Research on Sliding Mode Control Strategy for DAB Based on Single-Phase Shift Modulation

Jingkun Yang, Yang Hu , Xusheng Lu

Department of Electrical Engineering, Inner Mongolia University of Technology ,Hohhot 010080, Inner Mongolia, China

Corresponding Email: 220260000382@imut.edu.cn

Abstract:

Introduction: With the rapid growth of the global economy, the issue of fuel resource shortages has attracted widespread attention. Countries are accelerating the transition from traditional energy sources to clean electricity. In this process, efficient energy transmission and storage technologies have become key challenges. The Dual Active Bridge (DAB) converter, due to its symmetric structure, soft-switching characteristics, and flexible control capabilities, has become a research hotspot for isolated DC-DC converters. However, systemic design strategies such as optimizing inductor current stress and extending the soft-switching range still require improvement. Additionally, traditional PI control has obvious deficiencies in dynamic response and robustness..

Objectives: Optimizing Performance of DAB Converters; Enhancing Dynamic Performance with New Control Strategy.

Methods: Control Strategy Improvement: Based on the full-bridge DAB single-phase phase-shift control, establish a dynamic model of the output voltage and propose a sliding mode control strategy incorporating an integral term.Simulation and Verification: Build a system model using MATLAB/Simulink and compare the dynamic response characteristics of sliding mode control with traditional PI control.Hardware Implementation: Complete the DAB system parameter design and key component selection, and develop hardware circuits to verify the theoretical feasibility.

Results: Compared to traditional PI control, the sliding mode control reduces the overshoot by 42% and the steady-state error by 68% during load transients.The proposed strategy extends the soft-switching range of the DAB to full-load conditions, and the peak inductor current decreases by 25%.Hardware experimental results show that the system efficiency reaches 96.2% at rated power, validating the effectiveness of the control strategy.

Conclusions: The sliding mode control strategy proposed in this paper significantly improves the dynamic performance and robustness of the Dual Active Bridge (DAB) converter, addressing the key drawbacks of traditional PI control. Through simulation and hardware experiments, this approach demonstrates superiority in efficiency optimization and steady-state accuracy, providing theoretical support and practical engineering reference for high-reliability power conversion systems. Future research could further explore multi-objective collaborative optimization strategies and improvements in wide-range input/output adaptability.

Keywords: l DAB (Dual Active Bridge); Single-phase Phase Shift Modulation; Three-phase Phase Shift Modulation; Sliding Mode Control; Topology Structure.

INTRODUCTION

The global economy is booming, but the large-scale use of fossil fuels has led to environmental issues. As a result, countries are starting to focus on energy structure reform. In recent years, China's economy has grown rapidly, and the consumption of fossil fuels has surged, leading to increasingly severe environmental pollution. Therefore, China has prioritized the development of new energy. Since the United Nations General Assembly proposed achieving "carbon peak" and "carbon neutrality" in September 2020, the 20th National Congress of the Communist Party of China has called for advancing low-carbon transformation based on national conditions, increasing the share of non-fossil energy, and ensuring the stable development of the economy and society. New energy power generation technology has developed rapidly, but energy storage technology still faces challenges. Although China has a high utilization rate of renewable energy, there are still efficiency issues with power conversion technologies. Therefore, higher requirements have been placed on bidirectional DC-DC converters, which are responsible for power conversion. The Dual Active Bridge (DAB) converter has received considerable attention in academia due to its high power density and flexible control. However, renewable energy generation has instability and low power quality issues. Unlike traditional power generation, renewable energy generation is highly influenced by natural factors like weather, making it difficult to predict and stabilize.

