Research on Operation Control Strategy of Multi-Voltage DC Microgrid

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Abstract. In order to reduce the use of power electronic devices, adapt to different loads connected to the DC microgrid, and improve the reliability and safety of power supply, this paper proposes a multi-voltage level DC microgrid control strategy. The basic structure and operation mode of multi-voltage level DC microgrid are introduced. The control strategies of photovoltaic power generation and hybrid energy storage are proposed. The model of bidirectional DC/DC converter is established and the control strategy of hierarchical control of DC bus voltage is proposed. A power balance control strategy is proposed for AC/DC bidirectional power converter to realize smooth AC-DC power transfer. Simulation analysis on Matlab platform verifies the feasibility of the control strategy.

Keywords: Multi-voltage; DC microgrid; Bidirectional DC/DC converter; Hierarchical control.

1. Introduction

In order to efficiently utilize renewable energy, alleviate energy crisis and environmental pressure, the concept of a hybrid microgrid is proposed [1-2]. Microgrid is a small scale power system that can achieve independent autonomy [3-4]. Compared with AC microgrid, DC microgrid has many advantages, which further improves the controllability and reliability, has the advantages of higher power quality, low line cost, small transmission loss, high energy transmission efficiency, environmental protection, etc., and has broad development space, the application of DC microgrid is becoming more and more widespread [5-6]. Photovoltaics, energy storage devices, and converters are the key equipment of the DC microgrid. The stable operation of the DC microgrid is closely related to its energy management and coordinated control.

With the increase in the number and types of distributed power sources in DC microgrid, the expansion of the system scale, and coordination of the output power of different units, it is particularly important to improve the reliability of power supply while ensuring the stability of the system. In a DC microgrid containing photovoltaic and energy storage units, the system power affect the stability of the voltage, so it’s an important index to measure system power and the quality of the DC bus power supply. The DC microgrid in [7] is powered by photovoltaics and batteries. By controlling photovoltaic and battery converters, the DC bus voltage is stabilized, and a system is actually built, which verifies the feasibility of the control strategy. Reference [8] divides the bus voltage into three areas according to the load power, and proposes a control strategy to maintain DC bus voltage with distributed power, diesel generators and energy storage. This control strategy is relatively simple, but the scope of application is limited,
only applicable in island mode. Reference [9] established mathematical models of various converters in DC microgrids, and proposed corresponding control methods. Through the selection of reasonable control parameters, the stability of DC bus voltage is achieved. Reference [10] analyzed two operation modes of grid-tied and isolated islands, and maintained the bus voltage by controlling the AC/DC converter and energy storage unit. However, the energy storage unit is in standby mode in grid-tied mode, and the utilization rate is low. The literature [11-12] divides the DC bus voltage into five sections, and analyzes that when the DC microgrid is operated in grid connection, each unit adopts different control methods in different voltage sections, and a buffer area is increased for the smoothness of the voltage. Although this control strategy avoids fluctuations in bus voltage during mode switching, the control system is too complicated. This paper adopts the control strategy of hierarchical control bus voltage to switch the working mode according to the amplitude of bus voltage, and adds the hysteresis controller to make the switching smoother, prevent the converter from switching by mistake, and improve the system stability.

This article introduces multi-voltage level DC microgrid basic structure and the operation mode firstly. And then establishes a model of the bidirectional DC/DC converter and proposes a control strategy of hierarchically controlling the DC bus voltage. Then a power balance control strategy is presented for AC/DC bidirectional power converter. Finally, the simulation analysis was performed on Matlab platform.

2. The Multi-level DC Microgrid System Structure and Operation

Figure 1 shows the DC microgrid studied in this paper. It includes photovoltaics, batteries, super capacitors, bus interface converters and DC loads. This multi-level DC micro-grid can reduce the size of the power adapter, and is suitable for systems with more complex electrical equipment, and has higher power supply security.

