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Research on EPS Modulation Strategy of DAB Converter with Low Surge Current

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Abstract: Aiming at the problem that the Dual Active Bridge (DAB) converter has a relatively large surge current under the traditional modulation strategy, an improved extended phase shifted (EPS) modulation strategy is proposed. By introducing additional phase-shift angle control, this strategy increases the control degrees of freedom, enabling more precise regulation of the converter's operating state. The working principle, operating modes, and power transmission characteristics of the improved EPS modulation strategy are elaborated in detail. The mathematical model of the converter is established. Theoretical analysis and simulation verification demonstrate that the new EPS modulation strategy can effectively reduce the surge current of the DAB converter during startup and abrupt phase-shift angle changes, enhancing the converter's stability and reliability. It can also maintain high efficiency and excellent performance under working conditions such as light load and wide voltage input. Experimental verification shows that under 20% rated load, the peak surge current of the improved EPS is 1.1 A, a 47.12% reduction compared with the traditional EPS. When the load suddenly increases from 20% to 80%, the output voltage recovery time is only 20 ms, superior to the 50 ms of the traditional EPS.

Keywords: Dual Active Bridge (DAB); Extended Phase Shift (EPS) Modulation; Surge Current; Soft Switching; Power Transmission.

1. Introduction

With the continuous advancement of new energy and energy storage technologies, the power generation mode is transitioning from the traditional centralized model to a combination of centralized and distributed models. The Dual Active Bridge (DAB) converter, benefiting from its high efficiency, high power density, and excellent soft-switching characteristics, has been widely applied in areas such as solar power generation systems [1], energy storage systems[2], DC power grids [3], and new energy vehicle charging[4]. It has become a research focus for scholars in the field of power electronics.

Surge current refers to the current that is much larger than the steady-state current when the power is connected or when an abnormality occurs in the circuit. In DAB converters, surge current mainly appears during the startup process and at the moment of sudden change in the phase shift angle. During the startup process, due to the low voltage on the load side, the phase shift control is difficult to effectively regulate the charging current size, resulting in a high startup current. A startup resistor can be connected in series at the input side of the converter to limit the startup current size, and the startup resistor can be bypassed through a mechanical switch after the converter completes the startup. Although this startup method is simple and convenient, the startup resistor is relatively large in size, and the series mechanical switch also increases the conduction loss.

Therefore, some people adopt an auxiliary circuit based on a coupled winding structure to achieve the soft start of the converter, which greatly increases the complexity of the circuit structure. On the other hand, during the start-up stage, by slowly increasing the duty cycle of the output square wave voltage on the primary side, the start-up current can be effectively reduced. Further, reference[5]proposed a two-stage charging control strategy. During the first stage, the output side switch tubes are locked, and the load side capacitor is charged by their anti-parallel diodes. When the output voltage stabilizes, the second stage of the start-up process begins, and the output voltage is regulated using phase-shift modulation. However, there is still a significant surge current during the transition between the two stages. Combining the above two strategies, a three-stage start-up strategy is proposed. The control strategy of the first stage is the same as that of the first stage in reference [5]. After the output voltage stabilizes at Vout1, the second stage begins, and phase-shift modulation is used with Vout1 as the output voltage reference value. After its output voltage stabilizes, the third stage begins, and the output voltage reference value gradually changes to the required output voltage reference value, ultimately completing the start-up process of the converter.

In practical application, DAB converters have also revealed many problems. For instance, in the case of multi-phase phase-shift control, once the phase angle of a certain phase changes, it may also cause fluctuations in the phase-shift angle regulation of other phases, which may further lead to the problem of inrush current.[6] Excessive inrush current may result in: 1. Damage to the equipment and affect its normal operation. 2. Possible triggering of faults in the system, leading to power outages or short circuits of the equipment. 3. Premature aging of components and a significant reduction in their service life. This paper proposes an improved extended phase-shift modulation (EPS) strategy, which effectively reduces inrush current by optimizing the sequence of phase-shift angle regulation and introducing a dynamic compensation mechanism.

