Control Strategy of VSG Considering Coordinated Energy Management of PV and ES

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Abstract. With the increasing permeability of distributed generation in power system, the problem of weak inertia of distributed generators cannot be ignored. By imitating the mechanical and electromagnetic characteristics of the synchronous generator, the virtual synchronous generator (VSG) has the ability of smooth power output, peak regulation and frequency modulation, and becomes a kind of grid-friendly distributed power supply. However, the traditional VSG coordinates the balance of power supply and demand through the energy storage device (ES), which requires a high capacity of ES. In this paper, a control strategy of VSG considering coordinated energy management of ES and PV is proposed. Through real-time analysis of VSG’s power output and the state of ES and PV, dynamic adjustment of power output of PV and virtual characteristics of VSG will be made to realize the coordinated control of PV and ES. This strategy effectively improves the dependence of VSG on ES’s capacity by giving priority to the adjustment of PV’s power and asymmetric control of ES’s SOC.

Keywords: Smart Grid, VSG, ES, PV, Coordinated Energy Management

1. Introduction

In order to cope with the energy crisis and environmental pressure, distributed power generation technology has attracted more and more attention. As an important new energy, photovoltaic (PV) power generation has been vigorously developed in the power grid[1]. However, the distributed generation system lacks the inertia and damping of traditional synchronous generators, and the integration of distributed power makes the power system more vulnerable to power fluctuations and system failures[2,3]. With the increasing permeability of distributed generation in power system, this problem cannot be ignored.

Therefore, European scholars firstly puts forward the concept of VSG[4]. Through imitating
synchronous generator in physics and mathematics characteristic\(^5,6\), the distributed generation system with VSG control strategy, have the ability of smooth power output and frequency modulation, become a grid friendly power supply. VSG technology effectively reduces the dependence of distributed power supply on power grid support and superior dispatching system, and opens up a new way to solve the stability problem of power grid\(^7,8\).

In the current research, scholars often pay attention to the control strategy of inverter and virtual characteristics of VSG, and assume the dc side to be a power source with constant voltage and infinite capacity\(^10\). However, the output power of PV is intermittent and volatility, whereas VSG need to adjust the output power according to frequency change of the grid, so the output power of PV and VSG is bound to exist a certain amount of active power unbalance, which makes the control of VSG involves complex energy management problems in practical application\(^11,12\).

In view of the above problems, the paper \(^13-16\) improves the control strategy so that it can output power at a certain ratio of the maximum power point and solve the problem of unbalanced active power by standby power generation of PV. However, this strategy reduces the utilization rate of PV and increases the operating cost. In literature \(^12,17-18\), ES is adopted in the dc bus to make up the power difference between VSG and PV. However, this scheme requires a large capacity of ES. When the ES's capacity is insufficient, the inverter may fail to work under the original control strategy. The literature \(^19\) proposed a virtual characteristic adjustment strategy considering the SOC state of energy storage, which can modify the active power order of ES and avoid over-charging and over-discharging of ES. Literature \(^20\) proposed an energy management strategy of ES by changing PV's output power, thus achieving SOC stability of energy storage device. However, these strategies still take ES as the only core of energy management of VSG, and the characteristics of the VSG are still completely dependent on the energy storage device.

Therefore, this paper proposes a control strategy of VSG which considers coordinated energy management of ES and PV. Through real-time analysis of VSG's power output demand, the state of PV and ES, dynamic adjustment of PV's power output and VSG's virtual characteristics will be made to realize the coordinated control of PV, ES and inverter. This strategy effectively improves the dependence of VSG on ES's capacity by giving priority to the control of PV's output power and asymmetric control of ES's SOC. Finally, a VSG system with PV and ES based on MATLAB/Simulink has been built to verify the proposed control strategy.

2. Typical VSG with PV and ES

2.1. The structure of VSG

The structure of the typical VSG system studied in this paper is shown in Fig.1\(^17\). At the DC side of the system, the PV array and battery are connected in parallel on the DC bus through DC/DC converter respectively. The DC current is converted to AC current by the inverter controlled by virtual synchronous strategy, and then output to the local load and power grid through the filter circuit. The VSG is connected to the grid through a switch. When the grid fails, VSG can work in off-grid state to provide power supply for local loads.
In order to achieve the maximize utilization of PV, the Boost converter of PV adopts maximum power point tracking (MPPT) control. The bidirectional Buck/Boost converter of battery adopts constant voltage control, which is responsible for maintaining the voltage of DC bus. The battery balances the difference between the power generation of PV and the output power of the inverter through charging and discharging. The inverter adopts VSG control strategy and works in the voltage source mode. Photovoltaic power generation and battery are equivalent to prime movers in synchronous generators.

