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Systematic Review on Phase-Shift Optimization Strategies of Dual Active Bridge based DC-DC Converter

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Abstract

Bidirectional DC-DC converters (BDC) between high and low voltage buses are the most promising in latest research for their use cases in micro-grids. Specifically, the dual active bridge (DAB) topology of BDC has vast number of applications and its ability to transmit power in both directions makes it effective for utilities in consumer-prosumer setup. In recent years, a substantial amount of research has been conducted to eliminate one of the crucial drawbacks of DABs which is the mitigation of DC-Bias current resulting from practical limitations of switches. DC-Bias current is the leading cause of switch stress resulting in reduced converter reliability and efficiency. Numerous strategies have been devised to overcome this issue which includes methods like flux suppression, dynamic optimization, transient control, and piecewise linear transient phase shift optimization. In each of these categories several studies devised various techniques to increase operation efficiency, the dynamic response optimization (including model predictive controls and ANNs) can also be seen in recent research trends. This state-of-the-art systematic review is conducted on the recent developments in phase shift optimization techniques developed to increase the overall efficiency of isolated DABs. Considering it as a wide research discipline, the intervention criteria of searching the relevant primary studies is chosen to be strict. Some systematic reviews accommodate all the recent studies of this area, this review particularly is conducted to enhance the view only towards the phase shift-based optimization strategies and provide boarder insights of DAB optimization to researchers and engineers. It was seen that other than 3 basic phase shift techniques (SPS, DPS, TPS), studies with modified versions enhance the efficiency of DAB by mitigating the DB current.

Keywords: Dual active bridge; DC-DC converter; phase shift modulation; Bi-directional Convertor

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1. Introduction

Global energy demand is proliferating, and after the involvement of governments in climate concerns the research trends in this area have seen tremendous progress. Economic researchers are trying to decrease the reliance of productivity on carbon fuel and studying the aspects of making this transition to green energy seamless (Brockway et al., 2019; Khan et al., 2021). Engineers are extensively researching micro-grid systems and studying the efficiency of renewable energy devices (RED) to devise new strategies in making green energy less expensive and reliable. It included various electronic, power and communication structures, the feasibility of micro-grids, and the components required for the seamless power transmission and distribution (like inverters, converters, transformers, relays). The two-part review by Tomislav covers the power architecture requirements, applications, standardization issues and control techniques of modern micro-grid system (Dragičević et al., 2015a, 2015b).

Micro-grid is an advanced architecture combining renewable energy sources (RES) with traditional and modern grids in harmony. One of the requirements in completing the micro-grid architecture to efficiently support the applications like Electric Vehicles (EVs) (Butt et al., 2021) is the use of device named bidirectional DC-DC converter (BDC) between high and low voltage buses. BDCs take energy from both sides, convert it to the required voltage and transmit. So, they are specifically useful in scenarios where grid requires extra energy of consumer (intentional back-feeding) to utilize it in another place. Different topologies and control schemes of BDC exists in literature – the most recent review on this lists 16 topologies of isolated (8) and non-isolated (8) converters and also enlist and reviewed the control strategies (with their limitations) to mitigate the efficiency problems of BDC (Dahale et al., 2017; Gorji et al., 2019).

In the 1991 an advanced topology named dual active bridges (DAB) to better handle high frequency isolated BDC was proposed, and it gained extensive attention (De Doncker et al., 1991). Hitherto, no other topology has proven to be more effective than DABs in micro-grid systems, and thus it is the most common one (Gorji et al., 2019). DAB topology consists of eight switches combined to form two galvanically isolated bridges and with the features like high power density, flexible power regulation, fast dynamic response, zero voltage switching (ZVS) and wide soft switching range, it is one of the most recognized inventions (Bu et al., 2021; Zhao et al., 2015).

