A Review of Advanced Control Methods for Dual Active Bridge DC–DC Converters

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Abstract This document examines the advanced control techniques for dual-active-bridge (DAB) DC-DC converters. It describes the phase-shift modulation enhancements, closed-loop control, model predictive and data-driven control, and classifies the previous research into multi-study confirmed, insufficient evidence and single-source conclusions. Four main obstacles are pointed out: real-time solution of triple-phase-shift, joint design of steady-state-dynamic, wide range zero voltage switching realization and uniform validation standards. A hierarchical technical plan is suggested: analysis of phase-shift modulation at the foundation, light-weight multi-objective compromise in the middle, and disturbance-observation-based compensation at the top. The construction of comparable evaluation bases is stressed rather than the design of new controllers. Uniform operating conditions, metric conventions and reports about transient-steady-state are necessary for fair comparison among different schemes and practical application of technology.

Keywords dual-active-bridge converter; phase-shift modulation; model predictive control; zero-voltage switching; evaluation benchmark

1 Introduction

Dual active bridge (DAB) DC–DC converters are frequently used for energy-storage conversion, DC microgrids, solid-state transformers and vehicle power conversion, not only for electrical isolation and bidirectional power transmission, but also because one phase-shift angle represents both the power magnitude and the current wave form. This type of structure, sacrificing modulation for performance, makes the DAB one of the few power-electronic configurations in which the control parameters correspond directly to the optimization goals, and this is why a large number of research papers during the past ten years have discussed the same criteria without reaching an agreed upon optimal solution (Bachman et al., 2024).

Previous research has pointed out the disadvantages of DAB: the backflow power increases when the voltage ratio differs from unity gain, the ZVS boundary becomes smaller at light load, and the steady-state optimization conflicts with the dynamic response. They differ in attributing the causes and proposing solutions. Studies oriented towards modulation attribute the shortage of degrees of freedom and extend the feasible range along the phase-shift direction; while control-oriented studies point out the discrepancy between the model and suggest reinforcing the feedback mechanism to compensate for the parameter variations. Recently, some predictive and data-driven studies doubt both aspects, suggesting that the wide-ranging performance cannot be ensured if the model relies on actual parameters. Each study has its own viewpoint but leads to various results on the same prototype -- related to the absence of a unified assessment method.

This review examines 27 publicly accessible Chinese and English documents from 2017 to 2026, involving the optimization of backflow power and current stress, phase-shift mode expansions, linear and nonlinear closed-loop control, and model predictive and model-free control. Chinese papers focus on engineering verification, whereas English papers concentrate on methodology and stability analysis. Classified into mechanism and modelling, modulation extension, closed-loop compensation and controversial boundaries, it distinguishes the replicated conclusions from those valid under single operating conditions and those not yet verified in method transfer.

2 Operating Principle and Modeling Fundamentals

2.1 Topology and Power Transfer Mechanism

The literature mentions the power transfer mechanism uniformly: both full bridges generate square waves with a duty cycle of about 50%, and the phase-shift angle between the bridges affects the voltage-second integral across the series inductor, thus determining the energy transferred per cycle. For single phase shift (SPS), the transmitted power is usually expressed as ,which is generally the basis for most discussions (Bachman et al., 2024). The formula has functions other than calculating power:

ISSN 3106-7018 (Print) ISSN 3106-5791 (Online)

power shows a parabolic relationship with the phase-shift angle, reaching its maximum at D = 0.5, but increasing the angle further decreases the power. Most modulation-optimization studies mainly consider the case where D < 0.5 and seldom mention the change in power direction near the limit - however, under load changes or voltage-ratio jumps, this results in a real tracking failure. The piecewise-linear inductor current is also well recognized: the size of the reverse current area is decided jointly by the voltage ratio and the phase-shift angle, which is the key to all the following optimizations. But the reverse current area is not determined consistently - some include intervals of negative instantaneous power, while others include intervals of opposite current-voltage polarity, and the standards are different in non-ideal situations, thus making it difficult to compare the backflow-power reductions from different methods.

