A Study on Staggered Parallel DC/DC Converter Applied to Energy Storage System

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Abstract

Because of the advantages of simple structure, low cost and no transformer loss, the traditional half bridge bidirectional Buck/Boost converter has been widely used. However, due to its shortcomings such as large current ripple coefficient, small capacity and large filter components, this paper proposes to apply two-phase interleaved parallel bidirectional DC/DC converter to energy storage system to overcome the disadvantages of half-bridge bidirectional DC converter disadvantages in the system. In this paper, the topology and operating mode of two-phase interleaved bidirectional DC/DC converter are analyzed and introduced. The PI controller in Boost mode is designed. Finally, the correctness of the theory is verified by simulation.

Keywords

Energy storage system; Interleaved; Bidirectional DC/DC converter; Phase shift control.

1. Introduction

In the energy storage system, bidirectional DC/DC converter plays an important role because it can realize the bidirectional flow of energy[1]. The bidirectional DC/DC converter acts as the interface between the energy storage device and the DC bus side, and bears the function of energy transmission. It controls the switch tube to achieve the purpose of bidirectional power flow. Meanwhile, the energy storage device is connected to the DC bus through the DC/DC converter, which can greatly reduce the voltage of the energy storage device, and make full use of the capacity of the energy storage device, enabling it to discharge flexibly and reduce the investment cost of the energy storage system.

Interlaced parallel as a new technology[2], it is mainly refers to the frequency of the same module, the phase angle staggered parallel operation mode[3]. Interleaved parallel bi-directional DC / DC circuit system, in addition to its own operating characteristics in addition to work, there are staggered parallel technology brings the advantages of[4]: staggered parallel topology of the input current ripple for the switching frequency of N (parallel unit number) times, greatly reducing the size of the filter and the need for magnetic materials, thereby increasing the power density and dynamic response of the entire system; the voltage gain of interleaved parallel topology is increased relative to a single module, and control is also easy to implement; staggered parallel structure can not only achieve power expansion, but also share power loss and improve the reliability of system operation; improve the dynamic response of the converter and conversion efficiency.

2. Topology and Operating Mode of Staggered Parallel Bidirectional DC / DC Converter

2.1 Staggered Parallel Bidirectional DC/DC Converter Topology

The two phase interlaced parallel bidirectional DC/DC converter is the topology of two bidirectional half bridge DC/DC converters in parallel[5]. The two units in parallel are connected in turn, the conduction time is the same in each cycle, but the phase difference of conduction is 180°, so it is called two phase interleaving bidirectional DC/DC converter[6]. In this paper, an interlaced parallel bidirectional DC/DC converter is selected, and its structure is shown in Fig. 1. U_1 is a energy storage terminal, and the R_L is a DC bus terminal load. According to the demand for power change at the load end, the bidirectional DC/DC converter can work in Boost mode or Buck mode.

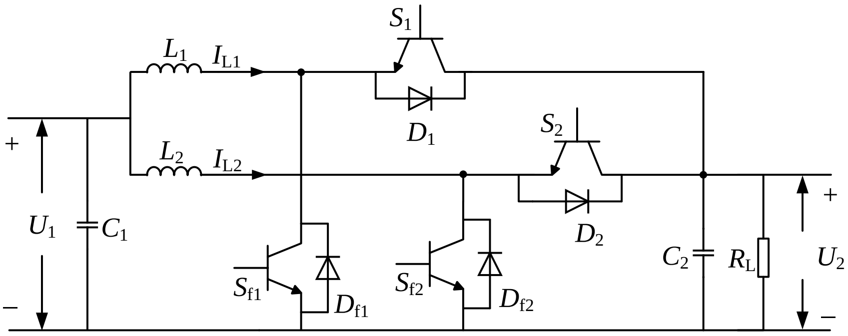
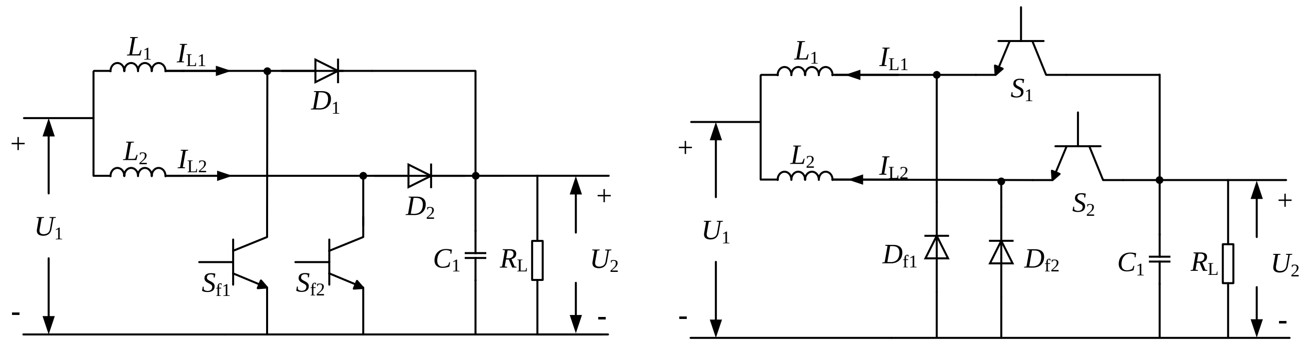