2. Analysis of Traditional Modulation Strategies for DAB Converters

2.1. The Principle of Single Phase Shift (SPS) Modulation

The topology of the dual-source bridge DC-DC converter is shown in Figure 1. Here, U1 and U2 are the DC voltages on both sides of the converter, C1 and C2 are the voltage stabilizing capacitors, L is the power energy storage inductor, T is the high-frequency isolation transformer, with its transformer ratio being n: 1, and the switching frequency of the converter is fs. The two capacitors play the role of stabilizing the DC voltage and filtering out the high-frequency and instantaneous difference signals in the circuit. The energy storage inductor serves as a temporary energy storage link, and the isolation transformer performs the functions of voltage isolation and voltage matching.

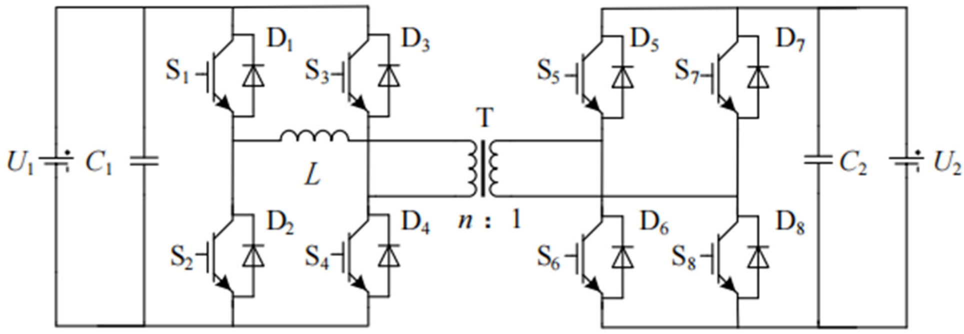

Figure 1. Topology diagram of dual-active DAB converter

Single-phase shift (SPS) modulation mode is the most traditional modulation mode of DAB converter. There is only one external phase shift D between the two bridges, resulting in relatively low control degrees of freedom. By adjusting the driving phase of the full-bridge switching devices on both sides to change the voltage on the inductor and thereby control the magnitude and direction of the transmission power, the transmission power always flows from the H bridge with a phase lead to the H bridge with a phase lag. The advantage is that the modulation mode is simple, while the disadvantage is that the current change rate during startup is large, and the peak value of the surge current can reach 3-5 times the steady-state value. Therefore, the SPS modulation has significant limitations.

By controlling power transmission through the original and secondary side external phase shift D, the expression is:

$$P = \frac{U_2^2}{R} = U_2 I_2 = \frac{nU_1U_2}{2f_sL} D(1-D) \tag{1}$$

Figure 2 depicts the curve of the power transmission power and the phase shift angle obtained from Equation (1). From the figure, it can be seen that as the phase shift ratio increases, the transmission power first increases and then decreases. The characteristic curve is symmetrical about D = 0.5 and reaches its maximum value at D = 0.5. In practical control, to ensure the stability of the control system, the range of D is generally controlled within the interval [0, 0.5]. Combining Equation (1), the expressions for the output voltage and the output current are obtained as follows:

$$U_2 = \frac{nU_1R}{2f_sL} D(1-D)) \tag{2}$$

$$I_2 = \frac{nU_1}{2f_sL} D(1-D)) \tag{3}$$

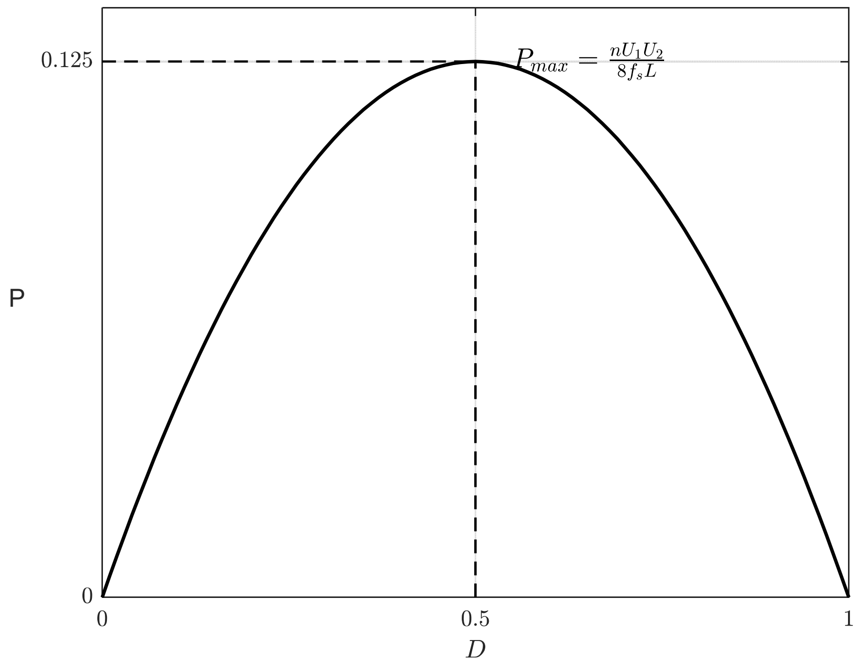

Figure 2. Curve of Transmission Power and Phase Shift Angle under SPS Control

2.2. Extended Phase Shift (EPS) Modulation

The Extended Phase Shift Modulation (EPS) strategy is an efficient control method in the dual-source bridge (DAB) converter. It adds an extra phase shift control degree of freedom on the basis of the traditional single-phase-shift (SPS) modulation, thereby enhancing the flexibility and efficiency of the system. The EPS modulation allows for the addition of an extra phase shift angle within the full bridge on one side of the DAB, providing more control degrees of freedom that can be used to optimize system performance, such as reducing circulating power, lowering current stress, expanding the soft-switching range, and improving overall efficiency. By reasonably selecting the phase shift ratio, the optimal performance can be achieved under different load conditions.

D1 is the phase shift ratio within the primary H-bridge, and D2 is the phase shift ratio between bridges.

The power expression can be obtained as:

$$P_E = \begin{cases} \frac{nU_1U_2}{4f_sL}(-D_1^2 + 2D_1D_2 - D_1 - 2D_2^2 + 2D_2), & 0 \le D_1 \le D_2 \le 1 \\ \frac{nU_1U_2}{4f_sL}(D_1^2 - 2D_1D_2 - D_1 + 2D_2), & 0 \le D_2 < D_1 \le 1 \end{cases} \tag{4}$$

The output current of single phase shift (SPS) modulation is obtained in the same way. The maximum current stress expression of extended phase shift modulation is:

$$\begin{cases} \frac{nU^2}{4fL}[K(1-D_1) + (2D_2 - 1)] & 0 \le D_1 \le D_2 \le 1 \\ \max\left\{\frac{nU^2}{4fL}[K(1-D_1) + (2D_2 - 1)], \frac{nU^2}{4fL}(1 - K + KD_1)\right\} & 0 \le D_2 < D_1 \le 1 \end{cases} \tag{5}$$

2.3. The Mechanism of Surge Current Generation

The surge current is mainly caused by the sudden change of inductor current when the phase jumps. In traditional EPS, with strong coupling, a slight disturbance at light load can lead to a drastic change. The improved extended phase-shifting method disperses the power regulation path by introducing new decoupling parameter relationships. As shown in Figure 3, when the power command changes, the new decoupling parameter relationships dominate the power adjustment, and only require minor adjustments, significantly reducing the current fluctuation.