2.2. Characteristic of VSG

Using VSG to simulate the mechanical and electromagnetic characteristics of the synchronous generator, the distributed power supply can have the frequency modulation capability and inertia of the synchronous generator.

The inertia of synchronous generator is determined by its mechanical characteristics and reflected by its rotor motion equation. The classical second-order model is adopted in this paper, as shown in equation 1\(^1\).

\[
\begin{align*}
J \frac{d\omega}{dt} &= P_a - P - D(\omega - \omega_s) \\
\frac{d\delta}{dt} &= \omega - \omega_s
\end{align*}
\]  (1)

In which, \(\omega_s\) is the angular speed of grid; \(J\) is the virtual inertia of the rotor; \(D\) is the damping coefficient; \(P\) is the output active power of VSG; \(P_m\) is mechanical power.

The frequency modulation process of synchronous generator is completed by the speed regulating system composed of governor and prime mover. The model that fully simulates the speed regulating system of synchronous machine will increase the complexity of VSG control strategy. Therefore, this paper simplifies the speed regulating process of synchronous generator and only introduces the static characteristics of governor, namely:

\[
P_{ref} - P = K_\omega (\omega - \omega_s)
\]  (2)

Where, \(P_{ref}\) is the reference power; \(\omega\) is the actual angular speed; \(K_\omega\) is the differential coefficient of prime engine.

The small signal model is established according to equation (1):
When frequency change, the power change due to the frequency change is:

\[
\frac{\Delta P}{\Delta \omega} = J \frac{1}{s} + \frac{(D - k_o)s}{k_o(s + k_o)} \quad (4)
\]

As can be seen from the above equation, when appropriate control parameters were selected, VSG could adjust the output power according to the change of system frequency and photovoltaic power, so as to stabilize the system frequency and improve the characteristics of distributed power supply. In addition, according to the final value theorem, VSG has frequency modulation characteristics similar to droop control.

2.3. Work mode of ES

Due to the advantages of high energy density and low price, lead-acid batteries are widely used in the optical storage and grid connected VSG system \[^{[19]}\]. In this section, a typical lead-acid battery model is used to analyze its charge-discharge characteristics and its working mode in VSG.

The residual capacity of the battery is usually expressed by SOC, and the SOC value of Battery, Ssoc, can be expressed as follows:

\[
S_{soc} = S_0 - \frac{1}{S_s} \int P_s dt \quad (5)
\]

In order to protect the battery, it should be prevented to over-charge or over-discharge, which means the SOC of ES needs to be kept within a certain interval. In addition, the energy storage device needs to consider the possibility of discharging and charging at the same time. Thus, the SOC of the energy storage device is generally adjusted at about 0.5 to ensure that the energy storage device has sufficient charge and discharge margin.

3. Coordination energy management of PV and ES

3.1. Basic principles of coordination energy management

The energy coordination management strategy proposed in this paper will enable all of VSG, PV and ES to participate in active power balance instead of using ES to balance the active power of PV and VSG, so as to reduce the dependence of VSG on ES. The basic principles of energy management strategies proposed in this paper are as follows:

1) When the output power of VSG is larger than PV, the energy storage device will discharge to make up the power difference. When the output power of VSG is less than PV, the ES will be charged firstly. When the energy storage device is fully charged, the output power of PV will be reduced.
2) The SOC of the ES should be maintained at a high level to allow for adequate discharge capacity in the event of a power gap. When the SOC of the energy storage device is lower than a certain level, the output power of VSG will be adjusted to charge the ES;

3) Given the limited capacity of ES, the inertia of VSG should be guaranteed first. In other words, when the SOC of ES is lower than a certain level due to continuous discharge, the frequency modulation coefficient of VSG should be reduced, and part of the frequency modulation function would be abandoned, so as to maintain the SOC level of the energy storage device.

According to these principles, the state of ES has been replanted according to its SOC level, as shown in figure 2.

![Figure 2. SOC mode of ES](image)

The SOC of ES has been divided into the following sections:

- \([\text{SOC}_{\text{max}}, 1]\): over-charge zone(H). It should be avoided in operation;

- \([\text{SOC}_{\text{opt}}, \text{SOC}_{\text{max}}]\): optimal operation zone(O). ES can charge and discharge normally to ensure the realization of SVG's inertia and frequency modulation functions in this zone;

- \([\text{SOC}_{\text{pro}}, \text{SOC}_{\text{opt}}]\): SOC protection zone(P). Part of frequency modulation ability of VSG should be gave up to avoid continuous discharge;

- \([\text{SOC}_{\text{adj}}, \text{SOC}_{\text{pro}}]\): SOC adjustment zone(A). When SOC drops to this zone, it starts to adjust the output feature of SVG to charge ES until the SOC reaches \(\text{SOC}_{\text{far}}\).

