Study on Optimal Backflow Power of Bi-directional Dual-active-bridge DC-DC Converter

Zhenhao Zhou

School of Shanghai Maritime University, Shanghai20000, China

1304293091@qq.com

Abstract

Double phase-shifting and triple phase-shifting control of bi-directional dual-active-bridge DC-DC converter will produce large backflow power and current stress, resulting in increased loss. In this paper, the mathematical model of output power and backflow power in triple phase shift control is established, the mathematical relationship between backflow power and shift ratio and input/output voltage regulation ratio is derived, and an optimal control strategy of triple phase shift backflow power with minimum backflow power is proposed. The control strategy is based on the establishment of the optimization model, and the internal point method is used to calculate the optimal shift ratio combination. Through simulation calculation, the backflow power curves of the optimal strategy and ordinary double phase shift control are compared and studied, and the effectiveness and feasibility of the triple phase shift reflux power optimal control strategy proposed are verified.

Keywords

Bi-directional dual-active-bridge DC-DC converter, phase-shifting control, backflow power, optimal control.

1. Introduction

With the continuous consumption of traditional energy sources and the increasing demand for new energy sources, Bi-directional Dual-active-bridge DC-DC Converters have been used more and more popular[1]. The bidirectional Dual-active-bridge DC-DC converter has many advantages such as soft switching, high reliability, high power density and simple structure symmetry [2]. It is widely used as an interface device for energy storage systems and power systems in microgrids.

At present, research on the control mode of bidirectional Dual-active-bridge DC-DC converters mainly focuses on phase shift control [3]. The traditional single-phase-shift (SPS) controls the flow of power by adjusting the phase shift angle between the square wave outputs of the H-bridges on both sides [4], but the input and output voltages do not match. This results in increased return power and converter losses, reducing power factor. In order to improve the shortcomings of SPS control, the literature [5] proposed an improvement on the hardware circuit, adding relevant circuits on the full-bridge DC-DC topology structure, and obtaining certain benefits. At the same time, due to the addition of hardware circuits, the cost of the device increases, and the system loss increases. The literature [6] proposed dual-phase-shift control (DPS). By controlling the phase shift angle of the H-bridge on both sides and the phase shift angle of the primary side, the variation range of transmission power is increased. The literature [7] studied the reflow characteristics of the converter under DPS control. By optimizing the size of the two phase shift angles, the simulation and experimental verification were established. The literature [8] proposes to improve the current stress while expanding the range of the soft switch to achieve the purpose of reducing losses. The literature [9] proposed a more flexible control method triple-phase-shift control (TPS), but there is no systematic analysis of the impact of the TPS control strategy on the converter. The literature [10] analyzed the effects of three phase shift angles on the performance of the converter under free combination and system parameters, and derived the range of transmission power in different modes.

2. Working principle of DPS control

The topology structure of a typical bidirectional Dual-active-bridge DC-DC converter is shown in figure 1. The H Bridges on the primary and secondary sides are connected by high-frequency transformer T. U_1 and U_2 are the dc voltage on both sides of the transformer respectively, and u_{ab} and u_{cd} are the ac voltage output through the H bridge.Inductance L is composed of primary inductance and transformer leakage inductance. C_1 and C_2 are the filter capacitors of the primary and secondary sides. S_1 to S_4 are switch tubes on the full bridge arm of the primary side, and D_1 to D_4 are reverse parallel diodes on the switch tube.