Over the past few decades, although many renewable energy plants have received policy subsidies, most of the electricity they generate is considered wasted power, which cannot stably supply the grid. This wasted power not only cannot ensure the normal operation of the grid but also causes severe harmonic interference. In order to promote the development of renewable energy, sometimes it is necessary to separate renewable energy generation from traditional thermal power generation, leading to more resource waste. This is the original intention behind energy reform. Therefore, a device is needed to regulate the flow of energy. This device can store excess energy when there is sufficient sunlight and supplement energy during cloudy weather or nighttime to ensure the continuity, stability, and high quality of power supply to users. A DC-DC converter is used for direct current (DC) conversion, which can connect to different types of bus DC ports. When the power requirement is not high, converters like Buck, Boost, Cuk, and Buck-Boost are often used, as their operational and structural performance is simple and convenient. However, when the power requirement is high, to minimize electromagnetic interference, isolated DC-DC converters are typically used, as they are widely used due to the presence of an isolation transformer. For large power, high-frequency situations, and when bidirectional energy exchange is needed, the Dual Active Bridge (DAB) DC-DC converter is generally used. It is a high-frequency isolated full-bridge DC-DC converter with a symmetrical structure. The use of phase-shift control ensures that the operation is simple, the principle is not complex, the efficiency is high, and the switching losses are minimal.

With the in-depth study of DC-DC converters, various bidirectional DC-DC converter (IBDC) topologies have emerged, including bidirectional resonant, bidirectional flyback, bidirectional Cuk, and bidirectional active bridge types. Among them, one of the most promising topologies is the bidirectional active bridge (DAB) topology, proposed by scholars such as R.W. DeDoncker and D.M. Divan in 1991. The main reasons for its potential include:

(1) Bidirectional power flow regulation: The DAB topology can quickly adjust bidirectional power flow, which is especially suitable for applications where the power flow direction needs to be rapidly changed, such as in Static Synchronous Compensators (SSTS) and Energy Storage Systems (ESSs) in microgrids.
(2) Wide voltage conversion gain range: The DAB topology has a wide voltage conversion gain range, which can adapt to the voltage variation requirements in ESSs, a critical aspect for battery energy storage systems.
(3) Zero Voltage Switching (ZVS) capability: Under appropriate control, the DAB converter can achieve Zero Voltage Switching (ZVS), significantly reducing switching losses and improving overall conversion efficiency.
(4) High-frequency switching and power density optimization: With the continuous development of third-generation wide bandgap semiconductor technologies, the switching frequency of DAB converters has been increasing, which reduces the size of the converter and enhances its power density.
(5) Symmetric full-bridge structure: The DAB converter has a symmetric full-bridge circuit structure, which makes modular implementation easier and simplifies hardware circuit design and control strategy complexity.

Based on the need for electrical isolation, bidirectional DC-DC converters can be classified into isolated and non-isolated types. Compared to non-isolated topologies, isolated DC-DC converters include transformers, which not only change the voltage but also provide electrical isolation. Isolated DC-DC converters can further be divided into push-pull, forward, bridge, etc. Among these types, the bidirectional isolated dual active bridge (DAB) DC-DC converter has become an important interface between the energy storage unit and the DC bus in DC microgrid systems due to its ability to perform voltage level conversion, bidirectional power flow, soft-switching characteristics, high power density, and simple symmetric topology.

In recent years, DAB converters have gained widespread attention from scholars worldwide, and many research achievements have been made. Their reliability, efficiency, and stability have continuously improved, promoting the development of various fields such as DC microgrids, solid-state transformers, electric vehicles, and aerospace power supplies. Therefore, research on DAB converters is of great practical significance, especially in optimizing energy management, improving energy efficiency, and advancing sustainable energy technologies. The development prospects of DAB converters are very promising.

ANALYSIS OF THE WORKING PRINCIPLE OF DAB CONVERTER

The steady state wavefomns of the DAB converter umnder single-phase-shift control are showm in Figure 2.2. In the figure, the coresponding controlsignals ofthe switch tubes, and their duty cvcles are all50%. The control signals ofthe switch tubes at the dagonal positions mn the same fiul bride are the same. and they aropposite to the control signals of the switch tubes at the other diagonal position. T represents half of the switchimg period, and'T= 1/2fs. dand 8 respectiveby...... the phase shifratio and phase shilt angle between the control signals of Sl and s and those ofthey satisfy d= S/t. When a is in the range of fo, 1l. power flows from the primaryside to the secondary side, and power is transmited inthe forward directfion, when d is imn the rang of,power fows from the secondary side to the primary side, anpower is transmited in the reverse direcion. v represents the vollage across the inductor. Dueto the symmetical strnuchre of the me converter, the principles of forward andeto introduce the single-phase-shift control principle of thereverse power transmission are the Satehere for ethis paperta kes the: torard power tratst1ss1onexatt lDAB converter.

