Research on control characteristics of AC/DC hybrid microgrid based on droop control

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Abstract. When the master-slave microgrid switches from the grid-connected operation mode to the island operation mode, the main converter and its control strategy are switched at this time. With the unintentional islanding of the microgrid, there is an uncontrollable voltage phenomenon during islanding detection, causing undervoltage or overvoltage, which endangers the overall microgrid stability and safety. Aiming at this problem, a microgrid control strategy is proposed in this paper: during grid-connected operation, both the grid-connected converter and the energy storage converter adopt droop control to jointly control the bus voltage stability, while also ensuring the power balance between the microgrid and the public grid. The grid-connected converter exits operation after islanding, and the energy storage converter becomes the main converter to stabilize the bus voltage while maintaining the power balance of the load. The output of the converter in this method has continuity, which can well realize the seamless switching of microgrid from grid-connected to island operation. A simulation model of the solar-storage microgrid was built in PSCAD. The simulation verifications of its grid-connected and island mode and seamless switching control prove the effectiveness of the control strategy proposed in this paper.

1. Introduction
Microgrid is an important form of utilization of renewable energy [1-2]. Various types of distributed generators (DG) are connected to the microgrid through appropriate control strategies [3]. DG can not only relieve the pressure of public grid power supply when connected to the grid, but also meet the power demand of regional users when isolated. Therefore, the microgrid needs to ensure the normal operation of the grid-connected and islanding modes. At the same time, the mode switching process also needs to minimize the impact on the microgrid to ensure the reliability of power supply.

In the grid-connected mode, the public grid is generally used as the main power source. In island mode, because the connection to the public grid is lost, and the energy storage unit has high reliability, it is used as the main power source to maintain power balance of the microgrid [4-5]. The intentional islanding operation is actively carried out by the microgrid itself, so the switching time can be predicted in advance and its operating status can be adjusted in time, which make it easier to achieve seamless switching [6]. But the time of the unintentional islanding is uncertain, and the power balance in the microgrid after the island is also uncertain [7], so it is the most difficult to achieve in seamless switch under the unintentional islanding.
The output voltage of the converter was controlled to accelerate the grid-connected current to zero during islanding operation in [8], thereby reducing the impact of the grid-connected switch's turn-off on the voltage, but this method was only applicable to the intentional islanding mode. The grid current was controlled when islanding to improve the voltage quality of this mode switch process in [9], which was not suitable for unintentional islanding. In [10], the mode switching of wind-solar hybrid systems was studied under PQ control (P refers to active power, and Q refers to reactive power) and droop control. The proposed strategy can ensure that the microgrid voltage and frequency remain within the operating range before and after the operating mode switching. But there was no effective improvement for the transient oscillations generated. In [11, 12], energy storage device was used as the main power supply of microgrid. It could reduce the closing inrush current when the island operation is turned to grid connection. However, the conventional PQ and V/f control (V refers to voltage, and f refers to frequency) direct switching was used when grid-connected, and the voltage amplitude could not be well controlled. In [13], an indirect current control method was proposed. In both grid-connected and islanding modes, the micro-source converter was controlled as a voltage source, but the peak voltage and current must be detected, which affected the accuracy of the control. In [14], a method with improvements to the indirect control of current was proposed. There was no need to detect the peak value of voltage and current. When grid-connected, the inverter output reference voltage was realized by adding an external current loop. At the same time, it also considered the voltage stability of the islanding detection process. But this method was aimed at three-phase grid-connected inverters, and further research was needed to apply it to main power inverters in microgrids.

A control strategy for the combination of master-slave control and peer-to-peer control was used in [15], which was suitable for the transition problem in the process of switching between parallel and off-grid optical storage microgrids. But it failed to effectively suppress voltage fluctuations. In [16], on the basis of the PQ and V/f direct switching, the V/f control was improved, and the frequency loop and parameter loop were added to the voltage and current. But the voltage amplitude still fluctuated obviously during the switching process. A current compensation algorithm was proposed in [17], which was for the main power controller to obtain the output of current control before switching and compensate it to the control structure after the island. But it only considered the smooth switching of the controller when intentional islanding.

