Research on Coordinated DC voltage Control Strategy of DC Microgrid based on Photovoltaic Power Generation System

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Abstract. DC microgrid system is a flexible and commonly used renewable power generation system. Among them, the energy storage system (ESS) can reduce the waste light of the photovoltaic (PV) power generation system and provide stable power output for the power grid. However, a reasonable control strategy is needed to realize the energy balance of PV, grid-connected converter and ESS, so as to ensure the safe and stable operation of DC microgrid. Therefore, this paper proposes a DC voltage coordination control strategy without communication. The control strategy can automatically coordinate the working state of each converter of DC microgrid, which according to the change of DC voltage and the ESS's state of charge (SOC). At the same time, the inertia of DC voltage in each working state is analyzed, and the stability of DC microgrid is improved through the backup inertia support of ESS. Finally, the effectiveness of the proposed method is verified by simulation and experiments.

1. Introduction

With the development of China’s economy and society, the demand for electric power is gradually increasing. Due to the characteristics of environmental protection and local consumption, the penetration rate of distributed renewable energy such as solar energy and wind energy in the power grid has a great growth. However, the power generated by the distributed renewable energy is intermittent. To increase the consumption of distributed renewable energy, and stabilize the output of distributed renewable energy, it is necessary to configure a certain energy storage system (ESS) [1]. This paper studies the DC microgrid system composed of photovoltaic (PV) and ESS.

There are some researchs analyse the coordinated control strategy of DC islanding microgrid [2, 3]. However, this paper studied the PV-ESS DC microgrid system connected to the distribution network. Among this system the output power of grid-connected converter need to frequent adjustment according to AC bus voltage. After that, the input power of PV also fluctuated according to the solar power and temperatures. Although the ESS can trade off the balance of input and output power. However, due to capacity constraints, there will be many operating modes of DC microgrid [4]. Therefore, it is necessary to specify a coordination control strategies to maintain the safe and stable operation of the PV-ESS DC microgrid power generation system. At present, some coordination control strategies adopting hierarchical control, which need a master-slave controllers, but they are complicated and expensive. There are also some simple and reliable coordinated control strategy can operate without communication [5]. The coordinated control strategy without communication is also adopted in this paper. About these control strategies, the control state of the converter is selected according to the fluctuation of DC voltage and the state of charge (SOC) of the ESS [6].
The DC voltage of DC microgrid will fluctuate sharply due to the power fluctuation of input and output. The amplitude of fluctuation depends on the inertia of DC side voltage, and the inertia of DC voltage depends on its control mode. Firstly, this paper analyses the inertia of DC link under different control modes. The Ref. [7] points out that ESS, as a flexible energy, has a certain inertia reserve. Therefore, in this paper, the inertia of DC link is enhanced through the control of battery.

The following contents of this paper are organized as follows. The second section introduces the topology of PV-ESS DC microgrid, the third section introduces the coordinated control strategy of PV-ESS DC microgrid. After that, section 3 analyzes the DC bus inertia under different control modes, and a control strategy of energy storage is proposed to enhance the DC link inertia. In the section 5, the effectiveness of the proposed method is verified by an example simulation and experiment. Finally, the section 6 section conclude the whole paper.

2. Low voltage distribution network structure based on PV-energy storage system

Figure 1 shows a typical PV-ESS connected to low voltage distribution network. The PV-ESS DC microgrid is composed of PV power generation systems and energy storage system (ESS), Due to the light and temperature of each PV arrays may be different, so the PV arrays is connected to the DC bus through DC/ DC converter. To make sure that PV arrays can work in the maximum power point tracking (MPPT) mode by using DC/ DC converter for control. The addition of energy storage unit can smooth the active power output of photovoltaic power generation system. The low-voltage distribution network consists of power supply and load. The PV-ESS microgrid system is connected to the system point of common coupling (PCC) through the grid connected inverter, and the power injected into the low-voltage distribution system is adjusted through the control of the grid connected inverter. The injected active and reactive power needs to be adjusted according to the safe operation conditions of the power grid to prevent voltage overrun in the low-voltage distribution network [8].

