Integrated optimization Control Strategy of DAB Based on DPS and Adaptive Genetic Algorithm

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Abstract. In order to comprehensively consider the energy transmission efficiency of the isolated Dual-Active-Bridge (DAB) DC-DC converter, this paper proposes a control method that maximizes the power transmission efficiency of the whole converter and optimizes the stress of the switching device by using the dual-phase-shifting control mode under the premise of simultaneously considering current stress, back-flow power and power loss. Firstly, we compare and analyze the advantages and disadvantages of DPS, SPS and TPS, and finally determine the control method using DPS. Then analyze and compare the basic principles of the traditional current stress optimization target control method and the comprehensive efficiency optimal control method proposed in this paper. We compared the working mode analysis with the stability, current stress and application range of soft-switching. The adaptive genetic algorithm is used to optimize the two duty ratio degrees of freedom of the control strategy, and the optimal duty ratio corresponding to the objective function is obtained. Finally, the correctness of the control method and the superiority of the power transmission efficiency are proved by simulation and experimental comparison.

1. INTRODUCTION

With the wide application of new energy sources, isolated dual-active full-bridge DC-DC converter with high power density and high transmission voltage ratio has gradually become the focus of research, which has attracted extensive attention. Dual-active full-bridge DC-DC converter has various topologies, among which H-bridge DAB has received extensive attention in the field of power electronics due to its electrical isolation, bidirectional energy transmission and the implementation of ZVS [1-2].

However, although some literature has been studied from the aspects of power back-flow, current stress and the full-range soft switching range [3-6], it is only optimized from a single point of view. The inductance current stress determines the transient peak value of the current and then affects the loss. Under the condition of a certain phase shift ratio, the larger the peak value of the current is, the larger the root mean square value of the current is and the greater the loss is. The back-flow power only means that the part of the reflow power source in the transmission power is the part of the inductance transmitted to the primary side. The minimum back-flow power does not mean that the current stress is small enough. In some working conditions, the back-flow power increases while the current stress is reduced. The specific relationship between current stress and back-flow power at the optimal working point has not been analyzed in the literature.

In order to maximize the power transmission efficiency and improve the performance of the converter, this paper proposes a control method that maximizes the power transmission efficiency of
the entire converter and optimizes the stress of the switching device by using the dual-phase control mode, considering the current stress, back-flow power and the loss of the switching magnetic device at the same time. This paper firstly deduces and analyzes the power transmission characteristics of DAB in DPS control mode, and then establishes the switch model under each switch state in stages, and then establishes the switch model under each switch state in stages, and derives the relationship between phase shift ratio and switching loss, back-flow power, current stress and loss of magnetic devices, the optimal control scheme is given by using the nonlinear genetic algorithm under the constraint of global ZVS. Finally, the correctness and superiority of the optimal control strategy are verified on the DAB experimental platform.

2. Materials and Methods

2.1 COMPARISON AND ANALYSIS OF DPS CONTROL METHODS

The Circuit schematic of the isolated DAB DC-DC converter is shown in Fig 1, where two high-frequency full-bridge (H-bridge) are connected by the intermediate high-frequency transformer, and the ratio of transformer is \( N_{ps} \). \( V_1 \) and \( V_2 \) are the DC voltage of the primary side and the secondary side of the converter, \( V_{ab} \) and \( V_{cd} \) are the output AC voltage of the H-bridge on both sides, and \( V_{cd}^* \) is the equivalent voltage of \( V_{cd} \) converted to the primary side of the transformer. \( C_1 \) and \( C_2 \) are the capacitors at the dc side of the primary side and the secondary side, and \( L_s \) represents the sum of the leakage inductance of the transformer converted to the primary side of the transformer and the external series inductance. The switch \( S_x \) consists of a switch tube and an anti-parallel diode, and the subscript \( x \) indicates the sequence number of the switch.

![Circuit schematic of DAB](image)

Define the voltage transfer ratio \( k = V_1/N_{ps}V_2 \), and in order to simplify the analysis process, specify \( k > 1 \). And define the standard value:

\[
\begin{align*}
P_x &= \frac{V_1N}{8f_sL_s} \\
I_y &= \frac{N^2V_2}{8f_sL_s}
\end{align*}
\]

When controlled by DPS, the operating waveforms of DAB is shown in Fig 2. \( S_{r}-S_{h} \) indicates the turn-on signal of the switch tube. This indicates the half-switching period, and \( D_1 \) is the internal phase shift ratio of H bridge 1, which corresponds to \( S_1 \) being on ahead of \( S_4 \). \( D_2 \) is the outward phase shift ratio of the H-bridge 1 relative to the H-bridge 2, i.e., corresponding to \( S_1 \) opening ahead of \( S_8 \). The ranges of the two phase-shift ratios are \( 0 \leq D_1 \leq 1, \quad 0 \leq D_2 \leq 1 \). There are four modes in the combined case. As shown in Figure 2, the voltage at both ends of the inductor is three-level in a switching period, and the converter can be divided into 10 operating modes for analysis.
Fig. 2 Operating waveforms of DAB with DPS control