The operation mode switching process has the impact of on the stability of the master-slave microgrid in the case of unintentional islanding. In this paper a seamless switching control strategy is proposed, for the analysis of the relationship between the main converter and the bus voltage. When the microgrid is connected to the grid, the stability of the bus voltage is jointly controlled by the grid-connected converter and the energy storage converter, both of which adopt droop control and maintain the power balance between the microgrid and the public grid. After the occurrence of unintentional islanding, the grid-connected converter exits operation, and the main converter is switched to an energy storage converter to stabilize the bus voltage and also supply power to the load. The output of the converter in this method has continuity, and no switching control strategy is required. Without control vacuum period, the seamless switching of the microgrid from grid-connected to island operation can be well realized. A simulation model of the solar-storage DC microgrid was built on the software PSCAD, as a research object to verify the effectiveness of the proposed control strategy in this paper.

2. Design of microgrid system operation method
AC/DC hybrid microgrid generally includes AC bus and DC bus, which can be connected to various distributed power sources and loads and energy storage devices [6]. The grid-connected end can be set on the DC side or the AC side. In this paper, the DC-side grid-connected microgrid is taken as the research object, whose seamless switching control strategy is analyzed. Since in this paper it mainly studies the seamless switching control strategy, it focuses on the bus voltage control at the grid-connected end side. Its topological structure is shown in Figure 1, which mainly includes three types of converters: grid-connected converter, energy storage converter, and photovoltaic grid-connected
converter. The DC bus end can also be connected to a converter to expand the AC bus and other units, but no research and analysis about them will be done here.

![Figure 1. DC side grid-connected microgrid.](image1)

As shown in Figure 1, the single-bus DC microgrid mainly includes grid-connected converter AC/DC, photovoltaic power generation unit and energy storage unit, all of which are connected to the DC bus. According to the operation requirements and conditions of the microgrid, a reasonable operation plan should be planned. The converters of each unit adopt the corresponding control strategy, so as to realize the normal and efficient operation of the microgrid system.

In the master-slave control strategy, one power supply is as the master power supply, and the others are as the slave power supply. The master and slave power supplies adopt different control strategies according to their different functions to improve the overall control effect of the system. In Table 1 three control strategies are listed, of which the method proposed in this paper is the third one.

![Figure 2. Photovoltaic power generation unit.](image2)

| control unit     | AC/DC         | DC/DC(Bat) | DC/DC(PV) | Vacuum period |
|------------------|---------------|------------|-----------|---------------|
| 1 Grid-connected | Constant voltage control | PQ control | MPPT | Yes |
| 2 Isolated island | Constant voltage control | Droop control | MPPT | No |
| 3 Grid-connected | Droop control | Droop control | MPPT | No |

Since the photovoltaic power generation unit is susceptible to fluctuations in its output power due to changes in the external environment, it is not suitable for application as a master control power supply. Therefore, in the Table 1 it shows that, among the three strategies, the photovoltaic power generation unit adopts the maximum power point tracking control strategy (MPPT) to realize the efficient use of solar energy and power the load. Its structure and control are shown in the Figure 2.

The photovoltaic array first undergoes a voltage amplitude conversion through a boost-chopper circuit [10], and then is connected to a DC port in the microgrid to implement grid connection. The MPPT module can calculate the PV array output port voltage reference value $U_{\text{pvref}}$ by the output current $I_{\text{pv}}$ and output voltage $U_{\text{pv}}$ of the photovoltaic array, which corresponds to the maximum power point of the photovoltaic array. The tracking algorithm is perturbation observation method in the MPPT module, whose principle is to periodically apply a small increment to the voltage of the photovoltaic array to observe the direction of change of the output power. The actual voltage value of the PV array output port $U_{\text{pv}}$ is compared with the reference value $U_{\text{pvref}}$, and the error is controlled by PI (proportional integral), so as to obtain the reference value of current $I_{\text{pvref}}$ of the inner loop controller. After the current reference value $I_{\text{pvref}}$ is compared with the actual value $I_{\text{pv}}$, the error is controlled by PI to generate a PWM (pulse width modulation) signal. When the external conditions change (illumination or temperature), the PV array is operated at the maximum power point.
In Table 1, it shows that the main difference lies in the control strategy of grid-connected converter AC/DC and energy storage converter DC/DC. Grid-connected converter AC/DC adopts constant voltage control or droop control, and energy storage converter DC/DC adopts PQ control or droop control. Their corresponding structure and control are shown in Figures 3 and 4 respectively.