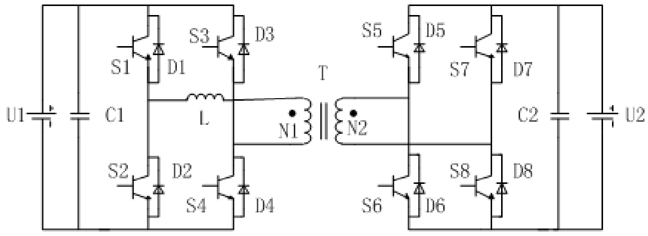

Figure 1. Topology of bidirectional Dual-active-bridge DC-DC converter

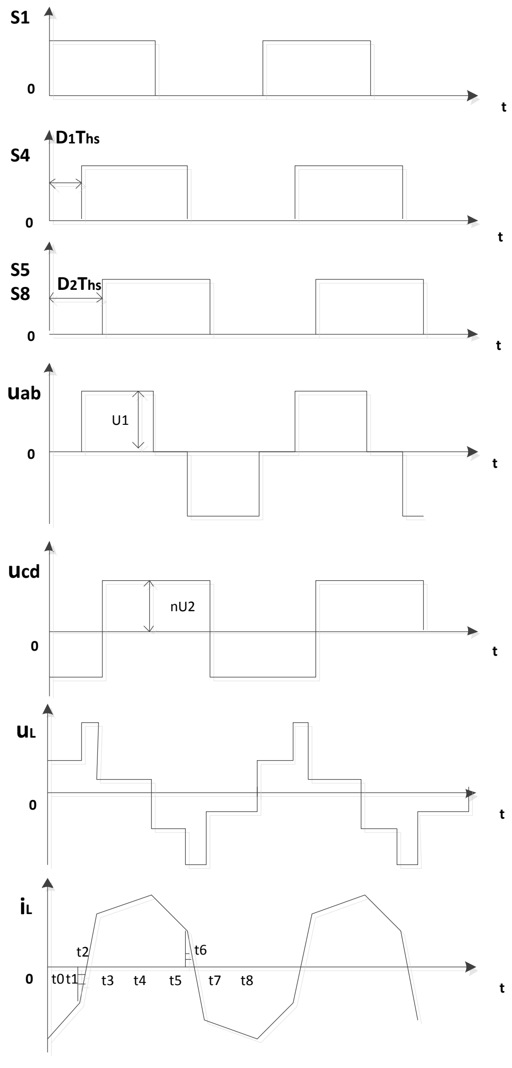

Figure 2 working principle of DPS down converter

Bidirectional Dual-active-bridge DC-DC converter can control the power transmission direction through the system needs. This paper analyzes the power transmission from the primary side to the secondary side. The working waveform of the converter is shown in figure 2. I_L represents the current flowing through L.U_L represents the terminal voltage of series inductance plus leakage inductance of transformer; The transformer ratio is n=1; T_{hs} represents half a switching cycle; D_1 represents the shift ratio within the full bridge on one side of half switch cycle; D_2 represents the shift ratio of the full bridge on both sides in half a switching cycle. It can be seen from figure 2 that in time periods (t_1-t_2) and (t_5-t_6), the energy stored in the inductance current i_L backflow due to the opposite phase of i_L and u_{ab} is called power backflow.

The difference between dual phase-shift control and single phase-shift control is that the shift ratio D_1 is increased, that is, the drive of S_1 is ahead of that of S_4.It can be seen from figure 2 that under a certain transmission power, DPS control can reduce the backflow power and current stress by adjusting D_1 and D_2. However, this method still has a large current stress, the same, will make the system loss increases, the converter efficiency decreases.