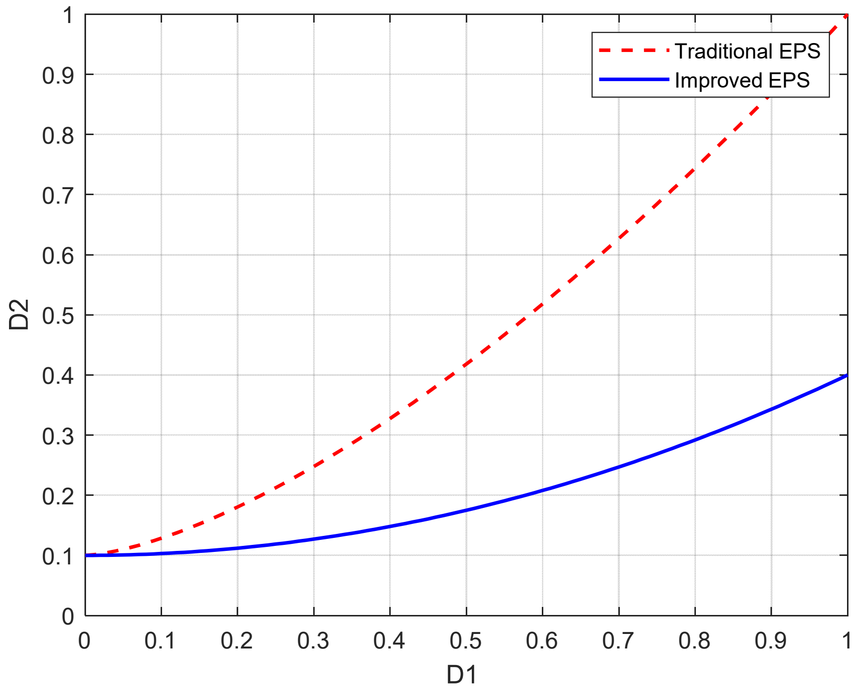

Figure 3. Sensitivity Comparison of Parameters between Traditional EPS and Improved EPS

3. Improved EPS Modulation Strategy

3.1. Modulation Principle

The improved extended phase-shift modulation (EPS) strategy is an advanced control method in dual active bridge (DAB) converters. It optimizes the performance of DAB by incorporating two independent control degrees of freedom and new decoupling parameter relationships. This strategy not only reduces the current stress of DAB but also improves the system efficiency to a certain extent. Under TPS control, the mathematical model of DAB changes with the values of the three phase-shift degrees of freedom. Since TPS modulation utilizes all the control degrees of freedom, modulation strategies such as SPS, EPS, and improved EPS can all be regarded as special cases of TPS modulation. Correctly classifying the operating mode of DAB and selecting the appropriate calculation model to calculate DAB under any phase-shift combination are the basis for achieving performance optimization. Due to the complex modulation methods, although multiple optimized modulation strategies have been proposed under TPS modulation, there is no unified application standard, and there are still issues such as discontinuity in all operating conditions and complex modulation strategies[7]. Therefore, this paper proposes the improved EPS modulation strategy, specifically targeting the dynamic performance optimization of DAB converters under low surge current conditions.

The improved EPS modulation controls power transmission through three phase-shift parameters:

Internal phase-shift ratio (α): Adjusts the switching sequence between bridge arms to optimize the current waveform.

External phase-shift ratio (β): Adjusts the phase difference between the primary and secondary sides of the voltage, determining the direction and magnitude of power transmission.

Unlike traditional EPS, the improved EPS allows for opposite phase shifts (bidirectional internal phase shifts) and satisfies the constraint conditions:

$$D_1 + D_2 \leq D_3 \leq 1 - |D_1 - D_2|$$

This constraint expands the feasible operation area during light load and reduces the sensitivity of parameters.

3.2. Transmission Power Equation

Based on the analysis of the switch status, the transmission power of the improved EPS is divided into three modes:

Mode I$(0 < D_1 \leq D_2/2)$:

$$P = \frac{nU_1U_2}{4Lf_s}[D_3^2 - (D_1 - D_2)^2] \tag{6}$$

Mode II$(D_2/2 < D_1 \leq D_2)$:

$$P = \frac{nU_1U_2}{4Lf_s}(2D_1D_2 - D_3^2) \tag{7}$$

Mode III$(D_2 < D_1 \leq (D_2 + 1)/2)$:

$$P = \frac{nU_1U_2}{4Lf_s}(D_1^2 + D_2^2 - D_3^2) \tag{8}$$

Similar to the traditional EPS control, if the improved EPS control is adopted to transmit constant power, there are countless combinations of D1 and D2. The results show that by using the proposed method, bidirectional power transmission can be achieved by operating the regions of D1 and D2. To control the transmission power, the combination of D1 and D2 is determined by the pre-set D2. D2 can be obtained from the lookup table determined by the command power, while D1 can be calculated based on D2 and the command power by the following formula. The D1 calculated by D2 and the command power can precisely control the direction of power flow.

Mode I$(0 < D_1 \leq D_2/2)$:

$$D_1 = -\frac{1}{3} + \frac{2}{3}D_2 \pm \frac{1}{3}\sqrt{1 + 2D_2 - 2D_2^2 - \frac{3P}{k}} \tag{9}$$

Mode II$(D_2/2 < D_1 \leq D_2)$:

$$D_1 = 1 \pm \sqrt{1 - 2D_2 + D_2^2 + \frac{P}{k}} \tag{10}$$

Mode III$(D_2 < D_1 \leq (D_2 + 1)/2)$:

$$D_1 = \frac{1}{3} + \frac{2}{3}D_2 \pm \frac{1}{3}\sqrt{1 - 2D_2 + D_2^2 + \frac{3P}{k}} \tag{11}$$

Compared with the traditional EPS modulation, the feasible regions of D1 and D2 have been greatly expanded. Figure 4 shows that a slight change of ΔD2 = 3% in D2 will not cause significant changes in D1. Therefore, a more stable current waveform can be obtained.

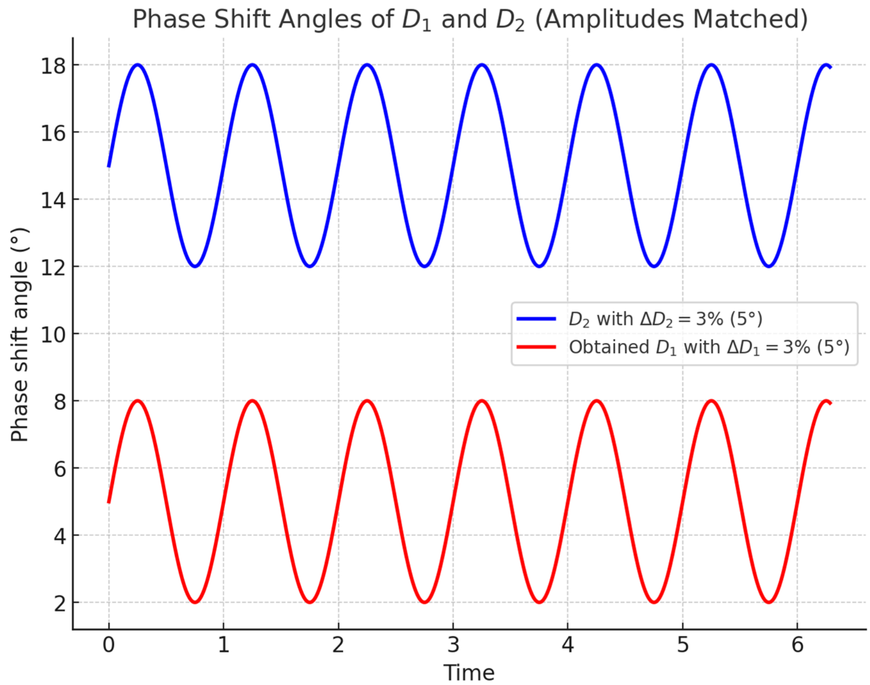

Figure 4. D1 and D2 of the specific power transmission controlled by the improved EPS system

4. Surge Current Suppression Mechanism

4.1. Dynamic Response Optimization

Considering the difficulty in solving the LMM method under complex optimization models, the literature[10] adopted the MATLAB particle swarm optimization algorithm to solve the numerical solutions of the corresponding control variables. Based on the results of the optimization algorithm, that is, the analytical solution or the numerical solution, the implementation methods of the optimization control are mainly divided into two categories: the formula method and the lookup table method[11]. The control loop usually consists of a single voltage (or current, power) closed-loop and the generation of optimization control variables. Through the closed-loop control, the phase shift of the external excitation or the control of the transmission power is generated. Combined with the real-time sampled input and output voltage parameters, the real-time optimization control parameters (D1, D2, D3) are obtained based on the formula method or the lookup table method, and then waveform modulation[12] is carried out.

