Design of Half-bridge Bidirectional DC-DC Converter Control Loop

Huan Cheng1,a, Yingna Guo2,b, Zhao Ma3,c, Sisi Bai4,d
1School of Electronic Engineering Xi’an Shiyou University Xi’an, China
2Shaanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells Xi’an, China
3School of Electronic Engineering Xi’an Aeronautical University Xi’an, China
4School of Electronic Engineering Xi’an Shiyou University Xi’an, China
a992974739@qq.com, b609546649@qq.com, c576772378@qq.com, 
d1579260212@qq.com

Abstract—In recent years, the direct current (DC) microgrid system has received extensive attention from industrial and academic circles worldwide. As an essential part of the DC microgrid, the bidirectional DC-DC converter can realize the bidirectional flow of energy according to the needs of the DC microgrid. In this paper, the half-bridge bidirectional DC-DC converter is taken as the research object, and the double closed-loop feedback control loop of the converter in the charging and discharging mode is designed based on the intermittent and fluctuating characteristics of distributed generation. Besides, a simulation model is built using MATLAB to analyze the operation of the converter in different modes and the control effect of the double closed-loop feedback control loop. The results verify the effectiveness and feasibility of the proposed control method.

1. Introduction
In recent years, DC microgrids have provided new practical areas for the rapid development, improvement, and innovation of renewable energy. Many renewable energy sources (such as photovoltaics) have DC output [1]. With the gradual increase of the proportion of DC power load, DC microgrid that can integrate various distributed power sources, loads, energy storage devices, and energy conversion devices have become a research hotspot. Considering that Distributed generation is currently one of the more mature energy that can be developed on a large scale, the reasonable use, distribution, and storage of its energy are particularly significant [2]. The energy storage device containing the bidirectional DC-DC converter has the function of "peak shaving and valley filling", by reasonably controlling the bidirectional DC-DC converter, the bidirectional flow of electric energy can be realized, and the utilization ratio of distributed generation and the power quality of the system can be effectively improved [3].

In terms of the features of distributed generation such as intermittent, random, and highly affected by weather conditions, this paper designs the voltage and current double closed-loop feedback control loop of the bidirectional DC-DC converter in the charge and discharge mode. The working principle of the half-bridge bidirectional DC-DC converter is analyzed, the small signal model of the converter in
different working modes is established, and the corresponding control loop is designed, so as to enhance the stability of the DC microgrid.

2. Working Principle
In this paper, the half-bridge bidirectional DC-DC converter is selected to realize the charging and discharging function. Its structure and control method are simple and efficient [4]. This converter has two operating modes: Buck operating mode and Boost operating mode. The topology of half-bridge bidirectional DC-DC converter is illustrated in the Fig. 1.

![Figure 1 Topology of half-bridge bidirectional DC-DC converter](image)

2.1. Buck operating mode
When the converter works in reverse, the DC bus transfers energy to the battery through the half-bridge bidirectional DC-DC converter. At this time, the switching tube \( Q_1 \) is turned on, and \( Q_2 \) needs to be turned off reliably. When \( Q_1 \) is turned on, the DC bus will charge the battery through the switch \( Q_1 \) and the inductor \( L \), since \( V_0 > V_g \), the inductor current \( i_L \) increases linearly, and inductive energy storage is induced, that is, electrical energy is stored in the inductor \( L \) in the form of magnetic field energy. When \( Q_1 \) is turned off, the diode \( D_2 \) is turned on, and the inductor current \( i_L \) flows through the diode \( D_2 \). Meanwhile, the voltage on the inductor \( L \) is \(-V_g\), thus, the inductor current \( i_L \) decreases linearly, the inductor releases energy, and the energy transfers to \( V_g \). The topology of Buck operating mode is illustrated in the Fig. 2.

![Figure 2 Topology of Buck operating mode](image)

2.2. Boost operating mode
When the converter is working in the forward direction, the battery transfers energy to the DC bus through the half-bridge bidirectional DC-DC converter [5]. At this time, the switching tube \( Q_2 \) is turned on, and \( Q_1 \) needs to be reliably cut off. When \( Q_2 \) is turned on, the battery voltage \( V_g \) is applied across the inductor \( L \); the inductor current \( i_L \) increases linearly, and the battery charges the inductor \( L \); then, inductive energy storage is induced, that is, electrical energy is stored in the inductor \( L \) in the form of magnetic field energy. Meanwhile, the capacitor \( C_1 \) provides energy to the DC bus to keep the DC bus voltage \( V_0 \) constant. When \( Q_2 \) is turned off, the diode \( D_1 \) is turned on, and the battery \( V_g \) and the inductance \( L \) provide energy to the DC bus through the diode \( D_1 \). Simultaneously, the capacitor \( C_1 \) is
charged, the inductor \( L \) releases energy, and the inductor current gradually decreases. The topology of Boost operating mode is illustrated in the Fig. 3.