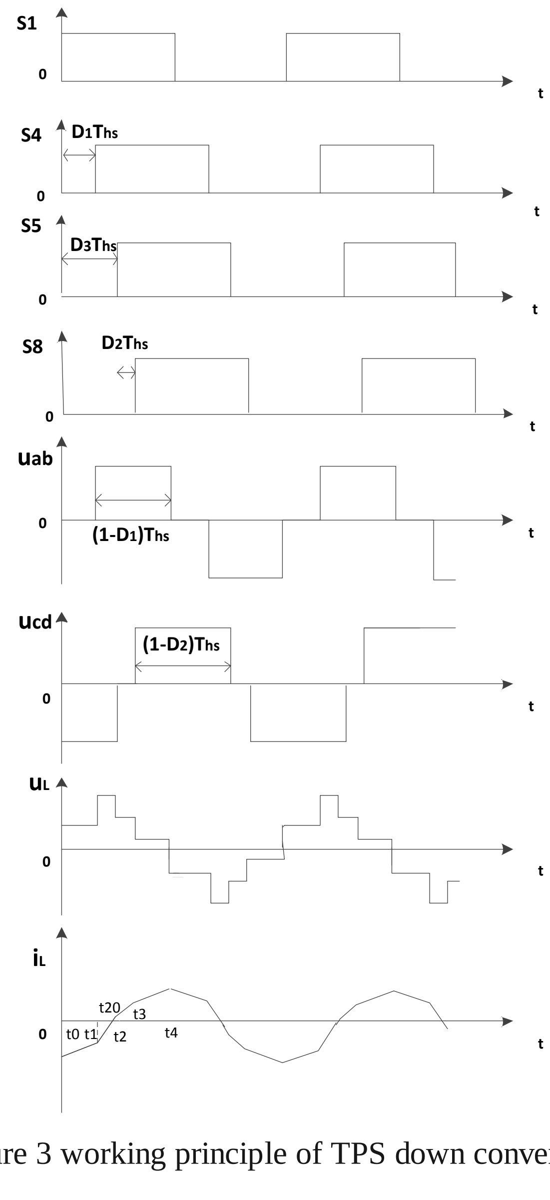

Figure 3 working principle of TPS down converter

3. Working principle of TPS control

For TPS modulation, there is phase shift D_1 in the whole bridge on the primary side, phase shift D_2 in the whole bridge on the secondary side, and phase shift D_3 between the primary side and the secondary side, where, D_1, D_2 and D_3 are within the range of [0,1].In order to simplify the analysis process, it is assumed that the converter under TPS modulation has been in a stable state, and the shift phase relation is $0 < D_1 < D_3 < 1, D_1 < D_3 + D_2 < 1$, and the ideal waveform of the bi-directional Dual-active-bridge DC-DC converter under the triple phase shift control is shown in figure 3.

The working mode of the converter with TPS modulation can be divided into the following five stages in half a cycle:

$$i_L(t) = \begin{cases} i_L(t_0) + \frac{nU_2}{L}(t - t_0) \\ i_L(t_1) + \frac{U_1+nU_2}{L}(t - t_1) \\ i_L(t_2) + \frac{U_1}{L}(t - t_2) \\ i_L(t_3) + \frac{U_1}{L}(t - t_3) \\ i_L(t_4) + \frac{U_1-nU_2}{L}(t - t_4) \end{cases} \quad (1)$$

Compared with the four stages in the dual phase-shifting control, the current i_L is subdivided in the triple phase-shifting control at the moment of (t_2-t_3). Because the voltage added on the inductance is slightly lower than that in the previous stage, the rise of the inductance current becomes slower and the rise speed becomes slower, and the peak current is reduced. At moment t_2, S_1, S_4 and S_7 are continuously on, and S_5 is about to be on, and the primary side current is positive.

According to the symmetry of the inductance current, $i_L(t_0) = -i_L(t_4)$, combined with equation 1, we can get:

$$\begin{cases} i_L(t_0) = \frac{nU_2}{2L}(1 - D_2 - 2D_3)T_{hS} - \frac{U_1}{2L}(1 - D_1)T_{hS} \\ i_L(t_1) = \frac{nU_2}{2L}(2D_1 - 2D_3 - D_2 + 1)T_{hS} - \frac{U_1}{2L}(1 - D_1)T_{hS} \\ i_L(t_2) = \frac{nU_2}{2L}(-D_2 + 1)T_{hS} + \frac{U_1}{2L}(2D_3 - 1 - D_1)T_{hS} \\ i_L(t_3) = \frac{nU_2}{2L}(-D_2 + 1)T_{hS} + \frac{U_1}{2L}(2D_3 + 2D_2 - 1 - D_1)T_{hS} \\ i_L(t_4) = -\frac{nU_2}{2L}(1 - D_2 - 2D_3)T_{hS} + \frac{U_1}{2L}(1 - D_1)T_{hS} \end{cases} \quad (2)$$

$T_{hS} = 1/2T$ represents half cycle signal; $f_s = 1/T$ represents the switching frequency.According to formula 2, can be obtained under the triple phase-shift control, the transmitted power of the converter is:

$$P = \frac{nU_1U_2}{4f_sL}(2D_3 - 2D_3{}^2 - D_1 + 2D_1D_3 - D_1{}^2 + D_2 - 2D_2D_3 + D_1D_2 - D_2{}^2) \quad (3)$$

