Research on Bi-directional DC / DC Converter for Energy Storage System

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Abstract. When the grid connected photovoltaic power is scarce, the energy storage device can play an important role in power supplement to stabilize the grid. A bi-directional three-level Buck / Boost converter topology has been studied, and its working principle has been introduced in detail in this Paper. Based on the working characteristics of energy storage battery, combined with the battery "Three-stage" charging method, the voltage and current closed-loop control strategy of three-level DC/DC converter has been studied. It can work in constant power charging and discharging as well as constant current charging and discharging. The simulation platform of 50KW energy storage power device has been set up, which can freely switch from charging state to discharging state. The results show that the research on bi-directional three-level DC / DC converter is feasible and effective.

Keywords: Bi-directional; DC/DC Converter; Energy Storage System; Three level.

1. Introduction
With the continuous expansion of photovoltaic grid connected power generation scale, the instability of photovoltaic system output and the unpredictability affected by the environment have increasingly affected the stable operation of traditional power grid. In order to improve the absorption capacity of traditional power grid for new energy grid connection, energy storage technology has become an important link, because it has two-way operation mechanism, which can be used as power station and load, and can absorb or release power flexibly and quickly according to dispatching. References [1-2] describe the application of energy storage batteries in new energy systems, and references [3-5] describe some bidirectional power electronic topologies. The common topology of energy storage converter is a two-stage structure including bi-directional DC / DC and bi-directional DC/AC. DC/DC converter is an important part of energy storage system. The two-level DC / DC converter is limited by the voltage and current bearing capacity of power transistor, which is generally suitable for medium and small power applications. The three-level bi-directional converter topology is studied in references [6-7], and the charging and discharging strategies of energy storage battery in references [8-10]. Based on the working characteristics of energy storage battery and the battery "Three-stage" charging method, a three-level bi-directional DC/DC topology has been studied in this paper, in which the voltage at both ends of the power transistor working is only half of the DC side voltage, and the inductance current fluctuates at twice the switching frequency. The three-level bi-directional DC/DC converter has the advantages of high power and small volume.

2. Principle of Three Level DC / DC Converter
The three-level bi-directional DC/DC topology is shown in Figure 1. \( E_1 \) represents the energy storage battery, \( U_1 \) is the energy storage battery output, \( E_2 \) represents the DC bus terminal potential and its
output voltage is $U_2$, $C_1$ is the filter capacitor of inductance output, $C_2$ and $C_3$ are the upper and lower capacitors of DC bus respectively. When the energy storage battery is discharged, the DC/DC converter adopts the boost mode, and the energy flows from $E_1$ to $E_2$; when the energy storage battery is charged, the DC/DC converter adopts buck mode, and the DC bus $E_2$ flows to the energy storage battery $E_1$. The boost and buck mode conversion of DC/DC converter can be realized by controlling $S_1$, $S_2$, $S_3$ and $S_4$ power transistors.

![Figure 1. Topology of three level bi-directional DC/DC converter](image)

### 2.1. Working Principle of Energy Storage Battery Discharge
When the energy storage battery is discharged outward, the converter works in boost mode. At this time, the power transistors $S_1$ and $S_4$ are used as diodes, $S_2$ and $S_3$ are used as controllable power tubes, $S_1$ and $S_2$ drive signals are complementary, $S_3$ and $S_4$ drive signals are complementary, and the $S_1$ and $S_4$ drive signals is running by 180° interleaving control. The control sequence is shown in Figure 2. In the figure, $U_{\text{carrier}}$ is the carrier signal and $U_m$ is the modulation signal.

$t_1-t_2$ stage: power transistors $S_2$ and $S_3$ are turned on at the same time, the current flows through $C_1-L_1-S_2-S_3-L_2-C_1$, and the inductance current increases linearly. The energy storage battery $E_1$ charges the two inductors $L_1$ and $L_2$, and the voltage at both ends of A and B is 0. $t_2-t_3$ stage: $S_2$ is turned off and $S_3$ is turned on. At this time, the inductor current will continue to flow, and the current will form a closed loop through $L_1-S_1-C_2-S_3-L_2-L_1$. The inductance current will decrease linearly, and the voltage at both ends of A and B is $U_{1/2}$. $t_3-t_4$ stage: $S_2$ and $S_3$ are turned on at the same time, which is the same as $t_1-t_2$ stage, and the voltage at both ends of A and B is 0. In $t_4-t_5$ stage, $S_2$ is turned on, $S_3$ is turned off, and the inductance current is continuous current. The current passes through $L_1-S_2-C_3-S_4-L_2-C_1-L_1$, the current decreases linearly, and the voltage at both ends of A and B is $U_{1/2}$.

It can be seen from the above analysis that when the duty cycle $D$ of $S_2$ is more than 0.5, the voltage of A and B terminal always switches between 0 and $U_{1/2}$ in each switching cycle time, and the ripple frequency of inductance current is twice of the switching frequency. The voltage conversion can be realized by changing the on-off time of $S_2$ and $S_3$ and the energy storage battery can output electric energy.
2.2. Working Principle of Energy Storage Battery Charging

When the energy storage battery is charged, it works in Buck mode. At this time, the power transistors S2 and S3 are used as diodes, and S1 and S4 are used as controllable power tubes. The control sequence is shown in Figure 3.

- **t₁-t₂ stage**: power transistors S₁ and S₄ are turned on at the same time, S₂ and S₃ are turned off. At this time, the electric energy flows from the DC bus E₂ to E₁, and the current flows through C₃-C₂-S₁-L₁-C₁-L₂-S₄-C₃ to form a closed loop. The inductance current increases linearly and the AB terminal voltage is $E₂$.