While being recognized as one of the promising topologies, DAB is not perfect. As an ideal device (in theory) its efficiency should be 100% but due to discrepancies in practical switches the switch stress and magnetic saturation of transformer core increases resulting in decreased efficiency and reliability. The inconsistencies of switches' gate driving voltage, terminal voltage pulse, dynamic phase shift adjustment increases the DC-Bias (DB) current which in excess leads switch stress. Existence of DB current is a practical issue because of the inconsistency between theory and practice (Zhao et al., 2015). For high frequency (HF) transformers, HFDB adds more problems making it difficult for transformer to attenuate the oscillations.

The DB current can be categorized into steady state and transient state, the suppression of former is possible with better hardware design and control chips (Yao et al., 2020), but the latter is more difficult to handle. When the converter starts, or the load changes abruptly or when power flow direction changes (dynamic changes), the unstable switches increase the transients in DC-Bias. To solve this problem various optimization techniques have been devised, including flux bias suppression (FBO), dynamic optimization (DO), straightforward transient control (STO) and piecewise linear transient phase shift optimization (PTPO). These categories are imitated from the review paper (Bu et al., 2021) which comprehensively created four categorizes of most prominent techniques in DC-Bias suppression. As DC-Bias suppression is one of the most important problems of DAB, so here a summary of these is provided:

Flux Bias Suppression: The FBO includes active and passive balancing methods in which DC bias is minimized by making hardware changings (like reducing transformer air gap, adding dc-blocking-capacitor) and by regulating the magnetic flux of core (saturation prevention) respectively.

Dynamic Optimization: DO includes various optimization techniques (machine learning, linear programming, heuristics algorithms) to minimize settling time and overshoot (improvement of dynamic response). Although it is stated in (Bu et al., 2021) that these strategies do not often mitigate the DB optimally due requirement of large number of high-sensitive closed-loop feedback model parameters. But by examining the latest studies trend on heuristics (cuckoo search (Sun et al., 2019), spider monkey (Lan et al., 2020)), machine learning (RL-ANN (Tang et al., 2021)) and use of other optimization algorithms also found with significant improvement.

Piecewise Linear Transient Phase Shift Optimization: Single phase shift (SPS) reduces transient and improves dynamic performance by adding a phase shift to a single switch, and similarly adding more degree of freedom (DOF) for phase control through extended (EPS), triple (TPS) and dual phase shift (DPS). Linearly regulating the inductor current IL in each switch cycle (piecewise). IL depends on voltage difference of load.

Straightforward Transient Control: Instead of regulating inductor current in piecewise linear fashion a simple linear regulation in some studies reduced settling time better and achieved better slope of IL.

A review from 2021 classify all the control strategies of DAB into six categories namely: pulse width modulation (PWM), proportional integral and derivative (PID), phase shift, sliding mode, fuzzy logic, model predictive (MPC), and artificial neural network (ANN) control (Ashfaq et al., 2021). For performance improvement the mitigation of DAB problems like DC-Bias, Current Stress, Dead band, and others an optimization technique belongs to some of this category is required. The systematic review conducted here summarize all the major studies using phase shift modulation (PSM) optimization technique (alone or in hybrid) to solve DAB problem. Techniques and novel strategies of 15 papers using PSM were reviewed systematically in this article. This paper is divided into 4 sections, (1) first the theory of phase shift techniques is covered, (2) then the search strategy of database searching is mentioned, finally after applying the inclusion and exclusion criteria following the PRISMA framework, (3) it is concluded with results, discussion and (4) conclusion section.

