Research and Implementation of Charging and Discharging Device Based on DSP Bi-directional DC-DC Converter

Shen FENG, Ting-hui LI* and Zhi-xian LIAO
Guangxi Normal University, Guilin of Guangxi, China
*Corresponding author

Keywords: Two-stage LC filtering, Buck - Boost, Double current loop, High precision, Digital power.

Abstract. With the development of new energy, the charge and discharge technology of battery is very important. Bi-directional buck-boost circuit is used as the circuit topology to realize bi-directional flow of energy. Two-stage LC filter circuit is adopted and current double-closed loop is used to reduce the current ripple of battery charging and discharging and improve the accuracy of charging and discharging current. This paper first simulates its circuit and algorithm with PSIM, and then makes a 300W prototype with TMS320F28335 DSP as the main control chip. The current accuracy obtained by simulation and prototype experiment is 0.00mA and 0.75mA, respectively. The test results show that the precision error of double current ring is small.

Introduction
Since the 1970s, the high-frequency switching power supply composed of high-frequency switching dc-dc converter technology has gradually replaced the linear regulated power supply. At the end of the 20th century, driven by the demand of IT and communication industry, dc-dc switching converter technology and industry developed rapidly. In the 21st century, the trend of green energy, new energy generation, energy storage are inseparable from dc-dc switch converter. At present, Chinese rapid economic development, continuous progress in science and technology, battery is a kind of new energy, and its price is low, stable power supply and other advantages, is widely used in electric cars, battery cars, power supply equipment, UPS and other fields. Therefore, the research on charge and discharge of battery is a hot topic in recent years. Using reasonable and stable current to charge and discharge the battery can maximize its energy utilization, reduce the damage to the battery and improve its service life. Although the accuracy of analog power is relatively high, it is difficult to upgrade, large volume and severe temperature fluctuation. Compared with digital power, it has the advantages of simple upgrade, easy secondary development, small size and stable system. In the process of charging and discharging the battery, the bi-directional dc-dc converter regulates the energy so that the bus voltage and the energy at both ends of the battery can flow bidirectionally. The second-stage LC circuit itself can filter out harmonics, but the accuracy of the ADC acquisition within DSP cannot reach, so, in view of this problem, the sampling accuracy can be improved through the acquisition of the external 24-bit ADC chip, and the double-loop control makes the output accuracy meet the requirements.

Bi-directional DC-DC Converter Topology

Working Principle
Dc-Dc converter can be divided into isolated type and non-isolated type by whether there is a transformer between the input and output. Non-isolated converter Buck, Buck-Boost and Boost converter, Buck-Boost pressure converter, Cuk converter, Sepic converter and Zeta converter. Isolated converter has forward, reverse, push - pull, half - bridge, full - bridge and so on. In this paper, a bidirectional buck-boost circuit topology is used. In order to improve the output accuracy, a first-stage LC filter is added. Its main circuit is shown in Figure 1. The circuit diagram includes two switching tubes, two diodes, two inductance and three capacitors. Two switch tubes are complementary to each other, that is, S2 is off when S1 is on, and S1 is off when S2 is on. When S1
plays the main control, the circuit is in Buck mode, while when S2 plays the main control, the circuit is in Boost mode. The Bus terminal is the input terminal of the Bus and the Out terminal is the battery terminal.

![Circuit topology of bidirectional dc-dc converter.](image)

**Figure 1.** Circuit topology of bidirectional dc-dc converter.

**Calculation of Main Circuit Parameters**

Because bi-directional dc-dc converters can work in Buck mode or Boost mode, it can be design only one of them when designing circuit parameters. The following study only Buck converter, can get two-way dc-dc circuit parameters. It consists of a switch tube, a diode, an inductance and a capacitor. The ratio of switching time $t_{on}$ to switching period $T_s$ is defined as duty cycle $D_C$, which is expressed as:

$$D_C = \frac{t_{on}}{T_s}$$

According to whether the inductance current is continuous or not, Buck converter has three operating modes: continuous conduction mode, intermittent conduction mode and critical mode. Critical mode is the mode between continuous mode and intermittent mode. When the inductance current is continuous, the output ripple is small and the filter design is simple. The increment of linear increase of inductance current is:

$$\Delta i_{L+} = \frac{t_1}{L} (U_S - U_0) dt = \frac{U_S - U_0}{L} t_1 = \frac{U_S - U_0}{L} D_C T_s$$

$U_S$ is the input voltage, $U_0$ is the output voltage, $L$ is the inductance, $t_1$ is the rise time of the inductive current, $D_C$ is the duty cycle of switch tube closure. The absolute value of linear decrease of the inductive current is:

$$\Delta i_{L-} = \frac{t_2}{L} (U_0 dt = \frac{U_0}{L} (I_{L-} - I_{L+}) = \frac{U_0}{L} (1 - D_C) T_s$$

In the formula, $t_2$ is a switch tube switch time.