- \([\text{SOC}_{\text{min}}, \text{SOC}_{\text{adj}}]\): SOC buffer(B). In this area, the energy storage device only charges, so as to avoid over-discharge of the energy storage device.

- \([0, \text{SOC}_{\text{min}}]\): over-discharge area of energy storage device, which should be avoided during operation.

3.2. Control strategy of coordination energy management

According to the control principle described in the previous section, the control strategy of energy coordination management is designed in this section. By analyzing the power output demand of VSG and states of ES and PV, the control strategy can determine the working modes of VSG, ES and PV, and outputs the corresponding enabling signals. The control strategy can be represented by Fig.3, and table 1 is the decision-making algorithm of the energy management strategy.
Figure 3. Coordination Energy Management strategy

| State of ES | $P_{PV} > P_{SVG}$ | $P_{PV} \leq P_{SVG}$ |
|-------------|-------------------|------------------|
|             | $P_{PV} > P_{max}$ | $P_{PV} < P_{max}$ | $P_{PV} = P_{max}$ |
| H           | PV: reduce P       | PV: increase P    | PV: remain unchanged |
|             | ES: maintain bus voltage | ES : maintain bus voltage | ES : maintain bus voltage |
|             | SVG : remain unchanged | SVG : remain unchanged | SVG : remain unchanged |
| O           | PV: remain unchanged | PV: increase P    | PV: remain unchanged |
|             | ES: maintain bus voltage | ES : maintain bus voltage | ES : maintain bus voltage |
|             | SVG : remain unchanged | SVG : remain unchanged | SVG : remain unchanged |
| P           | PV: remain unchanged | PV: increase P    | PV: remain unchanged |
|             | ES: charge         | ES : maintain bus voltage | ES : maintain bus voltage |
|             | SVG : remain unchanged | SVG: adjust $P_{ref}$ | SVG: adjust $P_{ref}$ |
| A           | PV: remain unchanged | PV: increase P    | PV: remain unchanged |
|             | ES: charge         | ES : maintain bus voltage | ES : maintain bus voltage |

Table 1. Energy management strategy decision table
3.3. Control strategy of Photovoltaic

The dynamic characteristics of PV can be qualitatively described by the power-voltage curve, shown in Fig.5. According to Fig.5, the output power of PV will vary with the port voltage. The following output features can be obtained:

1) Within the voltage range $[0, U_{oc}]$, there is only a single maximum power point $(U_{mpp}, P_{mpp})$.

2) When the output power is lower than the maximum power point, two operating points, A and B, with the same output power will appear, corresponding to different port voltages.

3) The power-voltage curve of PV can be divided into two operating areas with the MPP point as the boundary. In the left half plane, the output power $P_{pv}$ of PV will increase with the increase of DC voltage, namely $dP/dU > 0$; In the right half plane, the output power the PV will decrease with the increase of dc voltage, namely $dP/dU < 0$.

![Figure 4. The P-U characteristic of PV](image)

When the photovoltaic power supply runs at the point A, if the power demand increases, the power supply of PV is required to increase to meet the power demand. From the perspective of physical process, the increase of power demand will lead to the discharge of DC bus capacitance directly. Due to capacitor's discharge, the DC voltage of PV will be reduced. Further, according to the power characteristics of PV shown in figure 4, the voltage reduction on the dc side will increase its output power. Similarly, when the PV is running at the point A, if the power demand is reduced, the excess power needs will lead to the charge of DC bus capacitance and the increase of DC voltage. As shown in figure 4, an increase in the voltage on the dc side will reduce the output power of PV. According to the above analysis, point A is the stable operation point of PV, and it can be concluded that the area on the right in figure 4 is the feasible operation area of PV.

However, when the PV is operating at the point B, the power-voltage characteristic at this point
will cause the change of PV’s output power to be inconsistent with the power demand. Thus, the power gap will be aggravated, which will lead to a dc voltage drop and even collapse. It can be seen that the area on the left plane in figure 4 is not the area where the PV can operate stably.

According to the above analysis, the operation point of PV should be set in the right plane of its power-voltage curve, and the output power of PV can be dynamically adjusted by feeding back the DC bus voltage to the Boost converter[21].