2. Phase Shift Modulation

Phase shift modulation has been used for DAB since it was first proposed in 1991, where the authors proposed three topologies with first two (A & B) using a single transformer, but phase shift is between two different switches, and the third (C) is with three-phase transformer (3 Φ DBA). The SPS with a single degree of freedom is studied in that paper, and compared to other prominent converters of that time a significant increase in performance is discovered. In 2008, DPS is introduced as a novel approach to reduce the reactive power and the system output capacitance by changing pulse width plus phase-shift control (changing the voltages duty ratio and simultaneously applying phase shifts to gate signal) (Bai & Mi, 2008). Resultantly it increases the system power capability to up-to 33% and adds improvements in system stability (settling time). Although the mitigation of inrush current compared to traditional methods (before 2008) was also observed, but with the charged primary dc-link capacitor the big inrush current should needed a peripheral control circuitry which is a hardware problem of steady state DB control. Reactive power is a general problem in isolated bridges as the current flow from primary to secondary depends on leakage inductance IL of transformer. There is always a current flowing in the transformer (even if output power P_o = 0 – because of 0 phase shift ratio), and IL participate in increasing the reactive power which results in unintended phase shift between primary and secondary switches and reduces the system efficiency. So, basically the idea of adding more DOF control through phase shifts is to mitigate the reactive power which leads to DC-Bias current. The unintended change in phase shift can also occur because of the inconsistencies in practical switches. So, the reactive power problem due to unintended phase shift is solved, the problem of practical switches will still persist (Bu & Wen, 2020).

With SPS and DPS there were still problems of high reactive power, and to optimize these EPS was introduced in (Zhao et al., 2011). In theory, DPS and EPS propose the same solution of modifying the old method of 50% duty ratio with a phase shift ratio between diagonal switches (achieving three levels of transformer primary voltage), the difference is in EPS the inner phase shift of one bridge is optimized with that of the other bridge, while in DPS the inner phase shift ratios of both bridges are equal. With the addition of one more degree of freedom and by making adjustment to time sequence between the driving signals of diagonal switches of each bridge, in comparison to traditional phase shift controls the difference in efficiency and switch stress was observed (same as in DPS). The addition of another phase shift (TPS) (Wu et al., 2011) theoretical prove the stability of DAB in every stage because the input and output signals in derived equations would remain bound during transients. TPS is the most stable structure among all, while in practice various hybrid models (cascading TPS and MPC) are used to better optimize the performance. Other than these renowned methods older methods (like double phase shift (Zhang & Ruan, 2005)) studying phase shift for converters also exists in literature, but due their less significance in latest research they were manually excluded from the search results. Also, PSM research is not only limited for DABs, results for other topologies of BDCs (total 16 (Dahale et al., 2017; Gorji et al., 2019)) can also be stiffed from digital research-databases.

3. Review Strategy

To filter out the most relevant results, IEEE Xplore is searched, and then filtered the journal papers from these results. The query includes the salient terms extracted from the research question and paper title, which includes results of DAB topology of BDC, which are optimized with only phase shift (alone or in hybrid) techniques. The query is made simple to not exclude the important results. The results were then exported to external flat file and did manual exclusion from 66 returned results (after 2008) by reading titles and abstract of each. The results section however may discuss these strategies of excluded studies, but these are not included in the main review. The prime reason to exclude most studies was their irrelevancy to the main research question (extracted from database mainly because they mentioned some theory of phase shift techniques). Some papers studied techniques other than optimization of PSM (like fault tracing) were also excluded.

Following (Torres-Carrión et al., 2018), PRISMA (Figure 1) flow chart is used to systematically extract information from database, inclusion and exclusion criteria were also systematically developed (and tracked in flow chart). In the end 15 studies were finalized for the review. The review results are not reproducible because of the velocity of new research, but still the same methodology can be followed to conduct a broad review in future.

