Research on control technology of dual active full bridge DC-DC converter

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Abstract: Dual-active-bridge DC-DC converter is a widely used bidirectional converter. The current control method has some problems, such as return power and failure of soft switch characteristics under certain conditions. Based on the research results at home and abroad, this paper introduces the topology structure and basic working principle of the dual-active-bridge DC-DC converter, explains the causes of the problems, introduces the working principles of several representative phase shifting control methods, compares and summarizes the advantages and disadvantages of these methods and the links, and analyzes the advantages and disadvantages of some improved methods in recent years, the prospect is put forward.

1. Introduction
Dual active bridge (DAB) DC-DC converter is an isolated bi directional DC-DC converter (BDC). BDC can realize the bidirectional transmission of energy by changing the current direction according to the actual demand without changing the polarity of DC voltage on both sides. In recent years, with the rapid development of BDC applications such as new energy power generation, smart microgrid, aerospace and industrial control, the demand for BDC with better performance is also increasing [1]. Compared with other isolated BDC, DAB converter has the advantages of high power density, high efficiency, small size, and easy to realize zero voltage switching (ZVS), Therefore, it has been widely concerned and studied. In this paper, the control strategy and research status of DAB are reviewed.

2. Topology of DAB
The classic topology of DAB is shown in Figure 1. The circuit is composed of left-right symmetrical full bridge circuit. The square wave signal with a certain phase difference and a duty cycle of 50% is used on both sides of the transformer (in actual use, the square wave signal with a duty cycle of 48% is used to prevent the upper and lower switches from conducting at the same time) to drive [2]. S1-S8 is IGBT switching device, and l is inductance.
3. DAB control strategy

The control strategy has always been the focus of DAB converter research, and the research mainly focuses on the optimization of power regulation range, return power, ZVS characteristics and so on.

There are four typical control strategies for DAB Converters: single phase shift (SPS), extended phase shift (EPS), dual phase shift (DPS) and triple phase shift (TPS). Most of the other improved control strategies are based on these four control strategies, and some scholars try to introduce more control quantities \[3\], However, TPS control has shown the problem that it is too complex to be applied in large scale, so these methods can only achieve better control effect in theory and have little application significance.

In these control strategies, the forward and reverse working states of DAB converter are similar, so only half a cycle of forward working state is analyzed, and the switching state time is short, which is often ignored in the analysis.

3.1 SPS control

SPS control is the traditional control method of DAB converter, and the simplest phase-shifting control method is also the main control method at present. Under the control of SPS, the switches on the full bridge diagonal lines on both sides of the converter (such as S1 and S4, S2 and S3 on the primary side) are on and off at the same time. The control principle and working waveform are shown in Figure 2.

Under the control of SPS, the expression of primary input average power \( P \) is obtained:

\[
P = \frac{\int_{0}^{T} U_{AB} i_{L}(t) dt}{T} = \frac{K U}{2 L f} \cdot D_{2} (1 - D_{1})
\]  

(1)
The Maximum transmission power:
\[ P_m = \frac{K U_1 U_2}{8 f L} \]  
(2)

Taking \( P_m \) as the reference value (which will not be repeated in the later analysis), we can get the transmission power per unit value \( P_1 \) as the reference value
\[ P_1 = \frac{P}{P_m} = 4 D_2 (1 - D_2) \]  
(3)

\( D_2 \) is the duty cycle of half a cycle corresponding to the phase shift angle, and the positive and negative determination and size of \( D_2 \) determine the direction and size of power transmission respectively. By adjusting \( D_2 \), the transmission power of the converter can be adjusted. When \( D_2 = 0.5 \), the power transmitted by the converter reaches the maximum.

The necessary conditions for all switches to realize ZVS under SPS control are as follows:
\[ D_2 \geq \frac{k - 1}{2k} \]  
(4)
\[ D_2 \geq \frac{1 - k}{2} \]  
(5)

\( k \) is the voltage regulation ratio and
\[ k = \frac{K U_1}{U_2} \]  
(6)

From equation (4) (5), the ZVS limit diagram of full power range can be obtained

Fig. 3 restriction diagram of ZVS condition for SPS control in full power range

Combined with the above analysis, the main problems of SPS control are as follows:

1. In ideal operation, there is return power, that is, in the period of the shaded part of the inductance current \( I_L \) in Fig. 2, the phase of \( I_L \) and the primary side voltage \( U_{AB} \) is opposite, resulting in the negative transmission power of the converter.

2. It is easy to see from Figure 3 that when the voltage transfer ratio \( K \) is not 1, the DAB converter may lose its soft switching characteristics, which will increase the conduction loss and current stress of the converter.

In practical use, it is difficult to ensure the voltage transfer ratio of 1 by adjusting the transformer ratio in some occasions where the port voltage is constantly changing, so SPS control has great limitations.

In view of these problems in SPS control, some scholars have optimized the SPS control mode. Reference [4] pointed out the relationship between the duty cycle of the switch and the return power. The return power was reduced by changing the duty cycle of the switch, but the soft switching characteristics were not optimized. In reference [5], by changing the control signal of IGBT switch, the energy released from \( U_1 \) or \( U_2 \) to \( L \), and then fed back to \( U_1 \) or \( U_2 \), which only produces conduction loss, is eliminated. The simulation results show that it has good soft
switching characteristics, but this method can not eliminate the return power.

Some scholars try to introduce new models and control methods to optimize the control effect of the converter. Reference [6] points out some key information missing from traditional DAB discrete iterative model, and proposes a full state discrete iterative model to obtain more real output ripple. Reference [7] combines phase-shift control with PWM to improve the performance and fast dynamic response of DAB converter.

The optimal solution of SPS control is one-sided because there is only one free shift. Therefore, EPS, DPS, TPS and other control methods that introduce more control variables for optimization have been proposed.