![Topology of Boost operating mode](image)

**Figure 3** Topology of Boost operating mode

### 3. Design of Control Loop

Due to the presence of non-linear elements such as switching tubes and diodes in the half-bridge bidirectional DC-DC converter, the converter system is non-linear. However, it can still be approximated as a linear system when running near a certain steady-state operating point [6].

#### 3.1. Establish small signal model

When the converter is in Buck mode, set \( d \) as the switching function of the switch \( Q_1 \). Then, the small signal model can be obtained as:

\[
G_{vd}(s) = \frac{V_v(s)}{d(s)} = \frac{V_o}{LCS^2 + \frac{L}{s} + 1}
\]

(1)

\[
G_{id}(s) = \frac{i_L(s)}{d(s)} = \frac{V_o(Cs + \frac{1}{R})}{LCS^2 + \frac{L}{s} + 1}
\]

(2)

When the converter is in Boost mode, set \( d \) as the switching function of the switch \( Q_2 \). Then, the small signal model can be obtained as:

\[
G_{vd}(s) = \left. \frac{\tilde{v}_v(s)}{d(s)} \right|_{v_v(s)} = \left( \frac{V_v}{D^2} \right) \left( \frac{1 - \frac{sL}{D^2R}}{1 + \frac{L}{D^2R} + \frac{s^2LC}{D^2}} \right)
\]

(3)

\[
G_{id}(s) = \left. \frac{\tilde{i}_L(s)}{d(s)} \right|_{v_v(s)} = \frac{V_o(Cs + 1/R) + (1-d)i_v}{LCS^2 + sL/R + (1-d)^2}
\]

(4)

Where, \( V_o \) represents the DC bus voltage; \( V_v \) represents the battery voltage; \( D \) represents the duty cycle of the PWM control signal.

#### 3.2. Design of control system

In order to control the voltage stability of the DC bus side and battery side of the half-bridge bidirectional DC-DC converter, a double closed-loop feedback control strategy based on PI control is adopted. The operating principle is: the voltage sensor collects the output voltage of the bidirectional DC-DC converter to the negative electrode of the error amplifier and compares it with the given voltage value \( V_{ref} \) to obtain the outer loop error signal; then, the error signal is adjusted by PI to be the current reference.
signal of the inner loop of the inductor current, which is compared with the inductor current signal detected by the current sensor to acquire the inner loop error signal; next, the inner loop error signal is adjusted by PI and compared with the sawtooth wave, and the PWM control signal is generated in the PWM modulator; finally, the stability of the system is controlled by controlling the change of the duty cycle of the switch tube [7]. Its working principle block diagram is presented in Fig. 4, Its system control diagram is presented in Fig. 5.

![Working principle diagram of control system](image1)

![Diagram of control system](image2)

The open-loop transfer function of the current loop is:

\[
G_{\text{op}}(s) = \frac{G_{\text{pic}}(s)}{V_m} \times G_{\text{id}}(s) \times H_c
\]  

(5)

The open-loop transfer function of the voltage loop is:

\[
G_{\text{op}}(s) = \frac{G_{\text{pv}}(s) \times G_{\text{id}}(s) \times 1/V_m \times G_{\text{po}}(s) \times G_{\text{c}}(s) \times H_c}{1 + G_{\text{sp}}}
\]  

(6)

Where, \( G_{\text{pv}}(s) \) denotes the transfer function of the voltage loop PI controller; \( G_{\text{pic}}(s) \) denotes the transfer function of the current loop PI controller; \( 1/V_m \) denotes the transfer function of the PWM controller; \( G_{\text{id}}(s) \) denotes the transfer function of the inductor current to the duty cycle; \( G_{\text{c}}(s) \) denotes the transfer function of output voltage to inductor current; \( H_c \) and \( H_v \) denote the sampling coefficients of voltage and inductor current, respectively.

4. **Design of System Parameter**

The design requirements of half-bridge bidirectional DC-DC converter are as follows: Battery voltage is \( V_g = 12V \), DC bus Voltage is \( V_o = 30V \), DC bus current is \( I_o = 3.2A \), Switching frequency is \( f_s = 20KHZ \), Rated power is \( P = 96W \).
4.1. Design of energy storage inductor

The half-bridge bidirectional DC-DC converter can work in Buck mode or Boost mode. Therefore, the selection of the energy storage inductance L needs to meet the requirements for inductance when the Buck circuit and the Boost circuit work in a continuous state.