2.2 Evaluation Metrics

The metrics used in the references include power transfer capability, backflow power, current stress, ZVS range and dynamic response. The relationship between them is well understood: backflow power and current stress generally have the same trend, which reduces the ZVS region and increases the circulating current required to extend the ZVS boundary to light load, thereby raising the conduction loss (Cheng et al., 2024).

The deficiency lies in the lack of a unified standard for measuring trade-offs. Generally, most documents only discuss two or three indicators, mainly those which show significant increases, whereas indicators which decrease together are neglected or judged negatively. In the dual phase shift (DPS) method, the minimum-backflow-power solution frequently appears on the edge of the feasible region, where the current-stress margin is completely used up; if the prototype fails to achieve zero voltage switching (ZVS) at low power, the efficiency advantage stated may not be realized (Wang et al., 2025a). Therefore, this survey points out the disadvantage of each claimed improvement.

2.3 Modeling

Controller synthesis models are divided into three types. The reduced-order small-signal models integrate over the switching period and maintain the main dynamics, being applied for PI and active-disturbance-rejection bandwidth allocation; the generalized state-space averaging (GSSA) model keeps the harmonics close to the switching frequency and depicts the large-signal ripple and current envelopes; the discrete models, expressed as state-transition equations or local models, are used for the finite-control-set receding-horizon prediction.

The selection of the model type determines the performance of the subsequent methods. The linear design is not suitable for large voltage ratios since the small-signal model, which is linearized at the rated point, changes its gain and pole positions with the operating point; the predictive control becomes computationally intensive under triple phase shift (TPS) because the discrete model needs to be reconstructed mode by mode separately. Sahebi et al. (2026) suggested a unified reduced-order framework which integrates the different TPS modes into one set of state equations, thus reducing the overhead during mode switching. This kind of modeling for computation is more methodically significant than mere algorithmic enhancement, facilitating both the continuity at mode boundaries and the online solution difficulty.

3 Phase-Shift-Modulation-Based Control

3.1 Single Phase Shift

SPS has only one bridge-to-bridge phase-shift degree of freedom, a small number of control variables and simple protection logic, which makes it the initial stage to be used in engineering. The general opinion in the literature is that the performance is satisfactory when the voltage ratios agree, but the backflow power and current stress decrease sharply under disagreement, and zero voltage switching is lost early (Bachman et al., 2024). It has been verified on several prototypes and is considered one of the few stable agreements in the field.

Improvements are mainly based on two aspects. At the modulation level, no further changes can be made since the available degrees of freedom have been used up. At the control level, some new methods have been proposed which avoid using the outer voltage loop: Song and Zhu (2018) directly transferred the power command to a phase-shift correction by means of virtual direct power control, and their dynamic characteristics are better than those of the conventional double loop. This indicates that the feedback structure also influences the wide range performance, however it is unable to reduce the backflow power with the change of voltage ratio, thus it is still a transitional solution.

3.2 Extended and Dual Phase Shift

EPS makes an inner-bridge phase shift on one side while DPS adjusts inner shifts on both sides, producing two- or three-dimensional combinations. The additional degrees of freedom modify the current waveform, increasing the flat-top portion and decreasing the reverse peak, thus reducing the backflow power and current stress at the same power level.

The evidence is relatively strong. Wang et al. (2025) obtained the analytical expression for the backflow power under DPS, changed the operating points to the minimum-backflow boundary under certain conditions and maintained the stability by adjusting the voltage ratio; Guo et al. (2019) decreased the current stress in the EPS system by considering the ZVS boundary and increased the efficiency in the light-load state. Though their condi-

tions and demands may be slightly different, the results indicate the same advantage: introducing one more inner-bridge degree of freedom leads to significant enhancements in the medium- and high-power ranges.