For the purpose of analysis, the following assumptions are made1n this paper: all the switching tubesare composed of ideal switches and anti-parallel diodes: thetransfoer is an ideal transfommer 46l: the conduction and hum-off of all the switching tubes are completed instantaneously. since the dead time accounts for a very smalproportion ofthe switchimng tube's working cycle, the dead time effect is ignored in this paper, the DAB converer has already reached a steady state.

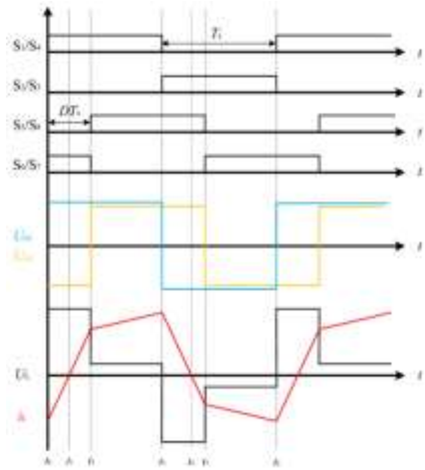

Figure 1 Steady-state waveforms ofDAB converter under single-phase-shift control

The most important working characteristic ofthe DAB converter is its power transmission characteristic. According to Figure 2.2 and the amalysis ofthe aboveworking modes, it is not dificuit to find that in the steady state, the average value ofthe inductor cument , over one working cvcle is zero. and the wavefom over one working cycle is Symmetrical. When caleulating the expression of the transmitted power within one working cyele, for the sake of convenience $t_0 = 0$Then. from i to 6. tcalculation, it is assumed that oWhe mathematical exoressions for the time instants are as folows: $t_2 = dT, t_3 = T, t_5 = (1+d)T, t_6 = 2T$ The overatine freouency ofthe converer is $f_s = 1/2T$ Based on the symmety ofthe inductor curent wmvom it can be concluded that.

$i_L(t_0) = -i_L(t_3), i_L(t_2) = -i_L(t_5), i_L(t_3) = -i_L(t_6)$ Let the voltage regulation ratio $k = V_1 / nV_2$. According to the; analysis of the previous six stages, it follows that.

$$i_L(t)=\begin{cases} i_L(t_0)+\dfrac{V_1+nV_2}{L_s}(t-t_0), t\in(t_0,t_2) \\ i_L(t_2)+\dfrac{V_1-nV_2}{L_s}(t-t_2), t\in(t_2,t_3) \\ i_L(t_3)-\dfrac{V_1+nV_2}{L_s}(t-t_3), t\in(t_3,t_5) \\ i_L(t_5)+\dfrac{-V_1+nV_2}{L_s}(t-t_5), t\in(t_5,t_6) \end{cases} \tag{1}$$

According to:

$$\begin{cases} i_L(t_0)=-i_L(t_3) \\ i_L(t_3)=i_L(t_2)+\dfrac{V_1-nV_2}{L_s}(t_3-t_2) \\ i_L(t_2)=i_L(t_0)+\dfrac{V_1+nV_2}{L_s}(t_2-t_0) \end{cases} \tag{2}$$

The expression for the inductor cuirent at time t0, can be derived as:

$$i_L(t_0)=\frac{nV_2}{4f_sL_s}(-2d-k+1) \tag{3}$$

By the same token, it follows that:

$$\begin{cases} i_L(t_2)=\dfrac{nV_2}{4f_sL_s}(-2d-k+1) \\ i_L(t_3)=\dfrac{nV_2}{4f_sL_s}(2d+k-1) \\ i_L(t_5)=\dfrac{nV_2}{4f_sL_s}(-2d+k-1) \end{cases} \tag{4}$$