This paper mainly studies the coordinated control strategy of photovoltaic energy storage system, realizes the energy management of PV-ESS DC microgrid system and improves the stability of optical storage DC microgrid power generation system. Research on voltage governance of PV connected to low-voltage distribution network.

3. Operation mode of PV-ESS DC microgrid

The proposed DC microgrid operates in three different modes as shown in Figure 2. The operation mode of PV-ESS DC microgrid is depending on the availability of PV power, the output active power of grid-connected converter and the ESS capacity of either charging/ discharging. \( P_{PV} \) is the power generated by the PV arrays, and the availability and magnitude of \( P_{PV} \) is determined by the sunshine. In order to make full use of the capacity of grid connected inverter, it can send active and reactive power, but only active power will affect the fluctuation of DC voltage of microgrid. \( P_S \) is set as the
active power send out by grid connected inverter; $P_{\text{ESS}}$ is the power delivered by the ESS. In this paper, the ESS charge and discharge range is limited to 20%~80%.

(1) Operating mode 1
In this operating mode, with the enough sunshine power and appropriate temperature, the PV works in MPPT power generation mode, and its generated power is $P_{\text{pv}}$, and the grid-connected converter is transmitting power from DC bus to power grid, and the transferred active power is $P_{s}$, and the SOC of ESS owns sufficient margin, at this mode, the ESS controls the DC voltage and works as a balance node, to maintain the $U_{dc}$ in the rated value of 1.0$U_{n}$.

(2) Operating mode 2
In this state, with the too many sunshine power, the power generated by the PV is more than the output power of grid connected converter, that is $P_{\text{pv}}>P_{s}$. However, the battery is sufficient (its SOC≥80%), at this time, the voltage of DC bus will rise up. To ensure the safety of DC microgrid, when the DC voltage is higher than 1.05$U_{n}$, the PV arrays needs to reduce its generated power and work in DC voltage control mode. And to maintain the $U_{dc}$ in the rated value of 1.05$U_{n}$. Moreover, if there are multiple photovoltaic arrays, they should adopt DC voltage droop control.

(3) Operating mode 3
In this state, it is in the night, and with no sunshine power, the PV power generation system operates in idle mode, thus the $P_{pv}$=0. Due to full discharge, the energy storage system reaches SOC≤20%, so no current is generated by ESS to make the $P_{\text{ESS}}$=0. At this time, the DC voltage will drop to 0.95$U_{n}$. In order to make full use of the reactive power of the grid connected converter, it will works in STATCOM mode, and maintains of the DC voltage at 0.95$U_{n}$.

![Figure 2. Operation mode of DC microgrid](image)

![Figure 3. Flow chart of operating modes](image)
Figure 3 shows the flow chart of operating modes of DC grid. In this paper, the PV arrays can always work in the MPPT mode when the energy storage system is not fully charged. But when the energy storage is full (SOC greater than 80%), it needs to run at reduced power mode (constant voltage mode). At night, the photovoltaic array will work in an idle state. The battery carries out reasonable charge and discharge control according to its SOC state. In order to effectively extend the service life of the battery, when SOC of the energy storage system is greater than 20%, it provide a certain amount of active power support for the grid-connected inverter. If the energy storage is insufficient, the grid-connected inverter will work in STATCOM mode, which fully uses the reactive power regulation capability of the grid-connected inverter.

4. Control Strategy of PV-ESS DC microgrid.

4.1 DC voltage inertia analysis

In Figure 2, the PV power generation system, ESS and grid-connected converter all have the ability to provide inertial support to the DC microgrid. The relationship between the output active power of each converter based on different control modes and the actual active power injected into the DC bus can be expressed as

$$P_{\text{out}} - P_{\text{in}} = P_{\text{C}} = C_{\text{dc}} u_{\text{dc}} \frac{du_{\text{dc}}}{dt} \quad (1)$$

where $P_{\text{in}}$ is the power injected into the DC bus; $P_{\text{out}}$ is the active power output by the grid-connected converter; $P_{\text{C}}$ is the discharge power of the capacitor $C_{\text{dc}}$ at the DC bus; $U_{\text{dc}}$ is the DC bus voltage. When the DC microgrid operates stably, $P_{\text{C}}=0$, that is, $P_{\text{in}}=P_{\text{out}}$. When the DC microgrid is disturbed, increases or decreases power is $\Delta P_{\text{out}}$, this unbalanced power will cause the DC bus voltage to drop or rise. In order to suppress the voltage change of DC bus, the DC side capacitance will release or absorb power according to the voltage change, but the suppression effect is very limited to the capacitor capacity. However, with appropriate control strategy, the controllable power sources such as the energy storage system can be provided additional inertia of DC bus voltage.