**Figure 3.** Grid-connected converter AC/DC.

The bi-directional AC/DC converter can realize two-way transmission of energy [12]. The difference between constant voltage control and droop control lies in the voltage reference value $U_{\text{ref}}$. With droop control, $U_{\text{dc}}$ and $I_{\text{dc}}$ through the droop curve generate voltage reference $U_{\text{dcref},1}$. With constant voltage control, the voltage reference value $U_{\text{dcref},2}$ is a given constant. The DC port reference voltage $U_{\text{dcref}}$ is compared with the actual value $U_{\text{dc}}$, and the reactive power of grid $Q_{\text{ref}}$ is compared with the actual value $Q$, then the error is controlled by PI. After voltage and current decoupling control, the control signals are generated.

The bi-directional DC/DC converter can realize two-way transmission of energy. With droop control, when the grid-side voltage is high, which shows that the energy is excessive, the battery is charged. when the grid-side voltage remains stable. $U_{\text{dc}}$ and $I_{\text{dc}}$ through the droop curve generate voltage reference $U_{\text{dcref}}$. The DC port reference voltage $U_{\text{dcref}}$ is compared with the actual value $U_{\text{dc}}$. After the error is controlled by PI, the battery terminal current reference value $I_{\text{batref},1}$ is obtained. With PQ control, it can absorb excess power when the microgrid power overflows, and supplements the power shortage when the microgrid power is insufficient. The battery power reference $P_{\text{batref}}$ is compared with the actual value $P_{\text{bat}}$. After the error is PI controlled, the battery terminal current reference value $I_{\text{batref},2}$ is obtained. Then, after reference value $I_{\text{batref}}$ is compared with the actual value $I_{\text{bat}}$, the error is controlled by PI to generate a PWM modulation signal.

**Figure 4.** Energy storage converter DC/DC.
In method 1, during grid-connected operation, the public grid with the grid-connected converter AC/DC is used as the main control power source, which uses constant voltage control to support the stability of the microgrid bus voltage. Energy storage converter DC/DC adopts PQ control, which absorbs excess power when the microgrid power overflows, and supplements the power shortage when the microgrid power is insufficient. When the microgrid is operating islanded, since the public grid can no longer provide voltage support, the energy storage unit needs to switch control strategies to stabilize the bus voltage. When the unintentional islanding occurs, there is an uncontrollable voltage phenomenon during islanding detection, causing undervoltage or overvoltage, which endangers the overall microgrid stability and security.

In method 2, during grid-connected operation, the grid-connected converter AC/DC connected to the public grid becomes the main control power source, which also uses constant voltage control to support the stability of the microgrid bus voltage. But the energy storage adopts droop control as a backup power source. When the microgrid is operating islanded, although the public grid can no longer provide voltage support, the energy storage unit can seamlessly switch to island operation without switching control strategies, seamlessly supporting the stable control of the bus voltage. However, the disadvantage of this method is that due to the inevitably line impedance of busbar, when the DC port of the grid-connected converter AC/DC is far away from the DC output port of the energy storage unit converter DC/DC, the voltage falling caused by the line impedance will cause the energy storage battery to remain in a discharged state. And because the grid-connected converter adopts constant voltage control, it provides the main power required by the load. Therefore, the energy storage battery is in a low power supply efficiency discharge state, resulting in electrical waste and unnecessary battery performance loss.

In method 3, during grid-connected operation, both the grid-connected converter AC/DC and the energy storage converter DC/DC adopt droop control to stabilize the bus voltage together. At the same time, both can absorb excess power when the microgrid power overflows, and supplement the power shortage when the microgrid power is insufficient. With this method, even when the unintentional islanding occurs, although the public grid can no longer provide voltage support, the energy storage unit can seamlessly support to the stability of the bus voltage without switching control strategies. There is no uncontrollable voltage period during islanding detection, ensuring the stability and safety of the overall microgrid. And the corresponding output power of the two can be controlled by adjusting the droop coefficient of the two, which has higher flexibility.

3. Simulation results of microgrid operation method
In order to verify the effectiveness of the microgrid control strategy proposed in this paper, a DC-side grid-connected microgrid model was built on the PSCAD for verification and analysis.