Fig. 1 Interlaced parallel bidirectional Buck-Boost converter

2.2 Working Mode of Interlaced Parallel Bidirectional DC Converter

The circuit topology of a bidirectional DC/DC converter operating in Boost mode is shown in Fig. 2(a). In this mode, the energy flows from U_1 to U_2 and the switches S_{f2} and S_{f1} work as the main power switch. The switches S_2 and S_1 do not work, and the anti-parallel diodes D_1 and D_2 serve as freewheeling diodes. The circuit topology of a bidirectional DC/DC converter operating in Buck mode is shown in Fig. 2(b). In this mode, the energy flows from U_2 to U_1, switch S_2 and S_1 are interlaced and work as the main power switch; switch S_{f2} and S_{f1} do not work, and reverse-parallel diodes D_{f1} and D_{f2} serve as free-wheeling diodes.



(a) Boost mode (b) Buck mode

Fig. 2 Two working modes of interlaced parallel bidirectional Buck-Boost converter

2.3 Performance Analysis of Two-Phase Interleaved Paralleled Bidirectional DC/DC Converter

The two-phase interleaved DC/DC converter performance in Boost mode through the analysis of the performance of the Buck model can be obtained similarly, because of the limited space, this paper only analysis of the Boost mode of the two-phase interleaved DC/DC converter performance in Boost mode in Buck mode, the working performance of the same but, because of the Limited space, this paper makes analysis on the performance of all work under the mode of Boost.

For the traditional single-phase Boost converter, assuming that the minimum inductor current is also equal to zero, according to the literature[8], the current ripple in one cycle is expressed as:

$$\Delta i = \frac{D(1-D)U_2}{Lf_s} \tag{1}$$

In this paper, for the convenience of analysis, assuming that the minimum value of the inductor current during the operation of a two-phase interleaved parallel Boost converter is also equal to zero, according to its current expression in one cycle T_s, the two-phase interleaved parallel bidirectional DC converter D The output current ripple value is given by[9]:

$$\Delta i' = \begin{cases} \dfrac{D(1-2D)U_2}{L'f_s} \\ \dfrac{(D-1/2)(2-2D)U_2}{L'f_s} \end{cases} \tag{2}$$

When U_1=48V, U_2=100V, $L = L' = 2$mH, $f_s = 10$kHz, the correlation between current ripple Δi and $\Delta i'$ at different duty ratio can be obtained from equations and equations, as shown in Fig. 3.