3.2 EPS control and DPS control

Both EPS control and DPS control have two kinds of free shift comparison control methods. The difference between them is that EPS control adds an equal inward shift comparison between the primary side and the secondary side on the basis of SPS control, while DPS control adds an equal inward shift comparison between the primary side and the secondary side at the same time. The working principle and analysis process of the two methods are similar. There are many working modes in the two control methods, this paper will only select the most commonly used working mode to review.

Figure 4 shows when \( 0 \leq D_1 \leq D_2 \leq 1 \) Working waveforms of EPS control and DPS control principle at different time

![Figure 4 working principle waveform of EPS control (A) and DPS control (B)](image)

Without considering the power loss of the converter and ignoring the switching period, the standard unit value of transmission power and return power under EPS control is as follows:

\[
P_3 = 2(-D_1^2 + 2D_1D_2 - D_1 - 2D_2^2 + 2D_2)
\]

\[
Q_{\text{EPS1}} = \frac{k(1-D_1) + (2D_2-1)^2}{2(k+1)}
\]

ZVS condition:

\[
\frac{1-2D_2}{1-D_1} \leq k \leq \frac{1}{1-D_1-2D_2}
\]

The standard unit value of transmission power and return power under DPS control is:

\[
P_3 = 2(-D_1^2 + 2D_1D_2 - D_1 - 2D_2^2 + 2D_2)
\]

\[
Q_{\text{EPS2}} = \frac{k(1-D_1) + (2D_2 - 2D_1 - 1)^2}{2(k+1)}
\]

Where D1 is the inward displacement ratio of the whole bridge on both sides and D2 is the
outward displacement ratio of the whole bridge on both sides of U1 and U2.

ZVS condition:

\[
1 - 2D_1 \leq k \leq \frac{1}{1 + D_1 - 2D_2}
\]  
(12)

From formula (3) (7) (10), it can be seen that due to the introduction of new control quantity, the power regulation range has changed from a line controlled by SPS to a region, which greatly expands the range of transmission power regulation and enhances the flexibility of power regulation. In fact, SPS control is a special case of EPS and DPS control. The comparison diagram of transmission power adjustment range of the three control modes obtained from formula (3) (7) (10) is shown in Fig. 4.

As mentioned earlier, the generation of return power is due to the opposite phase of IL and UAB. EPS and DPS control can change the phase of UAB by changing D1, so as to optimize the return power. For example, EPS control divides the time period of generating reflux power into two sections, and the former UAB = 0, so the reflux power is also 0. Similarly, DPS control can not completely eliminate the two control methods, but it can effectively reduce the reflux power compared with SPS control.

In addition, it can be seen from equation (4) (5) (9) (12) that the soft switching range of EPS and DPS control is larger than that of SPS control.

DPS control is easier to implement than EPS control, and when the voltage transition state or power flow direction changes, EPS control needs to adjust the working state of the primary and secondary side, while DPS control does not need to adjust because the two sides of the full bridge move inward. In addition, the dynamic performance of the converter under DPS control is better. Compared with the two free shifting control strategies, DPS is obviously better, so the research on DPS control is more sufficient.

By optimizing the mathematical model of D1 and DC / DC converter under DPS control, some scholars have effectively reduced the return power, but they often ignore the problem that the transmission power is also decreasing while reducing the return power.

It can be seen from equation (10) (11) that both transmission power and return power are negatively correlated with D1. Reference [8] points out the different influence of the inward shift ratio of the primary and secondary sides of the full bridge on the transmission power and return power, and proposes an improved DPS control method. The inward shift ratio of the full bridge on both sides is divided into D1-1 and D1-2, so that D1-1 is no longer equal to D1-2, but equal to D2, and D1-2 is taken as another degree of freedom. Without adding new degrees of freedom and without significantly reducing the transmission power, the return power in the light load region is effectively reduced.

3.3 TPS control
EPS control and DPS control introduce the internal shift compared with D1 on the basis of SPS control, so that the better control performance is obtained. However, the optimal control effect of the two control methods is still one-sided. On this basis, TPS control method is born, which takes the internal shift comparison of primary side and secondary side as the free phase shift ratio D1, D3 to control the converter better. In principle, the three control methods in the previous paper are equivalent to the special case under TPS control. TPS control is a unified form under the phase shifting control strategy. TPS control is classified and power analysis is carried out in reference [9-10]. There are 12 modes of operation under TPS control, Fig. 6 shows the working principle waveform when $0 \leq D_1 \leq D_3 \leq 1$ and $0 \leq D_2 \leq D_3 \leq 1$.

![Figure 5 TPS control principle waveform](image)

The standard unit values of transmission power and return power under TPS control are as follows:

$$P_4 = D_2D_1 - D_1^2 - D_2 + D_1D_2^2 - D_2^2 - D_1^2 + D_2$$

$$Q_{\text{sid}} = \frac{k(1-D_1 ) + (D_2 + D_1 - 2D_3 - 1)^2}{2(k+1)}$$

Compared with EPS and DPS control, TPS control has a wider range of transmission power, return power and soft switch adjustment. It can flexibly adjust the control strategy according to different working environment. Although it is difficult to be applied on a large scale, TPS control is a better control method in theory. At present, there is no unified implementation standard for TPS control, Therefore, there are still a lot of researches on TPS control.

4. Conclusions

At present, the application and development of DAB converter are gradually mature, but in some practical applications, there are still some problems, such as backflow power is difficult to eliminate, ZVS failure. Some optimization methods based on phase-shifting control are gradually put forward. Some new algorithm technologies, such as genetic algorithm and particle swarm optimization algorithm, have also been tried to be applied to the control field of DAB converter, there is still a wide space for the research and development of DAB converter.

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