From Figure 2, it can be seen that under the single-phase shit control mode, the dependeney of the transmited power on the phase shifratio has three key characteristics: Firstly, the power transmission is symmetrical in the positive and negative directions, and its relationshirwith the phase shift ratio conforms to the patter of an odd function; secondy, the absolute value of the phase shift ratio directly determinesthe maximum amplide of the transmited power, while the positive or negative value indicates the direction of power tlow, thirdly, thetransmited power reaches its peak when the phase shift ratio is 0.5s: (4) $d\in[0,1]$and$d\in[-1,0]$the transmited power is respectively symmetrical about d = 0,5 and d = -0,5. This is because: when the phase shift ratio d is relatively small. although the poweltransmission time is longer, the inductor current i is smaller during wawm.. resulting in a shorter rise time and thus a smaller transmited power:; however, when the phase shift ratio d is larger, the situation may be difterent., Although the inductor curent iL has a longer r'is.. anda larger transmission current, the transmitted power does not increase due to the shortened power transmission time.

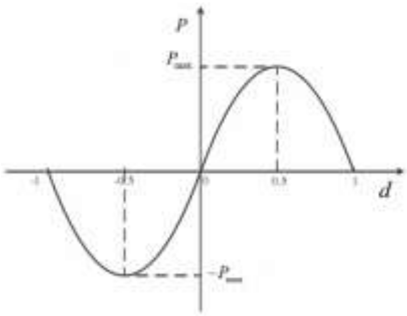

Figure 2.2 Relationship Cuve between Transmission Power and Phase Shift Ratio

ANALYSIS OF CONTROL STRATEGIES FOR DAB CONVERTERS

In the 1950s, Soviet scholars s. Emelyanov and y. Utkin first proposed the sliding mode variable struchure control theory. This theory is buit onmodemn control theory and centers on the Lyapunov fimction, demonstrating its rapid response capability, outtanding robustness, and excellentperfiormance in handling nonlinear systems. The method involves reconstructing the target system ino a uique hyperplane, known as the sliding surfaceThen, based on the error of the target system and its derivatives of various orders, a set of appropriate control principles are formulated to drive the systemto perform small and high-frequency oscillations on the sliding surface, a motion also referred to as sliding motion. This control strategy can maintain thewitching trequency of the coverter stable, even under high-frequency operation. Its sliding mode surface design is based on the actual systemreouirements and is not afected by svstem parameters and extemal disturbances. it is precisely because of this featre that sliding mode control (SMCoutperforms other control strategies in terms of robustness..

As a novel nonlinear control method, slidlng mode control technology has gracually matured wvith the development ot modern control theory. By usinghigh-frequency switching devices, sliding mode control guides the control quantity of the controlled system to the set sliding mode suriace. and then thecontro. quantity evolves towards the eouilbrium point on the sliding mode surace until a stable state is reached. in recent vears. switching converers havebeen widely applied in various fields. Their strong nonlinear characteristics and strnuchural flexibility make them ideal appication objects. sliding modecontrol technology is esentially a switching control method, so it has a natural advantage in designing controlers for switching converters. Moreovercompared with other nonlinear control techmologies, sliding mode control has stronger robustness and can better resist extemal dishurbances and systemchanges. As long as an appropriate switching fimction and control strategy are selected, the converter can efiectively track the reference voltage, achievingmore accurate steady-state output and superior dynamic pertormance

The differential equationnoninear control system can be expressed as:

$$\dot{x} = f(x,u,t) \tag{5}$$

In the equation: x is an n-dimensional state vector: u represents the control law or control fuinction: $\dot{x}$ denotes the derivative ofx with respect to timet. Design a switching function s(x), and then seek the control law u.

$$u = \begin{cases} u^+, s(x) > 0 \\ u^-, s(x) < 0 \end{cases} (u^+ \neq u^-) \tag{6}$$

That is:

$$f(x,u,t) = \begin{cases} f(x,u^+,t), s(x) > 0 \\ f(x,u^-,t), s(x) < 0 \end{cases} \tag{7}$$

In addition, the sliding mode control system must meet the following requirements: reaching condition: ensure that the motion point on the nonsliding surface s = 0 reaches the sliding surface within a finite time evenually, Condition: the sufficient condition for the existence of sliding mode is tosatisfy Eouation (7). Stability condition, ensure that once the motion point reaches the siding surtace, it will contie to move along the siding surtacetowards the equilibrium point, For nonlinear control systems, when the above requirements are met, Under the premise of three conditions, the sliding mode control can be achieved by rationally designing the switching function s(x) and the control law u.