![Figure 1. The topology of the multi-level DC microgrid system.](image)

During grid-tied mode, the AC/DC converter acts as an energy conversion interface between the DC microgrid, the utility grid, realizing the exchange of electric energy between the AC and DC systems, balancing the supply and demand of the grid load, and the DC microgrid can send excess power to the utility grid, you can also get the shortage of power from the utility grid. The photovoltaics are connected to the DC bus with DC/DC converter. All photovoltaics work at the MPPT(maximum power point tracking) mode, which makes full use of distributed energy.

The power balance and the bus voltage stability are maintained through droop control. Among them, the battery is used to compensate the fluctuation of the super capacitor terminal voltage. Capacitors are used to compensate for fluctuations in bus voltage. They take advantage of the high energy density of lithium batteries, and fast response times of supercapacitors. The DC load includes three voltage levels, DC750V, DC220V, and DC110V. No converter is required, direct access to the corresponding DC bus.
The DC buses of different voltage levels are connected through DC/DC converters. Among them, DC750V and DC220V are bidirectional, and DC220V and DC110V are buck converters. This paper mainly studies the converters of bidirectional DC/DC converter between bus DC750V and DC220V, and AC/DC bidirectional power converter.

3. Modeling and Control of Bidirectional DC/DC Converter

The Buck/Boost converter in Figure 2 is used for modeling analysis. By controlling T1 and T2, the Boost and Buck can be switched.

When the load on the low-voltage side decreases or the photovoltaic output increases, the converter works in Boost mode. Figure 3 (a) shows when T1 is on, and Figure 3 (b) shows when T1 is off. At this time, T2 does not work. The inductor current flows from left to right. On the contrary, the converter works in Buck mode when T2 operates.

DC microgrid usually takes the stability of the DC bus voltage as the control target. Because the DC microgrid is not affected by the frequency and phase angle, the randomness and the changes in the load are reflected in the change of the bus voltage. Therefore, the DC bus voltage is controlled to ensure the stable operation of the system.

As shown in Table 1, the bus voltage is divided into three different regions by two voltage thresholds. The voltage threshold interval is too small, which can easily cause malfunction. If the interval is too small, it may cause malfunctions.
large, it will affect the stability of the system. Therefore, an appropriate voltage threshold must be selected. Because the low-voltage DC bus voltage is 220V, set \( v_{\text{ref}} \) to 220V, the normal allowable fluctuation of the bus voltage is ± 2%, set \( U_L \) to 216V, \( U_H \) to 224V. Two voltage thresholds \( \Delta U_L \) and \( \Delta U_H \) are added to prevent instantaneous bus voltage fluctuations which cause the converter to switch frequently between different operating modes and reduce the harmonics caused by switching action. The bus interface converter has different working modes in different voltage ranges. In order to better distinguish its working mode, the variable \( SL \) is introduced and defined as follows:

\[
SL = \begin{cases} 
-1 & \text{Boost mode} \\
0 & \text{Idle mode} \\
1 & \text{Buck mode} 
\end{cases}
\]  

3.1. Switch between Boost Mode and Idle Mode
When the output of the low-voltage side photovoltaic power source increases or the load decreases, it will cause the low-voltage side bus voltage to rise. When the voltage amplitude is higher than \( U_H \), the bidirectional DC/DC converter works in Boost mode, \( SL = -1 \), and the low-voltage side provides power to the high-voltage side.

In order to avoid the malfunction of the converter caused by the transient fluctuation of the bus voltage, a hysteresis controller is introduced in the judgment conditions. When the low-voltage DC bus drops to \( U_H \), the converter still works in Boost mode, \( SL = -1 \). When the bus voltage drops to \( U_H - \Delta U_H \), the converter works in Idle mode, \( SL = 0 \). The selection of \( \Delta U_H \) should be appropriate, too small will cause frequent switching of the converter, too large will cause the interval of no action of the converter to be too large, affecting system stability.

Figure 6. Block diagram of the Buck/boost bidirectional converters in Boost mode.

When \( v_l \) is greater than \( U_H \), the output of the hysteresis controller is 1, and when \( v_l \) is less than \( U_H - \Delta U_H \), the output of the hysteresis controller is 0.

3.2. Switch between Buck Mode and Idle Mode
When the output of the low-voltage photovoltaic power source decreases or the load power increases, the DC bus voltage decreases. When the voltage amplitude is lower than \( U_L \), the bidirectional DC/DC converter works in Buck mode, \( SL = 1 \), and the high-voltage side provides power to the low-voltage side.