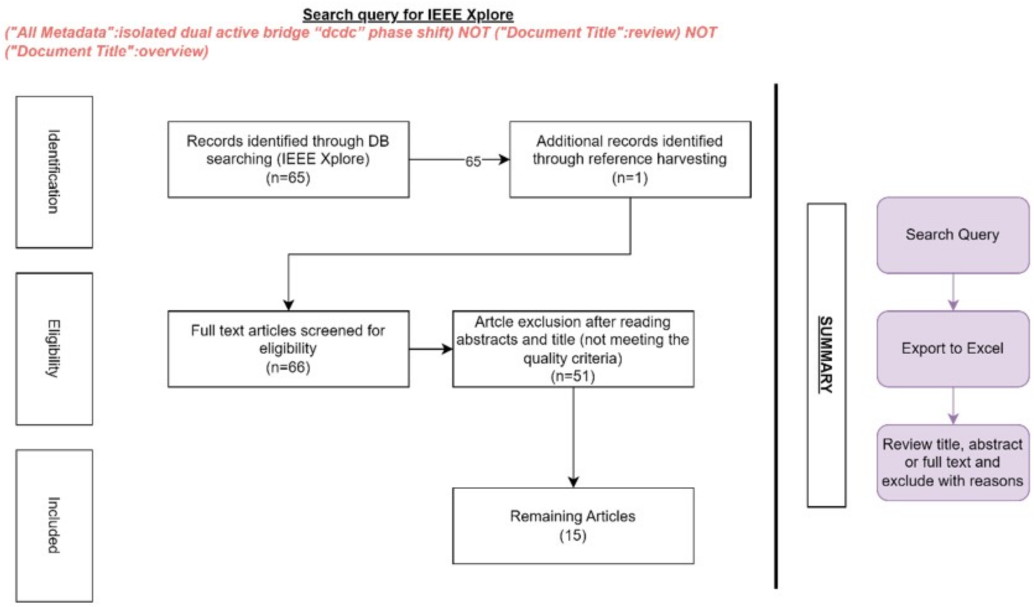

Fig. 1. Review Strategy to search using IEEE Explorer

4. Result & Discussion

The results are discussed chronologically, Table 1 though is sorted interpreting the relevance of paper with the research question. The index might be helpful to compare the text in this section with summary provided in Table 1. (1) The novel DPS strategy in (Bai & Mi, 2008), is an update research on isolated bridges to solve the problem of reactive power and efficiency by adding a DOF. The reasons of reactive power through previous studies are justified and based on the mathematical model, the dual phase shift is devised which theoretically reduced the reactive power and output capacitance. Compared to SPS the simulation of the impact the dc-link capacitor causing start up inrush current (overcharging) and dead band effect showed in increased performance of DAB with DPS. (2) TPS is introduced in (Wu et al., 2011) where authors proposed a mathematical solution of stability analysis and used Lyapunov function in every stage to determine the stability. Simulating all the solution states of complex variable non-linear systems is impossible, so as stated in paper, the mathematical model of stability is beneficial for better analysis. TPS is analysed in this paper for the first time, and the new mathematical solutions of stability provide better insights to behaviour of power converters under parameters changes. With this novel method of stability analysis, researchers theoretically show that TPS converters will remain stable at every stage of transition. The EPS in the same year is introduced as a phase-shift control scheme, and reduction in backflow current, efficiency improvement, and enhanced regulation and flexibility is proved mathematically and experimentally (Zhao et al., 2011). In extended phase shift the extra phase shift ratio either on primary or secondary side is proven to give better results as compared to traditional methods with 50% duty ratio for diagonal switches, and significantly increase system efficiency. (4) SPS as a strategy was introduced in 1991 paper DAB paper, in (van Hoek et al., 2013) an enhanced modulation strategy combining SPS, single phase triangular phase shift (STgPS) and single phase trapezoidal phase shift (STzPS) us used to increase the converter efficiency. The performances in this paper are compared only with SPS though MATLAB simulations, and substantial improvements in efficiency, filter cost and filter volume (for both single and 3ϕ transformer) were observed. (5) (Wen et al., 2014) show there are different operating cases of Extended DPS (EDPS), and by analysing the characteristics of conventional phase shift methods (before 2014) it is showed that ZVS is achievable by minimizing the non-active power loss (power loss due to backflow of current – useless power). The optimal phase-shift pairs of EDPS were determined by minimizing the non-active power loss. In a nutshell, the research used a phase shift strategy, model the non-active power loss and minimize it to obtain the optimal phase- shift pairs – it results in increased efficiency, achieved ZVS (with minimum non-active power loss), and experimentally verify the results on microcontroller calculating optimal points in real time. (6) Another optimization based strategy on TPS control is introduced (Huang et al., 2016), but unlike (Wen et al., 2014), achieving better modulation is carried out through current-stress minimization. The optimal control parameters were derived from a novel Karush–Kuhn–Tucker (KKT) conditions. (7) Liu et al. in (Liu et al., 2016) proposes modification of DPS stating the conventional DPS control exhibits large variations of current losses (on light load conditions). By setting the inner phase shifts (between legs of bridges) of both bridges in bidirectional direction and widening the operation region of outer phase shifts (between primary and secondary side), the decrement of transients and variations at light load conditions were observed. (8) The triple phase shift technique proposed in (Wu et al., 2011) is complicated to calculate, for better optimization the authors first simplify the calculation of TPS, and then use Lagrange multiplier to optimize TPS controlled DBA. The experiments show the peak efficiency of 98%. The majority of losses were due to RMS current (Tong et al., 2017).