It shows: \( i_{L0} = -i_{L0+Ths} \), the half-period of inductance current is nearly symmetrical, so only half-period of operation needs to be analyzed. From the basic theorem of energy transmission and circuit, the inductance current values of each subinterval can be obtained as follows:

\[
\begin{align*}
\frac{d}{dt}i_L(t) &= -\frac{V_{IN} - V_{OUT}}{L} (t - t_0), & t_0 \leq t \leq t_1 \\
\frac{d}{dt}i_L(t) &= \frac{V_{IN} + V_{OUT}}{L} (t - t_1), & t_1 \leq t \leq t_2 \\
\frac{d}{dt}i_L(t) &= \frac{V_{IN}}{L} (t - t_2), & t_2 \leq t \leq t_3 \\
\frac{d}{dt}i_L(t) &= -\frac{V_{OUT}}{L} (t - t_3), & t_3 \leq t \leq t_4 \\
\frac{d}{dt}i_L(t) &= \frac{V_{IN}}{L} (t - t_4), & t_4 \leq t \leq t_5 \\
\frac{d}{dt}i_L(t) &= -\frac{V_{OUT}}{L} (t - t_5), & t_5 \leq t \leq t_6 \\
\frac{d}{dt}i_L(t) &= \frac{V_{IN}}{L} (t - t_6), & t_6 \leq t \leq t_7 \\
\frac{d}{dt}i_L(t) &= -\frac{V_{OUT}}{L} (t - t_7), & t_7 \leq t \leq t_8 \\
\frac{d}{dt}i_L(t) &= \frac{V_{IN}}{L} (t - t_8), & t_8 \leq t \leq t_9 \\
\frac{d}{dt}i_L(t) &= -\frac{V_{OUT}}{L} (t - t_9), & t_9 \leq t \leq t_{10}
\end{align*}
\]

Where, the specific derivation time of each time node is:

\[
t = \begin{cases} 
  t_0 = t_4 + T_m = 0 + T_m \\
  t_1 = t_5 + T_m = D_1T_m + T_m \\
  t_2 = t_6 + T_m = D_2T_m + T_m \\
  t_3 = t_7 + T_m = \frac{D_1(3-1)}{4k}T_m + T_m \\
  t_4 = t_8 + T_m = (D_1 + D_2)T_m + T_m \\
\end{cases}
\]

2.2 MATHEMATICAL MODEL ANALYSIS OF DAB UNDER DPS CONTROL MODE

2.2.1 Global Range Soft Switching Analysis

The reverse parallel diode will turn on when the switch is turned off. In the process of switching from cut-off to turn-on, the voltage at both ends is clamped to zero by the diode, thus realizing the zero-voltage opening of the switch. The constraint conditions for realizing global ZVS of the switch tube need to be judged from the direction and magnitude of inductance current. From the sequence diagram, the conditions for realizing global ZVS of each switch tube can be deduced, and the conditions for the realization of the upper and lower switches of the same bridge arm are the same. As shown in the following table:

| Switch tube | Current | Satisfied condition |
|-------------|---------|---------------------|
| \(S_1, S_2\) | \(i_{L1}(t_1) \leq 0\) | \((1 + k)(1 - D_1) + 2(D_2 - 1) \geq 0\) |
| \(S_3, S_4\) | \(i_{L3}(t_4) \geq 0\) | \((k - 1)(1 - D_1) + 2D_2 \geq 0\) |
| \(S_5, S_6\) | \(i_{L5}(t_5) \geq 0\) | \((1 - k)(1 - D_1) + 2kD_2 \geq 0\) |
| \(S_7, S_8\) | \(i_{L7}(t_7) \leq 0\) | \((1 + k)(1 - D_1) + 2k(D_2 - 1) \geq 0\) |

It can be obtained that the global ZVS can be established under the following conditions:
2.2.2 Analysis of Power Transmission and Back-flow Power

According to the analysis of each working mode above, we can get the expression of transmission power. In the previous section we have defined the per-unit value of power as $P_N = NV_1V_2/8fLr$. The standard inductor current and turn-on time of switch tube are:

$$i_c = \begin{cases} 
\pi - \frac{\pi}{T_{s1}}t - \frac{D_1\pi - D_2\pi}{2} & 0 \leq t \leq t_1 \\
-\frac{D_1\pi - D_2\pi}{2} & t_1 \leq t \leq t_2 \\
\frac{D_1\pi - D_2\pi}{2} & t_2 \leq t \leq t_3 \\
\frac{\pi}{T_{s2}}t - \frac{D_1\pi + D_2\pi + 2dD_1\pi}{2} & t_3 \leq t \leq t_4 \\
\frac{D_1\pi + D_2\pi + 2dD_1\pi}{2} & t_4 \leq t \leq T_{s1} \\
-\frac{D_1\pi + D_2\pi + 2dD_1\pi}{2} & t \leq t_{s1} 
\end{cases}$$