By establishing an current prediction model:

$$i_L(t+1) = i_L(t) + \frac{\Delta t}{L}(V_{ab} - nV_{cd}) \quad (12)$$

Combining Model Predictive Control (MPC), optimize the combination of D_1 and D_2 to minimize the current fluctuation. In the load sudden change experiment, the current overshoot of the improved EPS is only 32% of that of the traditional EPS (Figure 5).

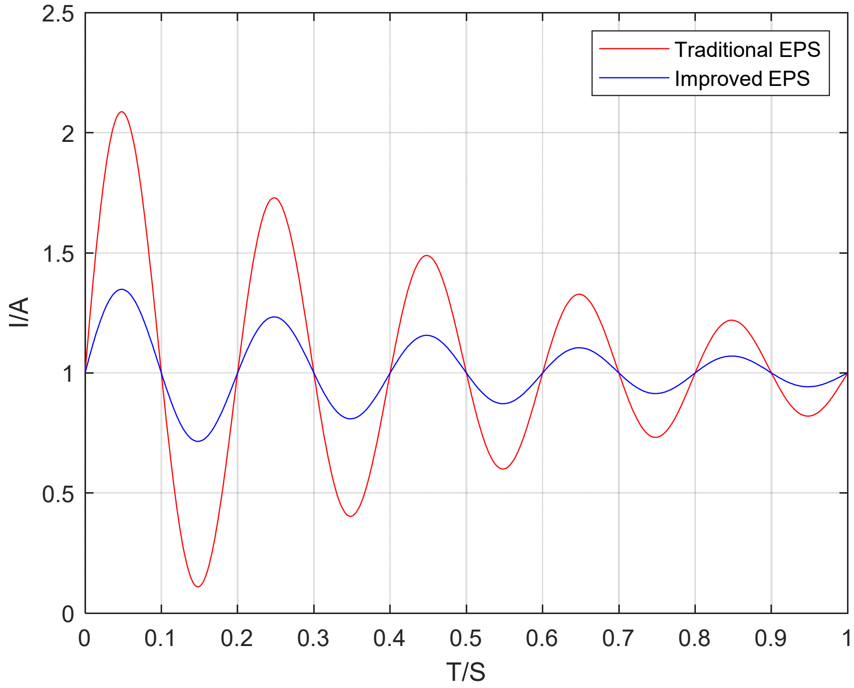

Figure 5. Comparison of Current Overshoot between Improved EPS and Traditional EPS

4.2. Wide-range Stability Analysis

The parameter sensitivity analysis indicates that the new EPS can maintain the output voltage deviation within ±1.2% even under the parameter fluctuations of ±20% for the inductance and ±15% for the capacitance, demonstrating stronger robustness.

5. Experimental Verification

The parameters of the experimental platform are as follows: input voltage 30V, output voltage 30V, switching frequency 10kHz, transformer ratio 1:1, leakage inductance 185μH. The simulation model of the DAB converter was built based on the MATLAB/Simulink simulation software, and the improved EPS modulation method was adopted, and it was compared with the traditional EPS modulation method.

The experimental results show:

Surge current suppression: Under 20% rated load, the peak value of the surge current of the improved EPS is 1.1A, which is 47.12% lower than that of the traditional EPS (Figure 6).