The real difference occurs at light load and mode changing. The optimal point of DPS is near the boundary of the feasible region, beyond which the performance decreases sharply, thus mode changing is necessary as a backup; the resulting power and current discontinuities affect the output voltage. Cai et al. (2022) integrated current-stress optimization with virtual voltage compensation to eliminate the fluctuation caused by mode changing - this implies that it is impossible to achieve both the steady-state optimal point of the modulation layer and the transient one, and the controller should intervene. This conclusion is also mentioned in the discussion of the predictive control, connecting the two approaches.

3.3 Triple Phase Shift

TPS simultaneously adjusts three phase-shift degrees of freedom; the feasible set changes from a curve to a three-dimensional area, which enables a comprehensive compromise for various objectives throughout the whole power range and all voltage ratios theoretically. Gu et al. (2019) included the backflow power, current stress and efficiency in a common objective function and studied their mutual relationships; Zeng et al. (2021) solved the conflicts between metrics by using a multi-objective optimization method with weighting and constraint forms; Cheng et al. (2024) developed a unified control law aimed at minimizing current stress for the full-power range ZVS, covering both light-load and heavy-load conditions by means of one set of expressions – the nearest solution for a closed-form expression under all circumstances in TPS research.

The limitations are also clear and mutually support each other. Mode division: the differences of the three shifts indicate different current waveforms, usually more than six divisions, each having its own power expression, solution type and separately considered boundary conditions, thus increasing the design and verification costs. On-line calculation: the analytical solution needs to be discussed for each case and handle the constraints, whereas the iterative search has an uncertain number of iterations; with strict fixed-point margins within the control periods of several kilohertz, most prototypes operate at a lower frequency or use the off-line lookup tables. The sensitivity of the parameters: when the solution approaches the constraint boundary, the deviations of the inductor, the dead-time effects and the sampling delay cause the operating point to shift from the optimal value, leading to a difference between the laboratory efficiency curves and the actual products.

Furthermore, the literature mainly shows steady-state efficiency improvements but seldom discusses the switching dynamics; Sahebi et al. (2026) have considered this at the modeling stage and Yeter et al. (2026) reduce frequent switching by using a variable control set, but neither has evaluated the transient processes during switching—this deficiency reduces the persuasive power in engineering of TPS.

3.4 Summary

From SPS to EPS and DPS, and then to TPS, the increment of returns for more degrees of freedom becomes smaller gradually. The first expansion (SPS to DPS) provides the largest advantage; the second one (DPS to TPS) decreases this increment, but the cost increases when an additional multiplication is made together with online optimization. Hence, the research emphasis has been on reducing the solution cost: the use of look-up tables with local corrections, the simplification of order models to reduce the number of modes, and the learning-based approximation of the solution map (Sahebi et al., 2026). These methods are also compatible with the predictive-control and data-driven approaches below - both directions are getting closer.

4 Closed-Loop and Advanced Control

4.1 Linear Control

The single-loop PI structure is the most simple; its bandwidth is limited by the switching frequency and sampling delay. The double-loop structure includes an inner inductor- or output-current loop, distributing the disturbance rejection to the inner loop and the steady-state accuracy to the outer loop; input-voltage and load-power feedforward can correct the phase-shift predictively when the command changes. These schemes have been proven effective on several prototypes under rated conditions.

They only show their limitations over a large range of operation: when the voltage ratio changes from 1 to 2, the gain and poles of the rated-point small-signal model move together, and it is difficult to maintain phase margin with only one set of parameters; gain scheduling or piecewise tuning can solve this problem, but the boundary of each segment still depends on the model. Liu et al. (2024) integrated H-infinity design into an intelligent search, considering the model uncertainty by using robust performance indices and increasing the stability region in DC-microgrid systems, at the expense of a higher controller order and simulation-dependent tuning. Therefore, the problem of linear control is not the lack of performance, but the limitation of performance to the operating point: any linear method which claims universality should describe its gain-scheduling strategy, and many papers do not mention this clearly.