3.4. Adjustment of VSG’s frequency modulation characteristics

The output characteristics of SVG mainly include inertia and frequency modulation. By adjusting the frequency modulation characteristics of SVG, the output power of SVG can be adjust to realize the maintenance of ES’s SOC. In this paper, a frequency modulation characteristics adjusting strategy is proposed.

In this paper, segmented VSG frequency modulation characteristic is selected. The frequency modulation characteristic curve is divided into horizontal straight segment and oblique segment, shown as below:

\[
k_\omega = \begin{cases} 
P_{PV} / \Delta \omega_{\max} & \omega_{\min} \leq \omega < \omega_{\max} \\
0 & \omega < \omega_{\min} \text{ or } \omega > \omega_{\max}
\end{cases}
\]  

(6)

In this paper, when the SOC of ES is abnormal, the frequency modulation characteristics will be adjusted by changing the \( P_{\text{ref}} \) in Eq. (2), and shifting the frequency modulation characteristics curve of VSG.

Assuming \( P_{\text{ref}} \) increases, the frequency modulation characteristics curve will shift to the right as shown in Fig. 6. In the figure, \( P_V \) and \( P'_V \) are the active power assumed by VSG before and after adjustment respectively. \( \Delta P_V = P'_V - P_V > 0 \). This means that VSG will output more power as the curve shifts to the right.

![Figure 5. Right shift of frequency modulation characteristics](image)

On the contrary, when the frequency modulation characteristics curve is shifted to the left, as shown in Fig. 7, The frequency of the system goes down, and the active power output of VSG will decrease. In this case, other power sources in the system will assume more active power.
When the operating point is located in the negative half axis of the X-axis, VSG will absorb power from the grid to charge its own energy storage equipment. This situation should be avoided.

Figure 6. Left shift of frequency modulation characteristics

4. Realization of control strategy

4.1. Control of Inverter

The control of converter can be divided into two parts: one is the simulation of virtual characteristics, and the other is the adjustment of frequency modulation characteristics. The control of the inverter is shown in Fig. 7.

A. Control of virtual characteristics

The mechanical characteristics of the synchronous generator have been discussed in the previous section. Here, the electromagnetic characteristics and excitation characteristics of synchronous generator are mainly discussed. In order to simulate the electromagnetic characteristics of the synchronous generator, the conventional synchronous generator model is simplified. Without considering the damping winding, the synchronous inductance is set as \( L_s \) and the synchronous resistance as \( R_s \). In this paper, the VSG electromagnetic equation based on d-q coordinate system is adopted as follows:

\[
\begin{align*}
\dot{u}_d^* &= -R_s i_d - L_s \frac{di_d}{dt} + \omega L_s i_q + u_i \\
\dot{u}_q^* &= -R_s i_q - L_s \frac{di_q}{dt} + \omega L_s i_d
\end{align*}
\]  

(7)

The voltage regulation equation of synchronous generator’s excitation characteristics can be simplified as follow\(^{[22]}\):

\[
E = \left( U_{\text{ref}} - U_m \right) \frac{k_u}{s}
\]

(8)

Where, \( U_m \) is the effective value of VSG output three-phase voltage; \( k_u \) is the integral coefficient.

According to q-u droop characteristics:

\[
U_{\text{ref}} = U_n + n(Q_{\text{ref}} - Q)
\]

(9)
When, $n$ is the sag coefficient; $Q_{ref}$ is the reference value of reactive power; $U_a$ is the reference value of voltage.

The equation of the virtual excitation controller can be obtained as follows:

$$E = (U_a + n(Q_{ref} - Q) - U_w) \frac{k_v}{s}$$  \hspace{1cm} (10)

B. Adjustment of frequency modulation characteristics

When the system runs stably, the output of the frequency modulation characteristic adjustment module is 0.

When the SOC of the energy storage device is less than $SOC_{opt}$, the enabling signal $Enable_1$ of the frequency modulation characteristic adjustment module will be set to 1. The frequency modulation characteristic adjustment module starts to adjust the output of VSG, and gives up part of the frequency modulation capability, so that the SOC of ES device can be maintained in the P area. The control block uses the difference between $(SOC_{opt} + SOC_{pro}) / 2$ and SOC of ES as input, and it will be added to $P_{ref}$ after passing through PI controller.