The rated voltage of the DC bus is 0.75kV, and the rated voltage of the AC public grid is 0.38kV. The rated illuminance and temperature of PV generation are 1000 lx and 25℃, respectively. The line impedance between the DC port of the grid-connected converter AC/DC and the load is 0.05 Ω. So is the line impedance between the load and output port of converter DC/DC with energy storage unit. At t=0s, the initial load is 0.15MW, and the initial illuminance and temperature are constant values, 800 lx and 25℃, respectively. At t=10s, the load of 0.05MW was put in. At t=15s, the load of 0.05MW was removed. At t=20s, unintentional islanding occurred. At t=25s, the load of 0.05MW was put in. At t=30s, the load of 0.05MW was removed. In this paper, the reasonable PI parameters of the model are selected and its simulation effect can meet the experimental requirements. There are new optimization methods for tuning PI controller parameters, but no research and analysis about them will be done here.

3.1. Analysis of simulation results under the control of Method 1
In method 1, the energy storage converter DC/DC adopts PQ control, and its active power reference value $P_{ref}$ is set to 0.025MW. And since unintentional islanding occurs, the control strategy needs to be switched, so there is a voltage uncontrollable time, which is set to 0.2s. At t=20.2s, the control strategy of the energy storage converter DC/DC is switched from PQ control to droop control.
Figure 5. Simulation results under the control of method 1.

As shown in the Figure 5, the steady-state value of the DC load voltage is basically around 0.75kV. The steady-state values of the DC load voltage $U_{\text{Load}}$ after 5s are 0.745kV, 0.740kV, 0.745kV, 0.740kV, 0.730kV, 0.740kV, respectively. During the load change, the highest and lowest instantaneous values of the voltage amplitude are 0.780kV (1.04 $U_{\text{rated}}$) and 0.695kV (0.93 $U_{\text{rated}}$). In the process of islanding, the lowest instantaneous value of the voltage amplitude is 0.645kV (0.86 $U_{\text{rated}}$). The steady-state values of grid active power $P_g$ after 5s are 0.040MW, 0.090MW, 0.040MW, 0.0MW, respectively. The steady-state value of grid reactive power $Q_g$ after 5s is almost 0MVar all the time. The steady-state values of energy storage active power $P_{\text{Bat}}$ after 5s are 0.025MW, 0.060MW, 0.106MW, respectively. The steady-state value of PV active power $P_{\text{PV}}$ after 5s is almost 0.088MW.

3.2. Analysis of simulation results under the control of Method 2

In method 2, the grid-connected converter AC/DC adopts constant voltage control, and its voltage reference $U_{\text{ref}}$ is set to 0.75kV. The energy storage converter DC/DC adopts droop control, and its droop coefficient is set to 0.02. And since unintentional islanding occurs, the control strategy does not need to be switched, so there is no voltage uncontrollable time.

Figure 6. Simulation results under the control of method 2.
As shown in the Figure 6, the steady-state value of the DC load voltage is basically around 0.75kV. The steady-state values of the DC load voltage $U_{\text{Load}}$ after 5s are 0.745kV, 0.740kV, 0.745kV, 0.740kV, 0.730kV, 0.740kV, respectively. During the load change, the highest and lowest instantaneous values of the voltage amplitude are 0.770kV (1.03 $U_{\text{rated}}$) and 0.695kV (0.93 $U_{\text{rated}}$). In the process of islanding, the lowest instantaneous value of the voltage amplitude is 0.710kV ($U_{\text{rated}}$). The steady-state values of grid active power $P_g$ after 5s are 0.040MW, 0.067MW, 0.040MW, 0MW, respectively. The steady-state value of grid reactive power $Q_g$ after 5s is almost 0MVar all the time. The steady-state values of energy storage active power $P_{\text{Bat}}$ after 5s are 0.032MW, 0.053MW, 0.032MW, 0.065MW, 0.110MW, 0.065MW, respectively. The steady-state value of PV active power $P_{\text{PV}}$ after 5s is almost 0.088MW.