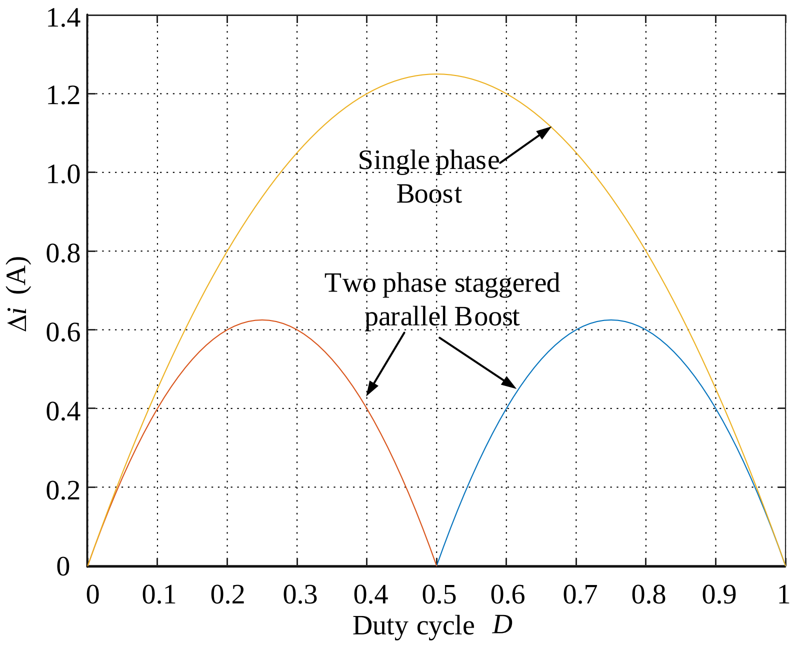


Fig. 3 The relation between current ripple and duty ratio

Thus, we can get the two-phase interleaved parallel Boost converter has the following advantages relative to the traditional Boost converter: the same as the current ripple index can effectively improve the system switching frequency; can reduce the design value of the inductance element, Quality and volume, increase power density.

3. Control of Interlaced Parallel Bidirectional DC/DC Converter

3.1 Principle of Phase Shift Control For Bidirectional DC/DC Converter

Buck/Boost type bidirectional DC/DC converter to reduce the voltage and current of parallel two-phase pressure devices, but in the in-phase PWM drive mode, the total current ripple into the storage system is not reduced, so this paper adopts phase shifted 180 ° of PWM drive, this way can effectively reduce the current ripple, improve the voltage stability[10].

In this paper, the principle of phase shift control and the reduction of ripple are analyzed in detail. In this system, under the bidirectional DC/DC converter working and current continuous conduction mode (CCM), it is assumed that the circuit works in the Boost mode, as shown in the Fig. 2(b), inductance $L_1 = L_2 = L$, L is the size of inductance. When the switch S_{f1} and S_{f2} is on:

$$\begin{cases} L_1 \dfrac{di_{L1}}{dt} = U_{L1} = U_1 \\ L_2 \dfrac{di_{L2}}{dt} = U_{L2} = U_1 \end{cases} \quad (3)$$

Similarly, whens switch S_{f1} and S_{f2} is off :

$$\begin{cases} L_1 \dfrac{di_{L1}}{dt} = U_{L1} = U_1 - U_2 \\ L_2 \dfrac{di_{L2}}{dt} = U_{L2} = U_1 - U_2 \end{cases} \quad (4)$$

Since the inductances are equal, the slopes of the rising and falling currents of L_1 and L_2 are the same. Let k_1 is the slope of the current rising phase, k_2 is the slope of the current falling phase, then:

$$\begin{cases} k_1 = \dfrac{U_1}{L} \\ k_2 = \dfrac{U_1 - U_2}{L} \end{cases} \quad (5)$$

In the same phase driven mode, i_{L1} and i_{L2} in the same phase, the total peak peak of the current pattern $\Delta i_{L同相}$ is:

$$\Delta i_{L同相} = \Delta i_{L1} + \Delta i_{L2} = 2Dk_1T \quad (6)$$

In the case of 180 ° phase-shift control, the coordinate system is established based on the inductor L_1 current at the initial time of one carrier period [0, T]. For convenience of calculation, it is assumed that i_{L1} at time 0 (Under the CCM, the actual minimum is not 0), the same carrier cycle inductor current i_{L1} and i_{L2}, respectively, as shown in Fig. 4.

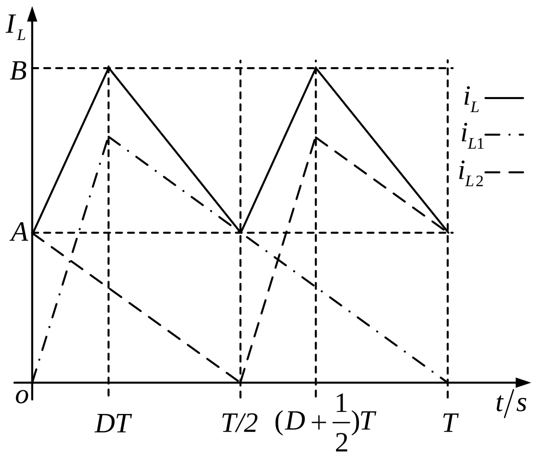


Fig. 4 Two-phase inductor current and total current at $D \le 1/2$ in Boost mode

The two inductor currents in period [0, T] are:

$$i_{L1} = \begin{cases} k_1 t & t \in [0, DT] \\ k_2 t - k_2 T & t \in [DT, T] \end{cases} \quad (7)$$

$$i_{L2}=\begin{cases} k_2t-\frac{1}{2}k_2T & t\in\left[0,\frac{1}{2}T\right] \\ k_1t-\frac{1}{2}k_1T & t\in\left[\frac{1}{2}T,(D+\frac{1}{2}T)\right] \\ k_2t-\frac{3}{2}k_2T & t\in\left[(D+\frac{1}{2}T),T\right] \end{cases} \tag{8}$$

According to the KCL law, the total current i_L can be expressed in one carrier cycle as:

$$i_{L1}=\begin{cases} (k_1+k_2)t-\frac{1}{2}k_2T & t\in\left[0,DT\right] \\ 2k_2t-\frac{3}{2}k_2\mathrm{T} & t\in\left[DT,\frac{1}{2}T\right] \\ (k_1+k_2)t-k_2T-\frac{1}{2}k_1T & t\in\left[\frac{1}{2}T,(D+\frac{1}{2}T)\right] \\ 2k_2t-\frac{5}{2}k_2T & t\in\left[(D+\frac{1}{2}T),T\right] \end{cases} \tag{9}$$

Due to $U_2<2U_1, k_1+k_2>0$, and $2k_2<0$, the waveform of the i_L in the$\left[0,T\right]$ can be obtained as shown in theFig. 4. Thus the peak of the total current ripple peak $\Delta i_{L移相}$ at this time can be obtained:

$$\Delta i_{L移相}=(k_1+k_2)DT \tag{10}$$

By contrast, the peak peak of the current ripple peak is reduced by $(k_1-k_2)DT$ at $D\le 1/2$. In the same way, the peak peak of the current ripple peak at $D>1/2$ can be deduced at $\Delta i_{L移相}=(2D-1)k_1T$. To sum up, in the Boost mode, the total current ripple reduction is as follows:

$$\Delta i_{L同相}-\Delta i_{L移相}=\begin{cases} (k_1-k_2)DT=\frac{DU_2}{Lf_s} & D\le\frac{1}{2} \\ k_1T=\frac{U_1}{Lf_s} & D>\frac{1}{2} \end{cases} \tag{11}$$

Among them: f_s is a carrier frequency.

Similarly, when the bidirectional DC/DC converter works in Buck mode, the total current ripple peak reduction can be deduced accordingly. The derivation process is similar to the previous Boost mode derivation process, and no longer need to be emphasized.

3.2 Controller Design

The staggered parallel Boost circuit adopts the double closed loop control of voltage and current, and the block diagram of the control system is shown as shown in theFig. 5. Among them: (1) In order to reduce the influence of circuit ripple on the controller, we usually use low-pass filter to deal with the sampling value. (2) In order to make the electrical stress of the two module close, two inductor currents are independently controlled. The parameters of the set circuit are: input voltage U_1= 48V, output voltage U_2=100V, inductor L=1mH, equivalent load R_L =10Ω, output capacitance C=120μF.

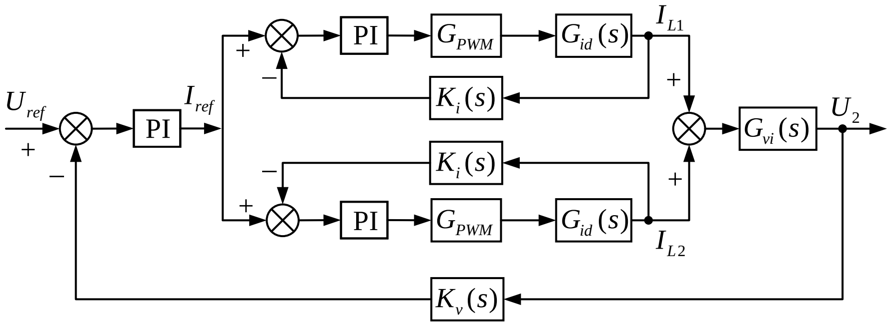


Fig. 5 System control block diagram under interlaced parallel Boost mode

4. Simulation Experiment and Result Analysis

In this paper, the traditional Boost converter and two intersecting parallel Boost converter are simulated in the MATLAB/SIMULINK, and the simulation characteristics in the Buck mode can be obtained in the same way. The simulation parameters set are as follows:

Table1. Simulation Parameters

Index	Parameter
Battery voltage	48V
DC bus side voltage	100V
Rated power	2kW
Voltage ripple factor	1%
Inductance current ripple factor	10%
Switching frequency	10kHz

The energy storage inductance of the two converters L=2mH, the capacitance value of the energy storage side C_1=500 μF, the DC side bus side capacitance C_2=2000 μF, and the load resistance R_L=32 Ω. The difference of the driving signal of the switch tube of the two phase interlaced parallel Boost converter is 180°, and the duty ratio of each switch tube is D=0.7. The simulation results of the traditional Boost converter are shown in the Fig. 6 and Fig. 7.

It can be seen from the figure: (1) The output current harmonics of the traditional single-phase Boost converter are dominated by 10kHz. The output current harmonics of the two-phase interleaved parallel Boost converter are mainly 20kHz, indicating that two-phase interleaved parallel Boost (2) The THD value of the output current of the traditional single-phase Boost converter is obviously larger than the THD value of the output current of the two-phase staggered parallel Boost converter, which shows that the output of the two-phase staggered parallel Boost converter The small amount of AC current can greatly reduce the amplitude of the current ripple, thus reducing the current ripple factor.

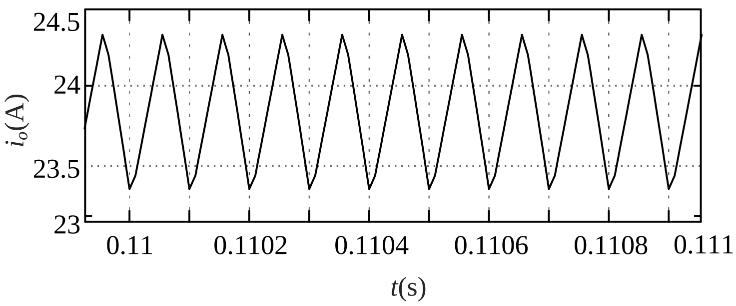


Fig. 6 Output current waveform of traditional single phase Boost converter

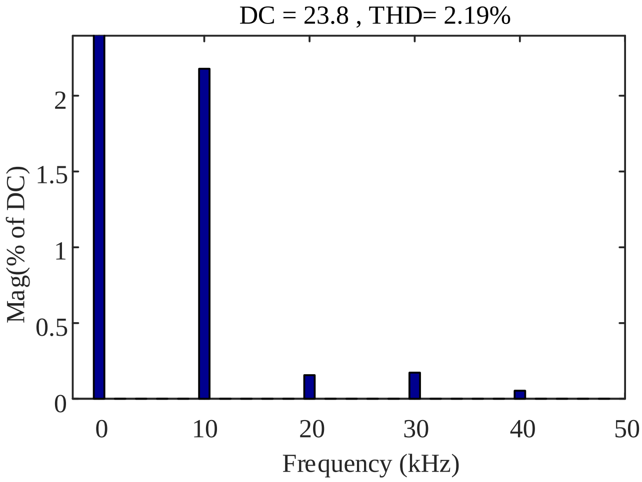


Fig. 7 Output current spectrum diagram of traditional single phase Boost converter

The simulation results of the two phase interlaced parallel Boost converter are shown in the Fig. 8 and Fig. 9.