When the low-voltage DC bus rises to \( U_L \), the converter still works in Buck mode, \( SL = 1 \). When the bus voltage rises to \( U_L + \Delta U_L \), the converter works in Idle mode, \( SL = 0 \).

Figure 7 is the Buck mode control block diagram of the hysteresis controller. At this time, \( U_L \) is lower than the rated voltage. When \( v_l \) is less than \( U_L \), hysteresis controller the output of the hysteresis controller is 1. When \( v_l \) is greater than \( U_L + \Delta U_L \). The output is 0.

Figure 7. Block diagram of the Buck/Boost bidirectional converters in Buck mode.

4. Modeling and Control of AC/DC Bidirectional Power Converter
In the grid-tied mode, the DC microgrid realizes power exchange with the large grid through AC/DC converters, balancing the surplus and shortage of microgrid energy. In order to maintain the smooth
transmission of power, this paper uses constant power control. The model of the AC/DC Bidirectional power converter is shown in Figure 8.

The instantaneous power of the AC/DC converter is:

\[
P = v_a i_a + v_b i_b + v_c i_c
\]
\[
Q = \frac{1}{\sqrt{3}} [(v_a - v_b) i_c + (v_b - v_c) i_a + (v_c - v_a) i_b]
\] (2)

The dq coordinate transformation of the formula(2) is:

\[
P = \frac{2}{3} (v_d i_d + v_q i_q)
\]
\[
Q = \frac{2}{3} (v_q i_d - v_d i_q)
\] (3)

When the phase-locked loop is used to orient the grid voltage, in order to facilitate the control to make the d-axis coincide with the voltage vector, keeping the q-axis component at 0, that is, \(v_q = 0\), which can obtain the current reference value:

\[
i_dref = \frac{2P}{3u_d}
\] (4)
\[
i_qref = \frac{2Q}{3u_d}
\] (5)

To enable direct comparison of AC, DC voltages, normalize the AC, DC voltages:

\[
U_{ac.pu} = \frac{u_{ac}-0.5(u_{ac,max}+u_{ac,min})}{0.5(u_{ac,max}-u_{ac,min})}
\]
\[
U_{dc.pu} = \frac{u_{dc}-0.5(u_{dc,max}+u_{dc,min})}{0.5(u_{dc,max}-u_{dc,min})}
\] (6)

\(U_{ac.pu}\) and \(U_{dc.pu}\) are the normalized values of the AC and DC bus voltages; \(u_{ac,max}\), \(u_{ac,min}\) and \(u_{dc,max}\) and \(u_{dc,min}\) are the maximum, minimum values of the AC bus voltage and DC bus voltage.

AC/DC bidirectional power converter control system is shown in the figure 8:
1) The AC bus voltage \(U_{ac}\) and the DC bus voltage \(U_{dc}\) are detected and normalized, and \(P_1\) is obtained through the PI controller.
2) The phase-locked loop shows that the AC frequency is different from 50, and \(Q_1\) is obtained through the PI controller.
3) \(i_{abc}\) and \(v_{abc}\) on the AC side of the converter can obtain \(i_\text{d}, i_\text{q}, v_\text{d}, v_\text{q}\) through coordinate transformation, and calculate \(P\) and \(Q\) through formula (3).
4) After the difference between \(P_1, P\) and \(Q_1, Q\), the PI controller gets active and reactive reference values \(\text{Pref}\) and \(\text{Qref}\).
5) Pass the formulas (4) and (5) to get the current reference values \(i_{dref}\) and \(i_{qref}\).

**Figure 8.** The design of the control system.
6) Finally, through the current inner loop decoupling control, and then get the PWM signal output through the dq0/abc module.

5. Simulation Verification

In order to verify the feasibility of the above control strategy, simulation was performed based on Matlab/Simulink platform.