It is assumed that additional inertia control is applied to the DC/DC converter to make the controllable power supply to the DC microgrid, of which can provide inertia power $\Delta P_{\text{vir}}$, in case of sudden voltage change. At this time, the power balance relationship on both sides of the capacitor can be expressed as:

$$P_{\text{out}} + \Delta P_{\text{out}} = P_{\text{in}} + \Delta P_{\text{vir}} + P_{\text{C}} \quad (2)$$

It can be seen from equation (2) that if the inertia power $\Delta P_{\text{vir}}$ is used to balance the disturbance power $\Delta P_{\text{out}}$, and then, the $P_{\text{C}}$ will decrease. Therefore, the voltage variation of the DC bus is smaller, that is, the inertia of DC bus is stronger.

The inertia power provided by the controllable power supply can be expressed as

$$\Delta P_{\text{vir}} = C_{\text{vir}} u_{\text{dc}} \frac{du_{\text{dc}}}{dt} \quad (3)$$

where $C_{\text{vir}}$ is the virtual inertia control coefficient of the DC/DC converter. The $C_{\text{vir}}$ can be used to adjust the virtual inertia power, which is provided by the DC/DC converter under the same voltage fluctuation. By Combining equations (1)-(3), the following equation can be obtained:

$$P_{\text{out}} - P_{\text{in}} + \Delta P_{\text{vir}} = P_{\text{C}} + \Delta P_{\text{vir}} = \left( C_{\text{dc}} + C_{\text{vir}} \right) u_{\text{dc}} \frac{du_{\text{dc}}}{dt} \quad (4)$$

According to equation (4), by applying additional inertia control strategy, and increasing virtual inertia control coefficient, the operating inertia of DC microgrid can be improved, which is conducive to the stable operation of DC microgrid.

4.2 Overall control strategy of DC microgrid

Figure 4 shows the control strategy of DC microgrid system, which composed of the PV, ESS and grid-connected converter (GCC). The PV converter adopts a Boost circuit to connect the PV with DC
bus. The ESS is connected to the DC bus through a bidirectional DC/DC converter to realize the
flexible flow of energy. The GCC adopts a three-phase full-bridge VSI, which connects the DC bus to
the low-voltage distribution network through a filter circuit.

The PV converter system has three working modes: MPPT mode, voltage control mode and idle
mode. When PV generated power can be absorbed by the load or the ESS, the PV converter works in
MPPT mode. However, if the generated power of the PV system cannot be disposal, the PV converter
will reduce power and works in voltage control mode. When at night, the PV converter works in the
idle mode.

\[
\begin{align*}
P_{\text{ref}} & = \frac{2}{3} U_{\text{ref}} \\
U_{\text{dc ref}} & = \frac{2}{3} U_{\text{ref}}
\end{align*}
\]

Figure 4. The control strategy of PV-ESS DC microgrid system.

As the ESS’s role is to balance the power generated by the PV and the output of GCC. Moreover,
the state of charge (SOC) of ESS should be fully concerned. When the SOC of ESS is within a
reasonable range, the ESS is work in voltage control mode. When the SOC is lower than the lower
limit, The ESS work in the current-limiting charging mode, and when the SOC is higher than the
upper limit, The ESS will work in the current-limiting discharge mode. Moreover, to suppress the
voltage fluctuations of the DC bus, the additional inertia control add an additional current to the
reference current of bidirectional conduction DC/DC converter.