- **t₂-t₃ stage**: power tube S₄ turns off and S₁ continues to turn on. At this time, the current direction remains unchanged and flows through C₂-S₁-L₁-C₁-L₂-S₃-C₂. At this time, the inductance current decreases linearly and the AB terminal voltage is $E₂ / 2$.

- **t₃-t₄ stage**: the power transistors S₁ and S₄ are turned on at the same time. The stage is the same as t₁-t₂ stage, and the voltage of AB terminal is $E₂$.

- **t₄-t₅ stage**: power switch S₁ is turned off, and S₄ is turned on, current flow direction is unchanged, and current flows through C₃-S₂-L₁-C₁-L₂-S₄-C₃, at this time, the current decreases, and the voltage of AB terminal is $E₂ / 2$. According to the above analysis, when the duty cycle D of S₁ is greater than 0.5, the voltage of AB terminal always switches between $E₂$ and $E₂ / 2$.

3. Bi-directional DC / DC Control Strategy

When the energy storage battery discharges to the DC bus terminal, the DC / DC converter is in the boost mode. The controller only needs to control the discharge current of the battery, so as to control the output power of the energy storage system. In this paper, the single current loop shown in Figure 4(a) is used to control the boost inductor current. $i_{bat}$ and $P_{ref}$ represent the given current and power respectively. When the switch is connected to $i_{bat}$, the converter operates at a constant current, the feedback current $i_L$ of the output inductor is different from the given current $i_{bat}$. The difference is output to the positive end of the comparator after PI, and the pulse signal is obtained after comparing with the carrier signal. The output pulse signal acts on the power transistor S₁, S₂, S₃, and S₄ respectively. When the switch receives the given power $P$, so the given current is $P/U_{bat}$, it differentiates with $i_{L}$ and outputs the control signal through PI control. The DC / DC converter can be either constant current discharge or constant power discharge, and once the battery voltage is lower than the set value, the discharge will be stopped.

When the DC bus charges the battery, the DC / DC converter is in the buck mode, and battery charging generally adopts three-stage charging method: constant current charging, constant voltage
charging and floating charging. The three-stage charging method imitates the best charging curve of the battery. The three-stage charging method can fully charge the battery in the shortest time without damaging the battery. In the initial stage, the battery power is low. At this time, constant current charging with a large current makes the battery power rise rapidly as shown in Figure 4 (a). When the battery power is close to the set value, the constant voltage charging method is adopted as shown in Figure 4 (b). $U_{\text{bat.ref}}$ refers to the given voltage. When it is set to constant voltage charging, the feedback voltage $U_{\text{bat}}$ at the battery terminal and the given voltage $U_{\text{bat.ref}}$ difference, the difference through PI control to get the inner ring given current $i_{L.ref}$, $i_{L.ref}$ is controlled by current loop to obtain the driving pulse signal of power transistor. Due to the self-discharge phenomenon after the battery is fully charged, floating charge is used to offset the self-discharge loss of the battery.

![Diagram of charging and discharging control strategy of DC / DC converter](image)

(a) Constant current and constant power control

(b) Constant voltage control

**Figure 4.** Charging and discharging control strategy of DC / DC converter

### 4. Experimental Results

In order to verify the working principle and control method of the three-level bi-directional DC-DC converter designed in this paper, the simulation model is built in MATLAB according to Figure 1, and the simulation verification is carried out with the charging and discharging method of energy storage battery. The simulation parameters are converter power set to 50(kW), DC bus voltage set to 800(V), which means that in a constant DC power grid, the voltage of energy storage battery is 600(V), the inductance is 1mH, the switching frequency is 16(kHz).

When the energy storage battery is charged, the voltage and current double closed-loop control strategy is used to charge the battery. A 0.1 (Ω) resistor in series with 2(F) capacitor is used to simulate the energy storage battery. The initial voltage of the battery is set to 500(V), and the DC bus voltage is simulated with 800(V) DC source. The simulation results are shown in Figure 5. In the first stage, when the battery voltage is low, the constant current charging mode is adopted, as shown in Figure 5 (b). At this time, only the single current loop plays a regulating role. In the second stage, when the battery voltage rises to 600(V), the constant voltage charging mode is adopted, as shown in Figure 5 (a). At this time, the voltage and current double closed-loop control is adopted.
Figure 5. Simulation results of battery charging

Figure 6 shows the simulation results of dynamic switching between charging and discharging of energy storage battery. The positive current indicates that the battery is charged, and the negative current indicates that the battery is discharged. As shown in Figure 6(b), before 1(s), we can charge the battery at a current of 80(A), and the charging current is reduced to 40A at 1s. At 2(s), battery discharge mode is started, and discharge battery is 40(A), and the discharge battery is 80(A) at 3(s). It can be seen from Figure 6 (a) that the battery voltage increases before the 2(s) and decreases after the 2(s).

Figure 6. Dynamic switching diagram of battery charge and discharge

5. Conclusions

DC / DC converter is an important part of two-stage energy storage converter. In this paper, a three-level bi-directional DC / DC converter is studied, and its working principle is analyzed in detail. Combined with the working characteristics of energy storage system, the control strategy of the converter is proposed, which realizes the automatic switching of energy storage system from charging state to discharge state. As a part of energy storage converter, the research results will play an important role in grid connected operation of energy storage and three-phase unbalance compensation.

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