4.2 Sliding-Mode Control

Sliding-mode control is immune to parameter variations and external influences, but suffers from chattering caused

ISSN 3106-7018 (Print) ISSN 3106-5791 (Online)

by the switching term, which enhances the appearance of extra harmonics and energy loss. The terminal sliding mode transforms the manifold into a finite-time-convergence type, thus making the errors disappear in a finite number of steps, although high-frequency switching still exists near it. The super-twisting algorithm, a second-order sliding-mode method, substitutes the sign-function switching with an integral term; therefore, the chattering is significantly reduced and no state derivatives are needed.

Sami et al. (2024) developed a double-integral super-twisting controller for the DAB to reduce the steady-state error and eliminate chattering during electric-vehicle charging and discharging; Wang et al. (2025) integrated super-twisting sliding mode with current-stress optimization, thus the sliding surface includes the optimization information of the modulation layer when tracking the voltage. The common point is to incorporate the modulation objectives into the sliding surface, which is more compact than the modulation optimization in series followed by a conventional closed loop.

The dispute is about the real chattering level. According to the theory, the super-twisting algorithm transforms the discontinuous action into an integral one; however, the digital implementation such as integrator saturation, sampling quantization and the discrete control period is difficult to maintain this; the measured THD from prototypes often differs from the simulation results, and in most literature reports, both are not included. Moreover, the sliding-mode gains and the control period are strictly limited: a larger gain leads to more chattering, a smaller one affects the finite-time convergence, and the effective range is shortened by the inductor current ripple (Wang et al., 2025).

4.3 Active Disturbance Rejection Control

Active disturbance rejection control (ADRC) handles parameter variations, load disturbances and unmodeled dynamics in a wider state, estimates it online by an enlarged state observer and modifies it in real time, transforming the system into the standard integral-cascade form. The linear ADRC adjusts the observer and controller bandwidths and is more suitable for engineering applications than sliding mode or predictive control. Li et al. (2023) used it for the DAB and maintained the output voltage constant when the inductance parameters changed and the load was altered, showing the observer's capability to estimate the distributed disturbances.

The controversy is about the conflict between bandwidth and noise. Increasing the bandwidth can speed up the convergence of disturbance estimation but also enhances the sampling noise and current ripple, which are transferred into the phase-shift angle via the compensation channel and form a new disturbance source. Therefore, tuning has to balance bandwidth with filtering; the advantage in speed mainly applies to low and medium frequencies, and rapid modulation-layer response is still necessary for millisecond-load changes. However, the assertions of strong disturbance rejection have not been supported by frequency domain analyses or tests on noise sensitivity, thus should be doubted.

4.4 Model Predictive Control

Finite-control-set model predictive control (MPC) divides the phase-shift angles into a finite number of candidates, cycles through them and chooses the best one according to a cost function, which is the most commonly used form of prediction in the DAB. The cost function usually includes the output-voltage tracking error, an inductor-current stress penalty and a ZVS constraint penalty. Tarisciotti et al. (2021) made early one-step predictions for voltage tracking, showing the advantages in dynamic performance during bidirectional power reversal; Meikap et al. (2026) improved the cost function by adding a ripple term and reduced the peak-to-peak value of the inductor current by selecting the control set.

The discussion covers three associated problems. Concerning computation, according to TPS, the number of possible combinations increases cubicly with the discretization accuracy, and it is unfeasible to list all of them on inexpensive controllers within a period; two pruning techniques have been presented - adjustable control sets (Yeter et al., 2026), which modifies the set according to the error dynamics, and moving discretized control sets (Yin et al., 2025), selecting a subset close to the previous optimal solution - both give up global optimality for real-time operation, thus may lead to local optima at the start or under large disturbances. In respect of weight modification, the coefficients of the voltage and stress terms influence the equilibrium between steady-state and dynamic characteristics; because there is no theoretical basis, they must be altered through trial and error and updated online according to changing situations, therefore the objection is that this kind of adjustment is a technical skill rather than a design method. Regarding model inconsistency, the inductance, capacitance and transformer parameters vary with temperature and saturation, and the stepwise prediction errors accumulate during the rolling optimization process; Zhu et al. (2023) put forward an on-line parameter identification method, Deng et al. (2023) reconstruct the current from the voltages and the phase-shift angle without the use of a current sensor, and Ma et al. (2026) replace the physical model with a data-based one - all transform the model errors into measurable and correctable quantities, which increase the computational load and make it hard to adjust.