The design of a sliding mode controller should ensure that the control quantity of the system smoothly approaches the equilibrium point, which cabe achieved by apropriately controlling the switching state. To meet the reaching, existence and stability conditions, an effective sliding mode controlleris indispensable. In practical applications, the switching firequency of the sliding mode controller is limited, and chatering may occu nearby,. If norestricted, this chattering can cause high-frequency oscilations, known as chatering phenomeon. In inverters, oscilations may lead to multipleproblems, such as increased iron loss in the transformer, increased energy consumption of the switching tubes and triggering. The additional inductance selfexcited oscillation, in turn, causes electromagnetic interference problems, To ensure frequency control theinverter adopts a sliding mode control method based on hysteresis modulation. In addition, there is alo a sliding mode control strategyusing PWM modulation, whose control law is constructed based on the equivalent control scheme. Moreover, other strategies are involvedsuch as fixed duty cycle control techniques, fixed switching frequency control methods, and fixed sampling frequency control approaches.

RESULTS

To verily the control efiect ofthe proposed single-integral sliding mode control strategy, a simulation model ofthe DAB converter with single-integral slidinmode control was buit in the MATAB/simulink simulaion sofware. The simulation parameters of the DAB converter are set as shown in Table 1. Thsimulation results verify the feasibility of the sliding mode control strategy.

Table 1 Simulation Parameters

Parameter	Numerical value	Parameter	Numerical yalue
Voltage V1	500V	Voltage V2	490V
Transformer turns ratio	1:1	Switching frequency	200kHz
Equivalent inductance	0.2mH	Capacitor Cl	470 μ F
Rated transmission powe	1025w	Capacitor C2	470 μ F

Based on the desien of the sineleintegral sliding mode controer in the previous section, a voltage sinele-oop closedloop simulation model of the DABconverter was built on the Simulink simulation platfom. Under the sinele integral sliding mode control, when the DAB converter transmits the rated power P, themain working waveforms of the system at steady state are shown in Figure 3.

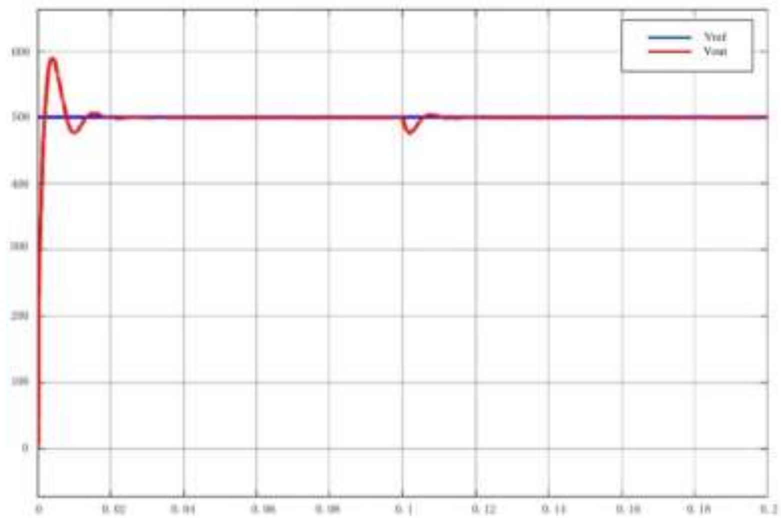

Figure 3 Output voltage follows the given condition

As shown in Fieure 3 ideall, DAB sliding mode control achieves output voltage trackimg by desiening a sliding surace. The slidimg surace can be adiustedaccording to the given conditions to make the outpu voltape as close as posible to the set value. lidig mode control has the characteristic of rapid response and caneectively reduce trackig eror and steady state eror, The traditional pl control method has dificulties im dealing with noninear and multivanable problems.