The specific simulation parameters are shown in Table 2.

| Parameters                      | Simulation       |
|---------------------------------|------------------|
| **Utility Grid**                |                  |
| nominal voltage $u_s$           | 380V/50Hz        |
| line inductance                 | 0.036mH          |
| line resistance                 | 3 ohms           |
| **DC microgrid**                |                  |
| High-voltage side bus voltage   | 750V             |
| Low-voltage side bus voltage $u_{dc}$ | 220V          |
| line resistance                 | 5 ohms           |
| **AC/DC converter**             |                  |
| switch frequency                | 10kHz            |
| filter inductance               | 4mH              |
| filter capacitor                | 45 $\mu$F        |
| **Bidirectional DC/DC converter** |                  |
| DC-link capacitor $C_1$         | 470 $\mu$F       |
| DC-link capacitor $C_2$         | 0.6F             |
| Inductance $L$                  | 7mH              |

5.1. Bidirectional DC/DC Converter

In order to simulate the low-voltage side bus voltage fluctuations, an AC power supply is connected in series on the low-voltage side. The structure of the low-voltage side is shown in Figure 9 below.

![Figure 9. The structure of the low-voltage side bus system.](image)

At this time, the waveform on the low-voltage side is shown in Figure 10(a). The fluctuation range is 190-250V, which far exceeds the allowable fluctuation range (220 ± 220 × 5%).

![Figure 10. Simulation waveform of the low-voltage side DC bus voltage.](image)

Figure 10(b) shows the instantaneous waveform of the low-voltage side DC bus after being controlled. At 0s, the low-voltage side bus voltage starts to decrease and reaches the threshold of 216V at 0.2s. At this time, the converter enters Buck mode. When 1.8s-2.2s, the converter stops operating. After 2.2s, the converter reaches the critical value of Boost mode. The fluctuation on the low side is between 216~224V, which is within the allowable range.
It can be seen in the whole process that the low-voltage side first obtains the short-term power from the high-voltage side, and then transmits the surplus power to the high-voltage side. Compared to Figure 10(a), it can be seen that the waveform of the DC-link voltage on the low-voltage side has been significantly improved. Hysteresis control also improves the stability of the system and reduces the malfunction of the converter.

5.2. AC/DC Bidirectional Power Converter

![Figure 11](image)

**Figure 11.** Simulation operation of the AC/DC bidirectional power converter.

Figure 11 shows the simulation results of the AC/DC bidirectional power converter, 11 (a) is the waveform of the DC-side bus voltage, and 11 (b) is the active $P_{ac}$, $P_{dc}$, and active power transmitted by the AC/DC bidirectional power converter from the AC and DC sides. Power $P_t$ is positive when inverting and negative when rectifying.

As can be seen from Figure 11, in the initial state, there is no load on the DC side and the load on the AC side is 2000W. At this time, the load on the AC side is shared by both sides. The converter works in inverter mode and the DC bus voltage is stable at 759V.

At 0.5s, the load on the AC side does not change, the load on the DC side increases to 3660W, the converter works in rectification mode, the load on the DC side is shared by both sides, and the AC/DC bidirectional power converter transmits power from the AC side to the DC side. The DC bus voltage is stable at 755V.

At 1s, the DC side load remains unchanged at 3660W, and the AC side load increases to 5000W. At this time, the DC side voltage is reduced to 751V, and the AC side load is shared by both the AC and DC sides. The AC/DC bidirectional power converter works in inverter mode.

It can be seen in the whole process that the AC/DC bidirectional power converter first works in the inverter mode. The rectifier mode is switched at 0.5s, and the inverter mode is switched at 1s, which the stability of the DC bus voltage is maintained, the power balance between the AC and DC sides is achieved, and the stability of the system is improved.

6. Conclusion

In order to facilitate the connection of renewable energy and various loads, this paper studies the structure and operation of DC microgrid with multiple voltage levels as the research object. A hierarchical control strategy is proposed for the bidirectional DC/DC converter, and hysteresis adjustment is adopted to maintain the stability of the bus voltage and reduce the system's malfunction. A power balance control strategy is proposed for AC/DC bidirectional power converter, which realizes the smooth transfer of AC and DC power. Finally, a simulation analysis is performed on the Matlab platform to verify the feasibility of the control strategy.

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