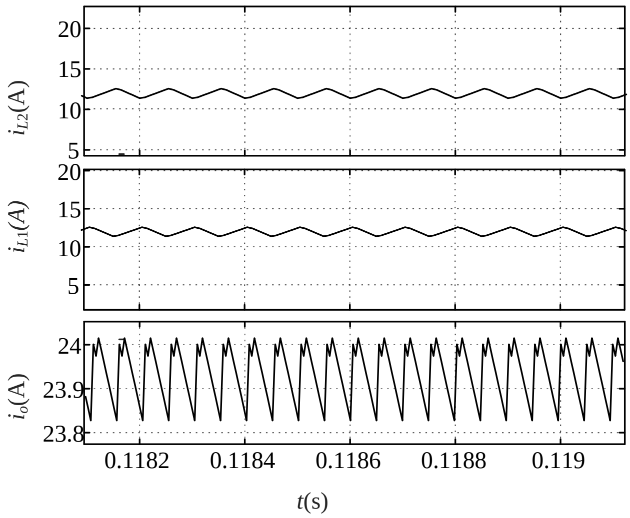


Fig. 8 Output current of two phase staggered parallel Boost converter

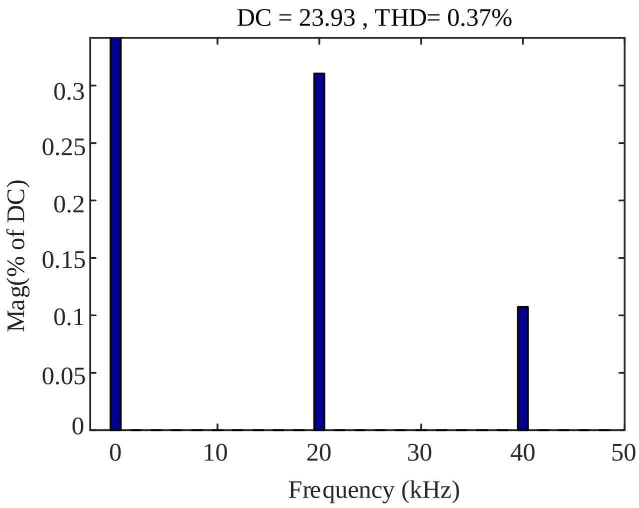


Fig. 9 Output current spectrum of two phase staggered parallel Boost converter

5. Conclusion

This paper analyzes the overall structure and mathematical model of two-phase interleaved parallel bi-directional DC converter, analyzes its working mode and working performance and designs the PI controller under Boost mode. Finally, it builds the simulation model in MATLAB/Simulink. The proposed control strategy is simulated and analyzed. The simulation results show that the current ripple of the two-phase interleaved parallel Boost converter is obviously smaller than the current ripple of the traditional Boost converter. This can be obtained two-phase interleaved parallel Boost converter has the following advantages: the current ripple index in the same case, can effectively increase the system switching frequency; can reduce the design value of the inductance element, so that the quality and volume of components, improve power density.

References

[1] Tong Y B, Wu T, Jin X M, et al. Study of bi-directional DC/DC converter[J]. Proceedings of the Csee, 2007.
[2] Lu Z, Zhu W, Liu J, et al. A novel interleaved parallel bidirectional DC/DC converter[J]. Proceedings of the Csee, 2013, 33(12):39-46.
[3] Jiang Y Y. A Novel Interleaved Bidirectional DC-DC Converter for Hybrid Battery Energy Storage System[J]. Telecom Power Technology, 2016.
[4] Park S, Song Y. An interleaved half-bridge bidirectional dc-dc converter for energy storage system applications[C]// IEEE, International Conference on Power Electronics and Ecce Asia. IEEE, 2011:2029-2034.
[5] Fei-Yang L V, Zheng L I. Analysis and Application of Staggered Parallel Technology in Ripple Suppression for the Bidirectional DC Converter[J]. Instrumentation Technology, 2017.
[6] Yamamoto Y, Takiguchi T, Sato T, et al. Two-phase interleaved bidirectional converter input-parallel output-series connection[C]// International Conference on Power Electronics and Ecce Asia. IEEE, 2015:301-308.
[7] Park S, Song Y. An interleaved half-bridge bidirectional dc-dc converter for energy storage system applications[J]. 2011:2029-2034.
[8] Yang Y, Ma J, Ye J, et al. A new coupled inductors used in interleaving bidirectional DC/DC converter[C]// Power Electronics and Application Conference and Exposition. IEEE, 2014:1014-1019.
[9] Zhang X, Song Y. Study on Inductor Current Ripple in Interleaved Bidirectional DC-DC Power Converters Under DCM[J]. Marine Electric & Electronic Engineering, 2010.
[10] Wang Y F, Xue L K, Wang C S, et al. Interleaved High-Conversion-Ratio Bidirectional DC–DC Converter for Distributed Energy-Storage Systems—Circuit Generation, Analysis, and Design[J]. IEEE Transactions on Power Electronics, 2016, 31(8):5547-5561.