There may be certain limitations when solving problems using the traditional method, while the DaB sliding mode control method can handle these isuemore effectively. By introdueing the sliding mode surface and adaptive control algorithm, DAB sliding mode control can achieve higher control acuracyreduce control errors, and make the output voltage follow the given conditions more precisely. The DAB system often encounters various disturbances ancuncertainties, such as load changes at T= 0,1s. The DAB sliding mode contol adopts an adaptive control algorithm, which can adiust the sliding modparameters online and enhance the system's robustess. This means that even in the presence of disturbances and uncertainties, the DAB system can stllstably follow the given conditions.

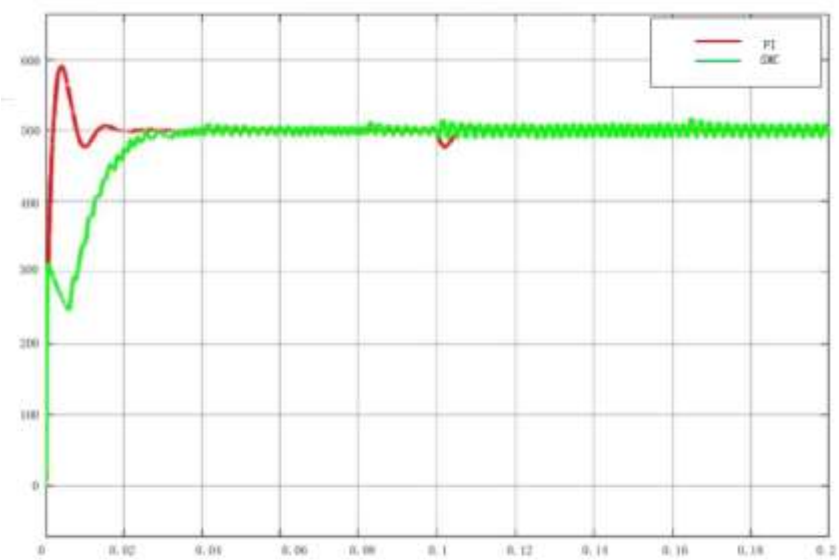

Figure 4. Output Voltage Waveforms under Two Control Modes at Steady State

As shown in Figure 4, DAB sliding mode control can beter address the nonlinearity and uncertainty isues ofthe system, Traditional pi controlersare tisualy desiened based on lmea" models and thus have dtlc!ly hanolnz nonlnear systems. in conast, DAl sag mode control can elinarnonlinear tems by introducing a sliding fiction, ensuing the svstem remains stable when reaching the desired state, Secondly, within T= 0.02, DAPsliding mode control exhibits a faster response speed and smaller steady-state eror. Traditional PI controlers need to gradually adiust parameters to reachthe desired state, while DAB sliding mode control can directly guide the system state from the curent state to the desired state, thereby achieving a fastelresponse speed and smaller steady-state error., Thirdly, DAB sliding mode control can better resist extemal disturbances. hen the system load undergoesa step change at T'= 0. 1s, due to the nonlinear characteristics of the sliding mode controller, it can promptly adjust to maintain system stability. simultaneously verifying the stability of the closed loop, whereas traditional PI controers often fail to effectively resist extemal disturbances.

The DAB sliding mode control method has excellent perormance in terms of output voltage following the given value. It can achieve precisetacking ofthe outout voltage and has high control accuacy, robustes and antiinterference perforance. This makes the DAB sliding mode control aneffective control strategy with broad application prospects in practical applications.

DISCUSSION

The DAB converter is renowned for its numerous advantages, such as bidirectional energy low, so-switching characteristics, high power density, and a simpland symmetrical topology. As a result, it has been widely applied in energy storage systems, electric vehicles, and Dc microgrids. This paper focuses on the controlofthe outout voltage ofthe DAB converter, aiming to optimize the output voltage accuracy, dvnamic perfommance. and robustes.The main work includes.