3.3. Analysis of simulation results under the control of Method 3

As shown in the Figure 7, the steady-state value of the DC load voltage is basically around 0.75kV. The steady-state values of the DC load voltage $U_{\text{Load}}$ after 5s are 0.745kV, 0.740kV, 0.745kV, 0.740kV, 0.730kV, 0.740kV, respectively. During the load change, the highest and lowest instantaneous values of the voltage amplitude are 0.770kV (1.03 $U_{\text{rated}}$) and 0.695kV (0.93 $U_{\text{rated}}$). In the process of islanding, the lowest instantaneous value of the voltage amplitude is 0.710kV ($U_{\text{rated}}$). The steady-state values of grid active power $P_g$ after 5s are 0.032MW, 0.053MW, 0.032MW, 0.065MW, 0.110MW, 0.065MW, respectively. The steady-state value of PV active power $P_{\text{PV}}$ after 5s is almost 0.088MW.

3.4. Microgrid operation methods comparison

Table 1 shows that there is a control vacuum period in method 1, but not in methods 2 and 3, which have different effects on the mode switching process of microgrid. In Figure 8, curves ① (black), ② (red), ③ (blue) correspond to the simulation results of method 1, 2, 3 respectively.
Figure 8. Mode switching process comparison.

It shows in Figure 8 that when unintentional islanding occurs and the grid-connected operation mode is switched to the islanding operation mode, different methods have different effects. With method 1, there is a busbar voltage control vacuum time, which causes a relatively serious undervoltage phenomenon. The lowest value of the bus voltage dropped to 0.645kV (0.86 $U_{\text{rated}}$), which affected the DC load power supply. However, methods 2 and 3 can seamlessly support the bus voltage control because of the energy storage battery unit, and there is no control vacuum time, and can realize seamless switching. The voltage control effects of methods 2 and 3 are similar, and the minimum value is 0.710kV (0.95 $U_{\text{rated}}$).

In conclusion, methods 2 and 3 have better control effects than method 1 for the overall stability control in mode switching process of the microgrid system.

Figure 9. Comparison of energy storage and public grid output power.

In Figure 9, curves ① (black), ② (red), ③ (blue) correspond to the simulation results of method 1, 2, 3 respectively. Due to the different control of the three methods, energy storage and public grid output power are also different. The Figure 9 shows that within 5-10s (grid-connected operation), under the control of method 1 and 2, both the outputs $P_g$ of the public grid are 0.04MW. While the energy storage output $P_{\text{bat}}$ under the control of method 1 is only 0.025MW, and the energy storage output of $P_{\text{bat}}$ under the control of method 2 is 0.032MW, which is 0.007MW more than that of method 1, accounting for 28% (0.007/0.025). The energy storage output $P_{\text{bat}}$ under the control of method 3 is 0.033MW, which is 0.001MW more than that of Method 2, but its public grid output $P_g$ is only 0.032MW, which is 0.008MW less than that of method 2, and the total output power is decreased by 0.007MW, accounting for 11% (0.007/(0.032+0.033)).

Within 10-15s (grid-connected operation), the energy storage output $P_{\text{bat}}$ under the control of method 2 is 0.053MW, the energy storage output $P_{\text{bat}}$ under the control of method 3 is 0.057MW. While the public grid output $P_g$ under the control of method 2 is 0.067MW, and the public grid output $P_g$ under the control of method 3 is only 0.055MW. The total output power under the control of method 3 saves 0.008MW, accounting for 7% (0.008/(0.057+0.055)).

In conclusion, method 2 not only causes more power waste, but also causes unnecessary battery performance loss. Compared with method 2, method 3 saves more power and improves the power supply efficiency of the energy storage unit.

4. Conclusions
When the unintentional islanding occurs in the master-slave microgrid, there is the uncontrollable voltage phenomenon during islanding detection. Aiming at this problem, a microgrid control strategy
is proposed in this paper. Through the model simulation verification in this paper, the following conclusions can be obtained:

(1) Under the control of method proposed in this paper, both grid-connected operation and isolated island operation can have excellent effects on bus voltage control. The steady-state values are within the range of 1.05 to 0.95 times the rated value. When the load changes, the dynamic instantaneous amplitudes are all within the range of 1.10 to 0.90 times the rated value.

(2) When unintentional islanding occurs, seamless switching can be realized with excellent control effect. The dynamic instantaneous amplitudes are all within the range of 1.10 to 0.90 times the rated value.

(3) Under the same load power condition, it saves power and improves the power supply efficiency of the energy storage unit, which will improve the economic efficiency of the grid and delay battery aging.

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