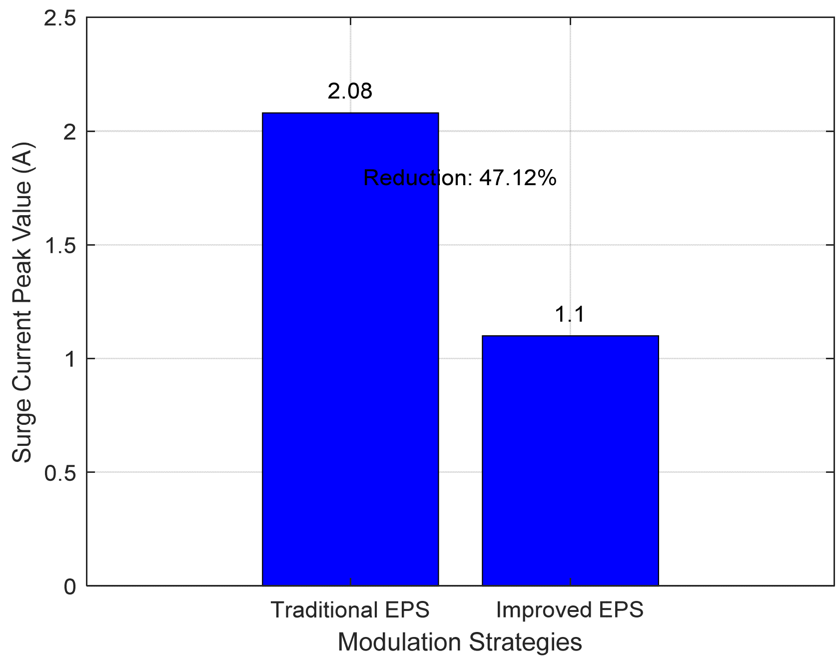

Figure 6. Comparison of Surge Current Peak Values under 20% Rated Load

Dynamic response: When the load suddenly increases from 20% to 80%, the recovery time of the output voltage is only 20ms, which significantly outperforms the 50ms recovery time of the traditional EPS modulation method (Figure 7).

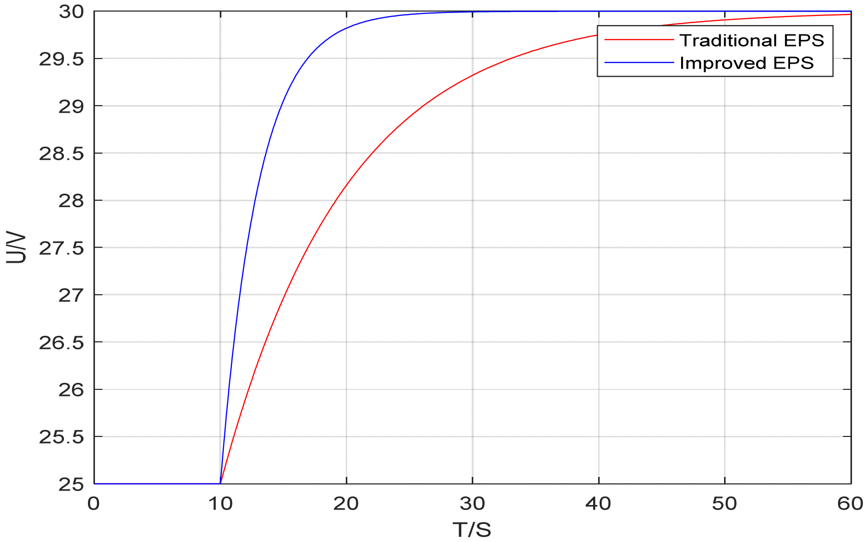

Figure 7. Comparison of Dynamic Response between Improved EPS and Traditional EPS

6. Summary

The proposed improved extended phase-shift modulation strategy in this paper effectively suppresses the surge current of DAB converter by expanding the operation range of phase-shift comparison and optimizing the control algorithm. It also enhances the dynamic response performance. The experimental results validate the effectiveness of this strategy within a wide load range, providing a new idea for the design of highly reliable DAB converters. In the future, further research can be conducted on the combination of this strategy with various control methods to achieve more complex multi-objective optimization.

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