slowly than the unmodulated grid frequency, and the deviation from the reference value is also smaller, which increases the system inertia and damping. Then, inverter #1 is shaded at \( t_3 \), and the irradiance is abruptly changed from 1000 W/m\(^2\) to 700 W/m\(^2\). The PV power of inverter #1 decreases, while the grid-connected power remains unchanged. Because the instantaneous active power is in short supply, the grid frequency drops twice, and the DC-side voltage drops. When the voltage is lower than the warning value, the lowest voltage-limiting module outputs negative power, such that the output power is stabilized near the MPP, and inverter #1 outputs the maximum power.
with FM. When the second drop in the power grid occurs, inverter #2 only provides small inertia and damping, owing to its own power limitation, so the power is increased slightly. At time $t_4$, the common load decreases suddenly. Because of the lower grid frequency, inverter #1 outputs the maximum power, and inverter #2 outputs power with small inertia and damping.

### 6.2 Master-slave control verification

The simulation results of the master-slave strategy are shown in Fig. 5. Inverter #1 is the master inverter, and the disturbance-observation method is applied. Inverter #2 is the slave inverter, which adopts the PV-VSG algorithm.

Fig. 5a shows the results with varying load and slave-inverter irradiance. At time $t_1$, a 0.5 MW resistive load is suddenly increased at the PCC point. The grid frequency drops, and the inertia and damping support are provided by the slave inverter. At time $t_2$, the irradiance of the slave inverter is reduced from 1000 W/m² to 700 W/m². With DC voltage control, the output power of the slave inverter is reduced to the maximum power, and the DC-side voltage does not drop significantly. At time $t_3$, a 0.2 MW resistive load is suddenly dropped at the PCC point. Since shade from clouds is not eliminated, the slave inverter only outputs the maximum power.

Fig. 5b shows the results with varying load and master and slave inverter irradiance. At time $t_1$, the inertia and damping support can only be provided by the slave inverter when a 0.5 MW resistive load is suddenly increased at the PCC point. At time $t_2$, the irradiance of the master and slave inverters is enhanced. Because the MPP of the master inverter is adjusted, the FM factor and reserve power of the slave inverter are adjusted, and the grid frequency increases. This process is mainly caused by a sudden change in

![Fig. 5](image-url) Simulation results of master-slave APR-PV-VSG control strategy
the output power of the master inverter and an increase in the reserve power of the slave inverter. The inverter detects a sudden increase in the grid frequency, resulting in negative output of the inertial energy. Therefore, the output power of the slave inverter is reduced slightly when the steady state is reached, and finally achieves balance. At time \( t_3 \), the load dips and the frequency is modulated by the slave inverter with large inertia and damping.

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