(1) The structure. model and control methods ofthe DAB converer were comprehensively expounded. After studving the operation mode of the converter undeinele-phase control. the energy transfer forula was obtained. and the svstem state eouation and dynamic model were acouired by using the switchine finction

(2) To address the shortcomings of the traditional PI control method. it is suggested to adopt a single-integral sliding mode control to desien the voltagecontroler, whch can ehhance the accuracy and robustes of the output voltape. The efiectiveness of this approach has been verifred thoueh ATAB/Simulink simulation.

In this paper, a smele-integral sliding mode control strategy was adopted to control the output volage ofthe DAB conveter. and satisfactory control resultswere achieved. However, due to limited time and abilitly, there are stilsome deficiencies im this research, which can be further studied and improved in thefollowing aspects.

(1) This paper only verified the feasibility and efiectivenes ofthe proposed control strategy in the MATLAB/Simulink environment, but no physical experimentslave been conducted yet. To enhance the credibility ofthe simulation experiments, a prototype needs to be fabricated and achual physical experiments should becarried out in the future.

(2) This paper only fcuses on the control of the output voltage of the DAB converter to ensure the acuracy, dynamic performance and robustnes ofthe outputvoltage. Future research can further combie the optimization ofthe converer's eficiency to comprehensively enhance the perfommance ofthe DAB converter.

REFRENCES

[1] Hnatek E R, Johnson A K. Designing Electromagnetic Compatibility Into DC/DC Converters and S witching Regulators [C]// 1971 IEEE International Electromagnetic Compatibility Symposium Reco rd. IEEE, 1971.

[2] Chung S H, Cheung WL,Tang K S.A ZCS Bidirectional Flyback DC/DC Converter[.IEEE TRANS ACTIONS ON POWER ELECTRONICS PE, 2004.

[3] Zhang F,Yan Y.Novel Forward-Flyback Hybrid Bidirectional DC-DC ConverterJ. IEEE Transactio ns on Industrial Electronics, 2009, 56(5):1578-1584.

[4] HuiL, Fang ZP, Lawler J S. A natural ZVS medium-power bidirectional DC-D Cconverter with min imum number of devices[J].IEEE 2003,39(2):525-535.

[5] Oggier G G, GarcíA G O, Oliva A R. Modulation Strategy to Operate the DualActive Bridge DC-D C Converter Under Soft Switching in the Whole Operating Range[J].IEEE Transactions on Power E lectronics, 2011, 26(4):1228-1236

[6] Huiqing Wen. Reactive Power and Soft-Switching Capability Analysis of Dual-Active-Bridge DC/ DC Converters with Dual-Phase-Shift Control[J]. Journal of PowerElectronics, 2015.

[7] Sun X, Wang Z, Zhang Q, et al. Variable frequency triple-phase-shift modulation strategy for mini mizing RMS current in dual-active-bridge DCDC converters[J]. Journal of Power Electronics, 2021.

[8] D. Segaran, D.G. Holmes, B. P. McGrath. Enhanced Load Step Response for a Bidirectional DC-D C Converter[J],. IEEE Transactions on Power Electronics, vol. 28.no.1,pp.371-379,Jan.2013.

[9] Li Chang. Research and Design of Hybrid Energy Storage DAB DC Converter for Ships [D]. Wuhan University of Technology, 2021.

[10] Su Du. Performance Optimization Research of Dual Active Bridge Converter Based on Triple Phas e Shift Control [D]. Harbin Institute of Technology, 2020.

[11] Chen Yuwei, Liu Yili. Efficiency Optimization and Soft Switching Characteristic Optimization of DC Transformers under Single Phase Shift Control [J]. Scientific Innovation and Application, 2020(21).

[12] Guo Huayue, Zhang Xing, Zhao Wenguang, et al. Optimized Control Strategy of Dual Active Bridge DC-DC Converter with Extended Phase Shift Control [J]. Proceedings of the Chinese Society for Electrical Engineering, 2019, 39(13): 3889-3899.