![Figure 7. VSG control block diagram](image)

When the SOC of the energy storage device is less than $SOC_{pro}$, the enabling signal 2 $Enable_2$ of the frequency modulation characteristic adjustment module will be set to 1. The FM characteristic adjustment module will start to adjust the output of VSG to charge the ES, so that the SOC of the energy storage device can return to the P area. The control block uses the difference between $SOC_{opt}$ and SOC of the energy storage device as input, and it will be added to $P_{ref}$ after passing through a PI controller. The control block will charge the ES until the SOC is above $SOC_{opt}$.
Considering that adjusting the SOC of ES mainly requires left-shift frequency modulation characteristic curve, the upper limit of PI module is set to be 0, and the lower limit of the PI module is the maximum allowable offset.

4.2. Control of PV converter

When the ES needs charging or the active power is insufficient, the PV works in MPPT mode. When the active power is excessive and the SOC of ES is above \( SOC_{\text{max}} \), PV works in the power-controlled mode. The enabling signal of PV is set to be 1, and the PV will maintain the DC bus voltage. In this case, the energy storage device does not work. The control block uses the difference between \( U_{dc,\text{ref}} \) and \( U_{dc} \) as input, and it will be added to the reference of PV's DC voltage \( U_{PV_{\text{ref}}} \) after passing through a PI controller.

In order to ensure that the PV operates on the right half of its Power-Voltage characteristic curve, the lower limit of PI module is 0, and the upper limit is the difference of PV's open circuit voltage \( U_{op} \) and \( U_{\text{MMP}} \).

![Figure 8. Control block of Boost converter](image)

4.3. Control strategy of ES converter

When the energy storage device does not work, the reference value of ES's current is 0. When the energy storage device is working in the mode of maintaining the DC bus voltage, the enable signal of the energy storage device will be set 1. The control block uses the difference between \( U_{dc_{\text{ref}}} \) and \( U_{dc} \) as input, and it will be set to be the reference of ES's current \( I_{ES_{\text{ref}}} \) after passing through a PI controller.

The upper and lower limits of PI controller are respectively the maximum charging and discharging current of ES.

![Figure 9. Control diagram for Buck/Boost converter](image)
5. Simulation and verification

In order to verify the VSG energy management strategy proposed in this paper, a VSG system with the structure shown in Fig. 1 was constructed under the MATLAB/Simulink simulation environment. The parameters of the system are shown in Table 2.

| Parameters                  | Values |
|-----------------------------|--------|
| Rate power of PV /kW        | 220    |
| $U_{OP}$ of PV /kV          | 400    |
| $U_{MMP}$ of PV /kV         | 320    |
| Power of ES /kW             | 15     |
| Voltage of DC bus /kV       | 1000   |

The simulation scene:

0-1s: the system runs steadily;

0-4s: the load level increased, which make the system frequency drop to 48.7Hz.

4-10s: the load level continues to increase, which make the system frequency drop to 49.6Hz.

The change of system frequency is shown in Fig. 11.

![Figure 10. The frequency of system](image-url)
Fig. 11~ Fig. 13 shows the simulation results of VSG’s output power $P_{\text{vsg}}$, PV’s output power $P_{\text{pv}}$, ES’s output power $P_{\text{es}}$, ES’s SOC, and DC voltage $U_{\text{dc}}$.

From Fig. 12 to Fig. 16, it can be seen that:

At 1-4s, the load level increases and the system frequency decreases. At this time, the PV has standby capacity, so the PV is controlled to increase the output power. By observing the DC bus voltage, the dynamic process of adjusting the output power of PV can be seen. At this time, the voltage of the dc bus drops, making the operating point PV constantly adjust to the maximum power output point. The output power of VSG basically reaches a balance with the output power of the PV, and the DC bus voltage returns to the original level.

At 4-7.1s, the load level continues to increase, and due to the frequency modulation characteristics, the power output by VSG is already larger than the output power of PV. Then the ES makes up the power difference, and the SOC of the energy storage device decreases rapidly.

At 7.1s-10s, the SOC level of the energy storage device drops below 0.5 to reach the SOC protection state of the energy storage device. Then, the frequency modulation characteristic of VSG is adjusted to reduce the output power of VSG. So that the SOC of the energy storage device will not further decline, to ensure the inertia of VSG.

![Figure 11. Output power of VSG](image)

![Figure 12. Output power of PV](image)
Figure 13. Output power of energy storage

6. Conclusion

In this paper, a control strategy of VSG considering coordinated energy management of ES and PV is proposed. By analyzing the power output demand of VSG and states of ES and PV, the proposed control strategy can adjust the working output power of VSG, ES and PV, so that all of ES, PV and VSG can participate in the balance of active power. Simulation based on MATLAB/Simulink verifies the effectiveness of this strategy. This strategy effectively improves the dependence of VSG on the energy storage device, which will be of great significance to the cost reduction and practical application of VSG.

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