The control of GCC is relatively simple. When there is sufficient energy output from the PV-ESS
DC microgrid, it works in PQ mode. When there is no enough output power, it works in STATCOM
mode to compensate the reactive power of the low-voltage distribution network.

5. Simulation
In this section, a simulation model of PV-ESS DC microgrid power generation system with
corresponding control block is established using the simulation software MATLAB/Simulink. The
total PV-ESS DC microgrid simulation model include a PV arrays, a ESS composed of battery, and
voltage source converter connected to 380V low voltage distribution network. The $U_{n, low}$, $U_n$ and $U_{n, high}$ are set to 680V, 700V and 720V, respectively. The DC microgrid composed of a PV arrays and ESS. In this simulation model, the light intensity and temperature of the PV arrays are respectively set to 1000 W/m² and 25°C, the corresponding max power at this situation is 24 kW. Moreover, the other detail simulation parameters are shown in Table 1.

Table 1. The simulation parameters.

| System                  | Parameters values | System                  | Parameters values |
|-------------------------|-------------------|-------------------------|-------------------|
| PV arrays               | Open circuit voltage/V 64.2 | Grid voltage/V 380      |                   |
|                         | Short-circuit current/A 5.96 | Parral connected components 8 |                   |
|                         | Voltage of Max Power point/V 54.7 | Grid voltage/V 380      |                   |
|                         | current of Max Power point /A 5.58 | Grid frequency/Hz 50    |                   |
|                         | Seris connected components 8 | Filter reactor/mH 3     |                   |
|                         | Parral connected components 8 | Capacitor of DC bus/mF 4 |                   |
|                         | Rated capacity/Ah 50    | DC link voltage/V 700   |                   |
|                         | Rated voltage/V 360    |                         |                   |

To certify the effectiveness of the coordinated control strategy proposed in this paper, the control effect and operation of the system under multi-mode are simulated.

(1) At 1-2s, the PV power generation system can provide sufficient energy, and the ESS has sufficient SOC margin. Therefore, the PV works in MPPT mode. And the ESS maintenance the DC bus voltage with 700V, and the GCC outputs active and reactive power. The total system work at model 3 in the figure 3;

(2) At 2-3s, the output active power GCC is decreased, and the SOC of ESS reaches the upper limit, so the DC voltage rises. At this time, the PV should operates in the DC voltage control mode and maintains the DC bus voltage of 720V. The total system work at model 2 in the figure 3;

(3) At 3-4s, the output active power of GCC increases and is greater than the PV output power, so the DC voltage decreases, the ESS begins to discharge and maintains the DC voltage of 700V, PV operates in MPPT mode. The total system work at model 3 in the figure 3;

(4) At 4-5s, both PV and ESS work in the idle state. At this time, the GCC works in STATCOM mode, to maintains the DC voltage at 680V, and sends reactive power to compensate the low voltage distribution network. The total system work at model 1 in the figure 3.

Figure 5. The simulated waveform of PV output power
Figure 6. The simulated waveform of DC bus voltage from mode 3 to mode 2

Figure 7. The simulated waveform of DC bus voltage from mode 2 to mode 3

Figure 8. The simulated waveform of DC bus voltage from mode 2 to mode 1
As shown in Figure 6-Figure 9, the proposed control strategy can smooth the switching of various control modes according to the power change of the total system, as well as maintain the energy balance and stability of the total DC microgrid system. As shown in the Figure 6 and Figure 7, the inertia control strategy can improve the reliability when operation mode switching, and increase the voltage recovery speed, and decrease the fluctuation of DC bus voltage. When PV and ESS are idled at night, the GCC can also work in STATCOM mode to provide reactive power and voltage support for low-voltage distribution network. Therefore, the effectiveness of the proposed coordinated control strategy in this paper is verified.

6. Conclusion
In this paper, the relation of energy change of the system and DC voltage of DC bus are analysed, on the basis of theoretical analysis, a coordinated control strategy without communication based on DC voltage and ESS’ SOC is proposed. In order to enhance the inertia of the system during mode switching, the inertia support strategy provided by ESS is adopted. And then, an equivalent system simulation model are build. Finally, the control strategy of PV-energy storage system and voltage control method of GCC is verified.

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