(9) Through previous discussions, surges of DC-Link capacitors overcharging was a major problem and required external peripheral circuit, (Tian & Bai, 2018) proposes variable switching frequency (VFS) eliminate the need of power factor correction and thus the need of DC-Link capacitor. Furthermore, the paper uses novel single-dual phase shift control scheme with VFS (VFS-SDPS) and achieve ZVS both for light and heavy load and thus substantially improving the performance over wide region of operation. (10) (Wu et al., 2018) proposes a novel phase shift strategy modifying the traditional TPS. Some studies like (Bai & Mi, 2008), reduces the back-flow current, some like (Wu et al., 2011) introduced elimination of single side back-flow current. The main contribution of this study is the elimination of dual-side back flow current by introducing a novel cooperative TPS technique (CTPS). Using CTPS the optimal tuning region is then determined to reduce the current stress and increase the efficiency and stability of DAB.

(11) Another modification of TPS (improved TPS – ITPS) introduced in (Bu et al., 2019) to eliminate the DB current caused by magnetic saturation of isolated bridge transformer is proposed. To handle the complicated calculations of traditional TPS the minimum current stress oriented ITPS show better performance and reduce current. (12) Wei et al. presented a letter with novel deadbeat current controller. Current controllers are used as a separate circuit with DABs to provide overcurrent protection and elimination of DC current offset. The controller uses enhanced single-phase shift (ESPS) technique and achieves one-cycle settling time. (13) Zero-vector modulation (ZVM) is introduced in (Cúnico et al., 2020) to enhance the performance of 3ϕ DAB DC-DC converter. Although this is not a phase shift modulation but a significant difference between these two can be observed, and thus also included in this review. (14) The deterioration of dead band and transients is observed in CTPS (Wu et al., 2018), and to eliminate it a revised relationship between three-phase shifts is calculated for transients and phase shift

compensation is added for dead band. These two problems of CTPS control for DAB are solved for performance improvement in (Luo et al., 2020). (15) Finally, the recently introduced load current estimation (LCE)+SPS technique with delayed compensation improves and speeds-up the dynamic performance of DAB. Furthermore, the paper introduces performance setbacks, and resolves them – the damping coefficient is introduced to minimize the instability due to LCE. Improvements by analysing LCE with other modulation schemes (like ZVM) can be developed (Hou et al., 2021).