(5)

where the opening of the switch tube at each moment can be expressed as follows:

$$\begin{align}
    t_0 &= 0 & S_{t_{urn on}} \\
    t_1 &= D_1T_{s1} & S_{t_{urn on}} \\
    t_2 &= D_2T_{s2} & S_{t_{urn on}} \\
    t_3 &= D_1T_{s1} + D_2T_{s2} & S_{t_{urn on}}
\end{align}$$

(6)

Firstly, we consider the average transmission power under standardization.

$$P_n = \frac{1}{T_{s1}} \int_0^{T_{s1}} V_{ol}i_c dt = 2D_1(2 - 2D_1 - D_2)$$

(7)

2.2.3 Analysis of Inductance Current and Switching Stress

According to the symmetry of inductance current during steady-state operation and formula 3, he expression of the maximum value of the inductor current is as follows:

$$i_{i_{\text{max}}} = \frac{NV_1}{4fL} \left[ D_2(1 + k) + (k - 1)(D_1 - D_2) \right]$$

(8)

If the duty ratio optimization strategy is selected with reflux power or current stress as the single control goal, the transmission efficiency of DAB can be optimized to a certain extent, but the global optimal operating point cannot be sought. Moreover, taking the current stress as the optimization goal is simply to consider the minimum inductor current, and does not consider the specific loss value to obtain an accurately quantified model. Therefore, this paper proposes an optimal control strategy with integrated efficiency optimization as the control target, which not only accounts for the RMS loss and transient peak value of the inductor current on the inductor and the switching device, but also considers the copper loss of the high-frequency transformer, and the power part of back-flow power supply is also reduced to the optimization of total power transmission efficiency in the algorithm, and the mathematical model of transmission efficiency and duty cycle of the whole DAB is established uniformly. And the optimal duty ratio pair under this control strategy is obtained.

2.3 OPTIMAL CONTROL STRATEGY BASED ON DPS AND ADAPTIVE GENETIC ALGORITHM

Based on the existing research, this paper proposes the optimal control target with comprehensive efficiency, considers the back-flow power, quantifies the current stress as the loss of the inductor, high-frequency device and switching device, deduces the accurate mathematical model, and obtains the corresponding relationship between the comprehensive efficiency and the duty ratio, the efficiency is as follows:
\[ \eta = \frac{P_N}{P_N + Q + P_{es} + P_{of} + P_{st}} \times 100 \% \quad (9) \]

The input variables of this model are two duty ratios, and the comprehensive efficiency of the output variables is composed of multiple outputs, such as back-flow power, current stress loss, and high-frequency transformer loss. The mathematical model is not large in scale, but it is difficult to solve due to its nonlinear optimization. This paper uses genetic algorithm to solve the model. The block diagram is shown below.

3. Results & Discussion

The input power is 132W, the output impedance is 20Ω, the output voltage is 50V, the current stress is 1.77A, and the transmission efficiency is 94.7%. In order to verify the correctness of the algorithm, we build a DAB experimental platform based on TMS320F28335 as the control chip according to the parameters of simulation calculation.

The main parameters of the experimental platform are as follows: input voltage \( U_1 = 100V \), output voltage \( U_2 = 40-100V \), switching frequency \( f_s = 40kHz \), transformer ratio \( N = 1 \), energy storage inductance \( L = 0.5mH \). The waveforms of experimental results are shown as follows:
It can be seen from H-bridge voltage waveform on the first and second in Fig. 5 that both SPS, DPS can realize the stable output of 50V DC voltage on the secondary side.

Fig. 6 Inductance current under Comprehensive efficiency optimization.

| Optimization target     | Current stress value | Transmission efficiency |
|-------------------------|----------------------|-------------------------|
| Current stress          | 1.67                 | 91.4%                   |
| Back-flow power         | 1.94                 | 92.6%                   |
| Comprehensive efficiency| 1.78                 | 94.4%                   |

It can be seen from Fig. 6 that the minimum current stress can be reached by taking current stress as the optimization target, while the comprehensive efficiency optimization cannot reach the optimal current stress. When taking back-flow power as the optimization target, the current stress reaches the maximum, but the backflow power is the minimum. From the perspective of overall power transmission efficiency, the simulation results and experimental results of the proposed algorithm with comprehensive efficiency as the optimization target prove that it can improve the overall efficiency, achieve the maximum power transmission and achieve the optimal performance while considering the reduction of current stress.

4.CONCLUSION

Aiming at DPS control method of isolated dual-active full-bridge DC-DC converter, this paper analyses the power transmission characteristics of DAB, establishes switching models in different switching states, and establishes a mathematical model. On this basis, a comprehensive efficiency optimization control strategy based on adaptive genetic algorithm is proposed. Under the premise of global soft switching, the global optimal operating point with the highest comprehensive efficiency is calculated by considering current stress, back-flow power and power loss. The experimental results show that compared with the traditional DPS control strategy, the DAB optimal control strategy based on DPS and adaptive genetic algorithm can determine the global optimal operating point of the minimum current stress and the optimal power transmission efficiency under the premise of realizing the switching ZVS in the full power range. And the resulting optimal phase shift ratio can obtain the maximum DAB transmission efficiency.
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