In order to facilitate analysis, the transmitted power of the converter is standardized, and the reference value is $P_B = \frac{nU_1U_2}{4f_sL}$, and the unit value of the transmitted power is:

$$P_N = \frac{P}{P_B} = (2D_3 - 2D_3{}^2 - D_1 + 2D_1D_3 - D_1{}^2 + D_2 - 2D_2D_3 + D_1D_2 - D_2{}^2) \quad (4)$$

4. Analysis of converter backflow power

Backflow power has an important effect on loss and transmission efficiency of bidirectional Dual-active-bridge DC-DC converter. In practical applications, it is desirable to have minimal energy loss and minimize backflow power as much as possible. As shown in fig. 3, in the $t_1 \sim t_{20}$ stage, the inductive current is negative and the primary side voltage u_{ab} is positive, so that the transmitted power is negative. When the power is transmitted to the power supply side U_1, the backflow power is generated.For guaranteeing the transmission power, there are different combinations of D_1, D_2 and D_3, which can meet the requirements.Therefore, this section discusses how to find the optimal control quantity under the condition of minimizing Q_{cir}.At the same time.Under TPS modulation, the reflux power Q_{cir} is:

$$Q_{cir} = \frac{nU_1U_2[K(1-D_1)+(2D_1-2D_3-D_2+1)]^2}{16f_sL(K+1)} \quad (5)$$

Among them $K = U_1/nU_2, K \geq 1$。

The optimization problem of minimum backflow power can be described as follows:

The objective function

$$\min \ Q_{cir}(X)$$
$$\text{s.t. } g_u(X) \leq 0 \qquad (u = 1,2,3 \cdots m)$$

Where, $X = (D_1, D_2, D_3)$; Q_{cir} is the target function; $g_u(X)$ is the constraint condition, the target function is constrained on the given power condition $0 < P_N(X) - P_I < 1$ (P_I is the given transmission power), and there is the shift comparison constraint which is $D_1 < D_3 + D_2 < 1, 0 < D_1 < D_3 < 1$.For the optimization of the objective function, we use the interior point method to solve the problem, and the general expression of the penalty function is:

$$\varphi\left(X, r^{(k)}\right) = Q_{cir}(X) - r^{(k)} \sum_{u=1}^{m} \frac{1}{g_u(X)} \tag{6}$$

Type of $r^{(k)}$ is the punishment factor, for decreasing the positive sequence.By substituting each parameter into the above equation and solving the above equation iteratively through MATLAB, the combination of (D_1, D_2, D_3) with the minimum reflux power can be obtained.

5. The simulation results

Based on the above analysis, it can be seen that the bidirectional Dual-active-bridge DC-DC converters under the triple phase shift control can minimize the backflow power under the premise of ensuring the transmission power. In order to simulate and test the proposed TPS control strategy, the converter parameters are set as follows: U_1 =100V, U_2 =48V, f_s =20kHz, transformer ratio n=1, equivalent inductance L=80 H, output power P=300W.The waveforms of u_{ab}, u_{cd}, P_{h1} under the control of DPS and TPS can be obtained as shown in the figure below:

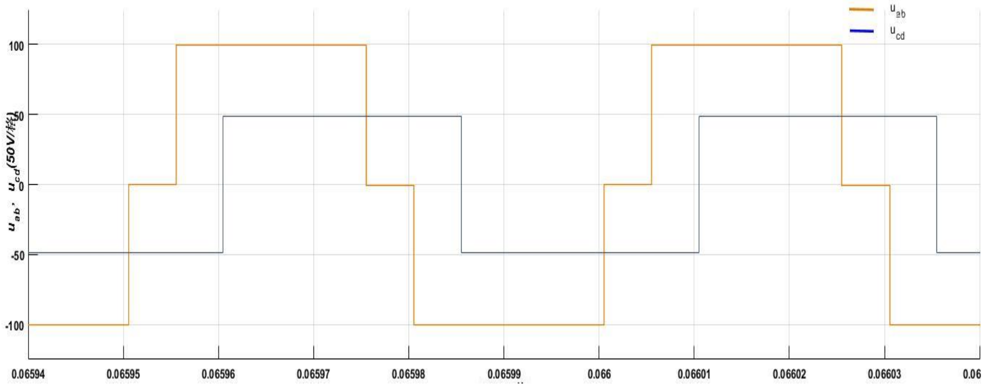

Figure 4 Working waveform u_{ab}, u_{cd} under DPS control

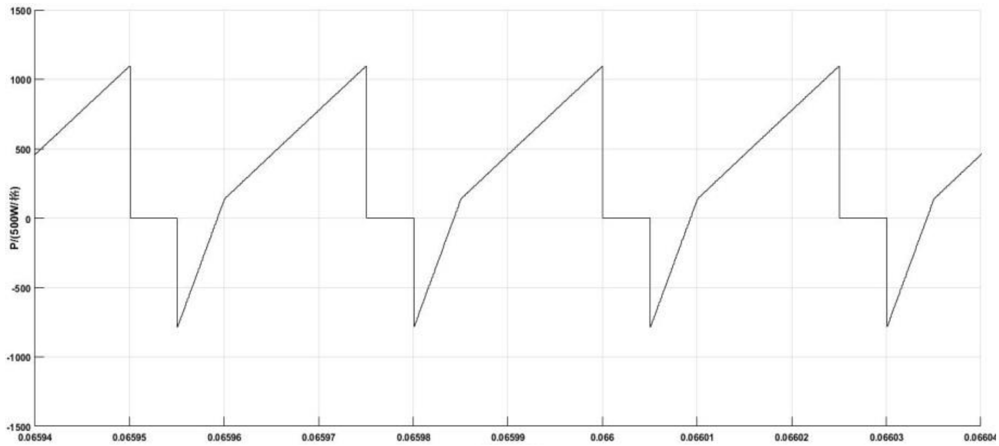

Figure 5 Working waveform P_{h1} under DPS control

Figure 4 and 5 shows the transmitted power of DC-DC converter under DPS control.The part of transmitted power less than 0 in the figure is backflow power.