Table 1. Systematic Literature Review of 15 Papers (* is on First Proposals) [I] – Improvements, [P] – Problems/Limitations, [N] – Novel

Notes	Related PSM	Summary & Results
Novel PSM to increase system power performance up-to 30%	*DPS	[I] Reactive power ↓, voltage ripple ↓, Power capability (33%) ↑, output capacitance ↓, Inrush Current ↓, Deadband Influence ↓ [P] Complex to solve for variable phase shifts, because of 3D independent control surface of 2 phase shifts ($D_1 \wedge D_2$) [N] DPS strategy (variable phase shift) introduced
Improve Performance - Low Surge and Stable Power	DPS	[N] Modified DPS with bidirectional inner phase and outer phase with wide operation region [I] Stability with no compromise on efficiency ↑, Surge current ↓ [P] Voltage is restricted to 30V (light-load conditions)
Cooperative TPS (CTPS) - Improve Current Characteristics	TPS	[I] Current Stress ↓, Efficiency ↑, RMD ↑ [N] CTPS is proposed to eliminate dual-side flow back currents. [N] Optimize for the tuning region. [P] Increased DC-Bias current and deadband
Improve Performance - Transient Elimination	TPS	[N] Introduced less complicated version of TPS (ITPS) [I] No compromise on efficiency, Stability ↑, DC-Bias ↓
Improve Performance	TPS	[N] Use Lagrange multiplier to minimize the RMS current [N] Derive the analytical less complex mathematical model of TPS [I] Efficiency (min RMS current through optimization) ↑
Enhanced SPS - Improve Performance by adding a special DOF	SPS	[N] Peripheral current controller for DAB is proposed. [I] Dynamic performance (achieve 1-cycle settling time) ↑
Novel PSM increased stability	*TPS	[N] Lyapunov function of each stage of TPS [N] Novel method to analyze the stability of any engineering system. [I] TPS controlled converter stability ↑
Unified TPS (UTPS) - Minimize Current Stress and Achieved full soft switching	TPS	[N] Introduced KKT optimization algorithm. [I] Efficiency ↑ of DAB controlled with UTPS, ZVS achieved
Hybrid SPS with a new modulation scheme (zero-voltage) Paper didn't mention the specificity of PS but as the shift ratio is same and thus categorized in SPS	ZVS	[N] Introduced Zero-Voltage modulation. [I] Substantial increase in converter efficiency ↑
Novel Extended DPS is presented	DPS	[N] Propose EDPS, find optimal phase-shift points of EDPS and determine the reasons of not achieving the ZVS [I] Achieved ZVS (through optimization), system effectiveness ↑
Load current estimation with SPS for better dynamic performance	SPS	[N] Introduce LCE+SPS with delay compensation. [I] Speed-up the dynamic performance, efficiency ↑, stability ↑ [P] Research with other PSM and modulation schemes is needed
Hybrid SPS with STgPS & STzPS	SPS	[N] Introduced hybrid scheme combining TgPS, PS and TzPS [I] Efficiency ↑, transformer filter volume ↓ [P] No comparison with other modulation strategy
Variable Switching Frequency introduced to eradicate the need of DC-Link Capacitor for ZVS improvement	SPS, DPS	[N] Novel single-dual PSM technique [I] Achieved ZVS both for light and heavy load [I] Eliminate the need of DC-Link capacitor through VFS
Solved a problem of CTPS	TPS	[I] Dead band ↓, DC-Bias transients ↓
Novel PSM to reduce current stress and improve efficiency	*EPS	Same as DPS [N] Did stability analysis

5. Conclusion

Systematic literature review of 15 IEEE journal papers is conducted on the piecewise linear transient phase-shift optimization techniques of isolated dual active bridge DC-DC converter, to enhance the view on current research and development. Some studies use optimization techniques on objective function developed by investigating the cause of low efficiency/stability and after minimization of that function achieve better results. Studies with DC-Bias elimination and dead-band were also conducted. This review gives the surface idea of research progress in performance improvement of DBA and is organized systematically to facilitate reader. Other strategies to optimize the performance of DABs also exist (like dynamic control), and these were also selected if some relation with phase shift is linked to it.

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