When the circuit is working in a steady state, the inductance current $i_L$ waveform must be periodically repeated. The increase in the inductance current during the switching on is equal to the decrease in the inductance current at its cut-off, that is:

$$\Delta i_{L+} = \Delta i_{L-}$$

$$D_C = \frac{U_S}{U_0}$$

At time $t_1$, if the inductive current just drops to zero, then the critical state of continuity and discontinuity of the inductive current is called. At this time, the relationship between load current $I_0$ and inductive current $I_L$ is:
\[ \Delta I_L = 2I_0 \]  
\[ I_0 = \frac{U_0}{R}, R \text{ is the load.} \]

The simultaneous equations (5) and (6) obtain the inductance of the critical state:

\[ L = \frac{1 - D \epsilon}{2} R T_s = \frac{U_o(1 - D \epsilon)}{2I_0} T_s = \frac{U_o(1 - D \epsilon)}{2P_s} T_s \]  

Where \( P_s = \frac{U_o}{R} \) is the output power. The voltage \( \Delta U_o \) generated by charging the capacitor by the current \( i_c = i_L - I_0 \) flowing through the capacitor is called ripple voltage, and its expression is:

\[ \Delta U_o = \frac{U_o(1 - D \epsilon)}{8LC}T_s^3 \]  

So circuit capacitance:

\[ C = \frac{U_o(1 - D \epsilon)}{8L \Delta U_o} T_s^3 \]  

Experiment and Conclusion

Simulation

The switching frequency of the bi-directional dc-dc converter is set at 100.00KHZ, the output power is 300.00W, the output voltage is 0 to 5.00V, the output current is 0 to 60.00A, and the input voltage is 12.00V. According to the calculation formula in section 2.2, inductance \( L_1 = 5.00 \times 10^{-6} \)H, capacitance \( C_2 = 600.00 \times 10^{-6} \)F, inductance \( L_2 = 1.00 \times 10^{-6} \)H, capacitance \( C_3 = 300.00 \times 10^{-6} \)F. The traditional Bi-directional dc-dc converter algorithm only samples the current on the inductance \( L_1 \), and then makes PI algorithm with the target value. PSIM software is used for simulation analysis, and the specific circuit simulation figure is shown in Figure 2. The input of the bi-directional dc-dc converter is connected to 12.00V, and the output is connected to 3.30V. Because TMS320F28335 MCU internal sampling is only 12, so \( 60.00 \text{A} / 2 ^ {12} = 14.65 \text{mA} \), low resolution. In the simulation, the inductance current collected on the inductance \( L_1 \) is multiplied by a coefficient not equal to 1 to simulate the internal collection of single-chip microcomputer. If the reference current is set as 60.00A, the waveform of the output current is shown in Figure 3. The maximum output current is 60143.00mA, the minimum current is 60132.00mA, and the ripple current is 11.00mA. Change the reference voltage to -60.00A, and discharge the battery, and the obtained discharge current is shown in Figure 4. The maximum discharge current is 59998.00mA, the minimum current is 59976.00mA, and the ripple current is 22.00mA. It is concluded that the sampling resolution is not up to the standard, and the average output current is not 60.00A whether charging or discharging, which means the current accuracy is not up to the requirement.
Therefore, it is necessary to collect the output current. The current I2 collected by the high-resolution acquisition chip is used as the outer ring of the current loop, and the current collected on the inductance current L1 is used as the inner ring to control the output current I2 to reach the set current, so as to improve the accuracy. The simulation circuit diagram is shown in Figure 5. The current I1 on the inner loop acquisition inductance L1 is multiplied by a coefficient K which is not equal to 1, and K=0.998. If the reference current is set as 60.00A, the waveform of the output current is shown in Figure 6. The maximum output current is 60006.00mA, the minimum current is 59995.00mA, and the ripple current is 11.00mA. Change the reference voltage to -60.00A, and discharge the battery, and the obtained discharge current is shown in Figure 7. The maximum discharge current is 60005.00mA, the minimum current is 59995.00mA, and the ripple current is 10.00mA. The output current of the double-current loop simulation is 60.00A, and the accuracy error is 0mA. Through comparative analysis, the double current loop improves the current accuracy.
Experimental Verification