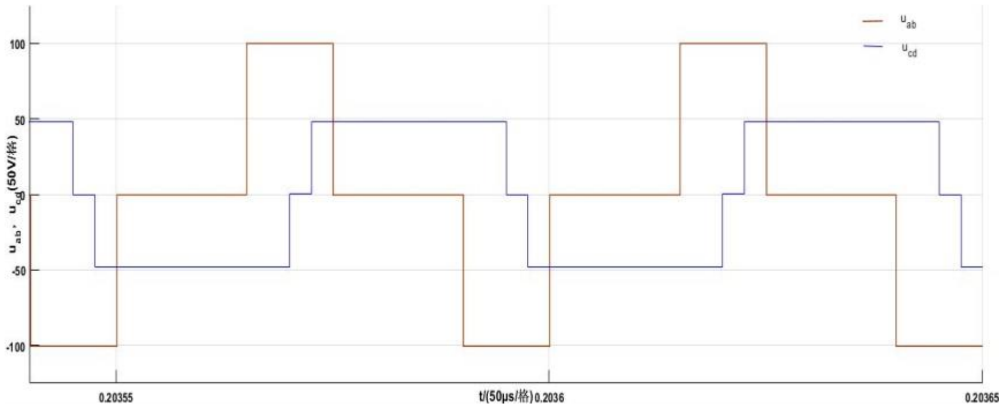

Figure 6 Working waveform u_{ab}, u_{cd} under TPS control

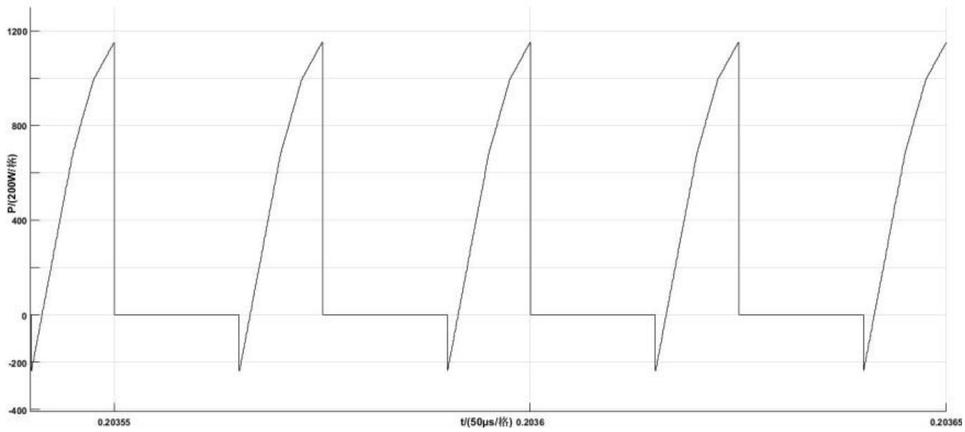

Figure 7 Working waveform P_{h1} under TPS control

The figure 6 and 7 shows u_{ab}, u_{cd} and P_{h1} the power waveforms of the primary side transmission under the control of TPS respectively. It can be seen from the waveform that the voltage waveform and the backflow power are different under various control modes. Under TPS controls, more negative power is clamped to 0, resulting in a significant improvement in the back-flow power under TPS control and a reduction in the power loss of the converter. Through the above experimental simulation and theoretical analysis, three optimal shift ratio combinations are calculated, which can reduce the backflow power and improve the efficiency of the system.

6. Conclusion

In this paper, the working principle of the converter under the triple phase shift control strategy is analyzed, the working mode under the DPS control is compared, and the steady-state mathematical modeling of the converter under the TPS control is deduced. As can be seen from the mathematical model, TPS control is more flexible than DPS control. The internal point method can be used to calculate the optimal shift ratio combination to reduce the influence of back-flow power on the converter and improve the efficiency of the converter.

References

[1] H. Akagi, T. Yamagishi, N.M.L. Tan, S. Kinouchi, Y. Miyazaki, and M. Koyama. Power-Loss Breakdown of a 750-V 100-kW 20-kHz Bidirectional Isolated DC/DC Converter Using SiC-MOSFET/SBD Dual Modules, IEEE Trans. Ind. Appl., vol. 51, no. 1, pp. 420–428, Jan. 2015.

[2] M.N. Kheraluwala, R.W. Gascoigne, D.M. Divan, and E.D. Baumann. Performance characterization of a high-power dual active bridge DC-to-DC converter, Ind. Appl. IEEE Trans. On, vol. 28, no. 6, pp. 1294–1301, 1992.

[3] F. Krismer and J.W. Kolar. Accurate Small-Signal Model for the Digital Control of an Automotive Bidirectional Dual Active Bridge, IEEE Trans. Power Electron., vol. 24, no. 12, pp. 2756–2768, Dec. 2009.
[4] B. Zhao, Q. Song, W. Liu, and W. Sun. Current-Stress-Optimized Switching Strategy of Isolated Bidirectional DC/DC Converter With Dual-Phase-Shift Control, IEEE Trans. Ind. Electron., vol. 60, no. 10, pp. 4458–4467, Oct. 2013.
[5] W. Choi, K.-M. Rho, and B. H. Cho. Fundamental Duty Modulation of Dual-Active-Bridge Converter for Wide Range Operation, IEEE Trans. Power Electron., pp. 1–1, 2015.
[6] A. K. Jain and R. Ayyanar, Pwm control of dual active bridge: Comprehensive analysis and experimental verification, IEEE Trans. Power Electron., vol. 26, no. 4, pp. 1215–1227, Apr. 2011.
[7] B. Zhao, Q. Song, W. Liu, and Y. Sun. Overview of Dual-Active Bridge Isolated Bidirectional DC-DC Converter for High-Frequency Link Power-Conversion System, IEEE Trans. Power Electron., vol. 29, no. 8, pp. 4091–4106, Aug. 2014.
[8] H. H. Zhou and A. M. Khambadkone. Hybrid modulation for dual active-bridge bidirectional converter with extended power range for ultracapacitor applications, IEEE Trans. Ind. Appl., vol. 45, no. 4,pp. 1434–1442, Jul./Aug. 2009.
[9] S. Boyd and L. Vandenberghe, Convex Optimization. Cambridge, U.K. Cambridge Univ. Press, 2009.
[10] H. S. Qin and J. W. Kimball. Generalized average modeling of dual active bridge DC–DC converter, IEEE Trans. Power Electron., vol. 27, no. 4, pp. 2078–2084, Apr. 2012.