Buck operating mode:

\[
L = \frac{V_s (1 - D_{\text{buck}})}{\Delta i_L f_s} = \frac{12 \times (1 - 0.4)}{16 \times 20} = 22.5 \mu H
\] (7)

Boost operating mode:

\[
L = \frac{V_o \times D_{\text{boost}} \times (1 - D_{\text{boost}})}{\Delta i_L f_s} = \frac{30 \times 0.6 \times 0.4 \times 0.4}{64 \times 20} = 22.5 \mu H
\] (8)

According to formula (7) and formula (8), and considering a certain margin, the final choice is \( L = 100\mu H \).

4.2. Design of capacitance

In the switching converter, the filter capacitor is usually selected according to the ripple requirement of the output voltage.

In Buck operating mode, Output voltage ripple of converter \( \Delta V_s = 500 \text{mv} \), Duty cycle \( D = 0.4 \).

According to the Buck circuit capacitance calculation formula:

\[
C_2 = \frac{V_s (1 - D)}{8 L f_s \Delta V_s} = \frac{12 \times (1 - 0.4)}{8 \times 22.5 \times (20)^2 \times 500} = 200 \mu F
\] (9)

In Boost operating mode, Output voltage ripple of converter \( \Delta V_s = 100 \text{mv} \), Duty cycle \( D = 0.6 \).

According to the Boost circuit capacitance calculation formula:

\[
C_1 = \frac{I_o D}{f_s \Delta V_o} = \frac{3.2 \times 0.6}{20 \times 100} = 960 \mu F
\] (10)

5. Simulation Results and Analysis

The simulation model of half-bridge bidirectional DC-DC converter in charge and discharge mode is built in MATLAB simulation conditions. The operation of the converter in different modes and the control effect of double closed-loop feedback control loop based on PI control are analyzed.

5.1. Simulation model of Buck mode

The simulation model in Buck mode is illustrated in the Fig.6, and the voltage waveform of DC bus and battery is illustrated in the Fig.7.
When the converter operates in Buck mode, the battery is in charging state. It can be seen from Fig.7 that the output of distributed generation has fluctuation in 0.6s, 1.2s and 1.5s. At this time, the double closed-loop control strategy based on PI controller can stabilize the battery voltage at 12V.

5.2. Simulation model of Boost mode
The simulation model in Boost mode is illustrated in the Fig.8, and the voltage waveform of DC bus and battery is illustrated in the Fig.9.
When the converter works in Boost mode, the battery is discharged to keep the bus voltage stable. It can be seen from Fig.9 that the output voltage of the battery fluctuates in 1s due to the interference of external environment. At this time, the double closed-loop control strategy based on PI controller can stabilize the DC bus voltage at 30V.

6. Conclusion
In this paper, a double closed-loop feedback control loop is used in a half-bridge bidirectional DC-DC converter. The simulation results show that the output voltage can be stabilized at the given value by using the double closed-loop control strategy based on PI controller when the distributed generation or battery fluctuates, which achieves the expected control effect and improves the stability of DC microgrid operation.

Acknowledgment
This research project is supported by the natural science foundation research program of Shaanxi Province (Program No. 2020JM-542) and the innovation and practice ability training project of Xi'an Petroleum University (Program No. YCS20213173).

Project Supported by Natural Science Basic Research Program of Shaanxi, (Program No. 2020JM-542).

The graduate student innovation and practical ability training project of Xi'an Shiyou University, (Program No. YCS20213173).

References
[1] Gao Xiaozhi, Gao Fan, and Jiang Feng. New Battery Charge and Discharge Control Strategy for Photovoltaic DC Microgrid System [J]. Journal of Electric Power System and Automation, 2019, 31(11): 75-80.
[2] Wu Shaolong. Research on Digital Control of Buck/Boost Bidirectional DC/DC Converter [J]. Electrical Appliances and Energy Efficiency Management Technology, 2018(20): 86-92.
[3] Ma Zhao. Research on Bidirectional DC-DC Converter Based on STM32 [J]. Industrial Instrumentation and Automation, 2018 (04): 87-90.
[4] L.S. Yang, and T.J. Liang, “Analysis and implementation of a novel bidirectional DC-DC converter,” IEEE Trans. Ind. Electron., vol. 59, no. 1, pp. 422–434, 2012.
[5] H. Ardi, R. Reza Ahrafi and S. Najafi Ravadanegh. Non-isolated bidirectional DC-DC converter analysis and implementation [J]. IET Power Electronics, 2014, 7(12): 3033-3044.
[6] Yan Shuhan and Zhang Junguo. Research on Charging and Discharging of Battery-based Energy Storage System [J]. Communication Power Technology, 2020, 37(7): 46-48.
[7] Yang Hui. Research on Control Strategy of Bidirectional DC-DC Converter for Photovoltaic Energy Storage [D]. Xi'an University of Technology, 2018.