Experimental Circuit

DSP chip TMS320F28335 is used to design bidirectional dc-dc power supply. Built-in 16-channel 12-bit ADC, 80.00ns conversion time, input range: 0.00-3.30V; There are 18 for PWM. This chip can control multiple bidirectional dc-dc modules. EMI filter is adopted in the input of bidirectional dc-dc module to filter the input high-frequency signal. The output load, in this case the battery, thus charges and discharges the battery. The internal ADC collects the current I1 on the inductance L1, and the output current I2 is collected by the 16-bit acquisition chip ADS131E02. The control strategy adopts the double-current loop algorithm. The main parameters of the circuit system are as follows: the effective value of the dc input voltage is 12.00V, the switching frequency is 100.00khz, and the output power is 300.00W. The value of the above simulation is adopted for the inductance and capacitance. The entire structural framework is shown in figure 8:
Software Process
TMS320F28335 single-chip microcomputer is a floating-point single-chip microcomputer, the speed of calculation, the peripheral interface, often used by industrial switching power supply. Although the sampling accuracy of 16-bit external ADC is high, the sampling speed is slow. Although the sampling speed of internal ADC is fast, the sampling accuracy is not high enough. Therefore, high precision outer ring and fast speed inner ring are adopted to compensate each other to improve current accuracy. The sampling point is set at the junction of increase first and decrease later. At this time, the inductance current is relatively stable. The interrupt is then triggered to enter the operation function and the duty cycle is given to the EPWM module to drive the switch tube. The software flow chart is shown in Figure 9.

Sampling Design
In this paper, hall sensor is used to detect the current and active devices are used to minimize the error. Of course, the resistance partial voltage can also be used for detection. However, from the perspective of industrial application, the resistance partial voltage is vulnerable to external interference. Figure 10 shows the current sampling circuit. The current collected by the hall sensor is IL, which is converted into voltage through the op amp chip. Because the ADC sampling port of the single-chip microcomputer cannot input negative values, it is raised by 1.65V to ensure that the value of the input ADC port is between 0.00 and 3.30V. The output current can be collected by ADC chip ADS131E02.
Experimental Results

Figure 11 is the bi-directional dc-dc prototype picture. There are two channels of bi-directional dc-dc on this PCB. Figure 12 is the output current waveform of battery charge and discharge switching. By using high-precision measuring instrument, the set value is 60A when charging the battery, and the two-way dc-dc output current is 60000.25 to 60000.75 mA. When discharging the battery, the set value is -60A, and the output current of two-way dc-dc is -59999.98 to -60000.65mA. When using a single current ring, the error accuracy is between 1.00-3.00mA, and that of a double current ring is 0.75mA. Therefore, the use of a double current ring improves the accuracy of output current, so as to charge and discharge the battery in a more balanced and safe way and improve the service life of the battery.

![Figure 9. Prototype images.](image1)
![Figure 10. Charge-discharge switching output current waveform.](image2)

Conclusion

In this paper, the topology of Bi-directional dc-dc circuit is analyzed, and the double-current loop control of two-stage LC circuit is tested by simulation, so that the output current fluctuates around the set value, which is more accurate than the traditional single-loop control. Using TI company's floating-point DSP TMS320F28335 as the controller, a 300W prototype is made. When the output is 60A, the precision error is smaller than that of the single-loop control. The external loop current sampling accuracy is high, and the inner loop current sampling speed is fast.

The Bi-directional dc-dc power supply with double current loop can charge and discharge the battery quickly and safely. Experimental results show that this circuit topology and control method can be applied to the battery charging and discharging power supply.

References

[1] B Mallikarjuna Reddy, Paulson Samuel. A Comparative Analysis of Non-Isolated Bi-directional DC-DC Converters, J. IEEE 1st International Conference on Power Electronics.2016.

[2] KS Alam, LAR Tria, D Zhang, etc. Design of a bi-directional DC-DC converter for Solid-State Transformer (SST) application by exploiting the shoot through mode, J. IEEE International Conference on Sustainable Energy Technologies. 2016.

[3] Gang Liu, Dan Li, Yungtaek Jang. etc. Over 300kHz GaN device based resonant bidirectional DCDC converter with integrated magnetics, J. Research Gate. March 2016.

[4] Haitao Hu, Xianyi Cheng, Jianshan Wang, etc. Control and simulation of bi-directional DC/DC converter for 5KW distributed wind/solar hybrid system., J. Chinese Control and Decision Conference. 2017.

[5] Peng Liu, Changsong, Chen, Shanxu, Duan. etc. A Dual Phase-Shifted Modulation Strategy for the Three-Level Dual-Active-Bridge DC-DC Converter, J. IEEE Transactions on Industrial. PP(99):1-1 April 2017.

[6] Jian Song, Zhitao Liu, Hongye SU. A Second-Order Sliding Mode Control Design for Bidirectional DCDC Converter, J. IEEE Transactions on Industrial.2017.
[7] Guodong Liu, Zhipo Ji, Ruichang Qiu, etc. The Research on Bi-Directional DC/DC Converter for Hybrid Power System, J. Part of the Lecture Notes in Electrical Engineering book series. 2018

[8] Zhengrong Huang, Zhengyang Liu, Fred Lee, etc. Critical-Mode-Based Soft-Switching Modulation for High-Frequency Three-Phase Bi-Directional AC/DC Converters, J. IEEE Transactions on Power Electronics PP(99):1-1. 2018.