The distinction between predictive control and modulation becomes vague: the cost function includes voltage tracking together with current stress and ZVS, which integrates the objectives of modulation layer into the control layer.

Yang et al. (2020) used dynamic matrix control to make multi-step predictions on step-response models under current-stress constraints, indicating that the impulse-response based methods can also accomplish modulation optimization with less requirement for model accuracy compared to state-space prediction. The constraint-based formulations are more in accordance with engineering intuition than the weight-based ones, but the multi-step matrix calculations increase with the horizon and require separate real-time arrangements.

4.5 Other Directions

Backstepping control is mainly used for the construction of Lyapunov functions which ensure the large-signal stability; its stage-wise design, numerous parameters and high cost in debugging restricts the public reports, thus it can not be compared at present. The model-free and data-driven methods are the most promising research field in the last three years: the ultra-local models summarize the dynamic behavior into an unknown function and an input gain, which is estimated online by observers or historical data (Wang et al., 2026); the voltage-difference based model-free prediction constructs the predictor directly from the input-output differences (Yin et al., 2026); the neural-network based predictive synthesis leaves the selection of the candidate to an offline trained network (Wang et al., 2026); the data-driven power sharing in the parallel DABs (Liu et al., 2025) and the efficiency improvement from the loss models and operational data (Li et al., 2017; Xiao et al., 2024) apply the data methods to the system level.

They have a disadvantage in the validation scale. Usually, their prototypes include only one unit and some operating points; the precision and stability outside the sample set cannot be guaranteed and the stability criteria are also unknown. In contrast with the model-based prediction, these methods rely more on the data coverage than the model structure and have low efficiency in the operating range. Using such examples as sufficient evidence is appropriate; regarding them as an alternative is not suitable.

5 Conclusions and Outlook

Analysis of 27 papers shows the existence of three evidence levels. The consensus results which are confirmed by several independent studies show that the voltage-ratio mismatch is the main reason for the increase in backflow power; adding one inner-bridge degree of freedom reduces the backflow power and current stress at medium to high powers compared with the original condition; the predictive control provides better dynamic responses to load steps than the traditional PI double-loop control. Some doubts remain unsolved: whether the optimal steady-state of TPS can be reproduced under all working conditions, whether the super-twisting chattering suppression is effective in the digital implementation and whether the model-free methods give reliable predictions outside the given data sets. The majority of the reported numerical reductions in power loss and efficiency are from single studies without complete records of the operating conditions.

Four problems have been found. The solution of lightweight online TPS involves a compromise between accuracy and generality among piecewise analytical solutions, locally corrected lookup tables and learning-based mappings, without a uniform complexity evaluation or real-time comparison among different schemes. In the integrated steady-state-dynamic design, ZVS is considered as a restriction and the current stress is included in the cost function, while the weights and constraint limits are determined empirically without strict stability conditions. The deviations in wide-range ZVS performance between laboratory models and actual products are caused by dead-time effects, junction-capacitance nonlinearity and parasitics, and additional compensation techniques increase the difficulty of control. Moreover, the absence of standard verification standards makes it impossible to compare various schemes fairly, resulting in repeated research and a slow reaching of an agreement.

A multiple-stage solution is proposed. In the first stage, phase-shift modulation is employed to improve the reliability; in the second stage, multi-objective compromises are attained through simple prediction or learning models; in the third stage, observers are utilized to compensate for the changes in parameters and loads. It does not require global optimization for each cycle and ensures continuity when the operating point varies. We should concentrate on general evaluation criteria instead of designing new controllers, because the expected best results are effective only for particular test equipment under unstandardized conditions, evaluation processes and reporting systems.

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ISSN 3106-7018 (Print) ISSN 3106-5791 (Online)

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