

RESEARCH ARTICLE



Implementation of Single-Phase Shift (SPS) and Extended Phase Shift (EPS) for Dual Active Bridge (DAB)

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Abstract

Objectives: To improve power transfer and efficiency in Dual Active Bridge (DAB) converters, this study compares and assesses the Single-Phase Shift (SPS) and Extended Phase Shift (EPS) control techniques. **Methods:** Using the Dual Active Bridge (DAB) arrangement, the research focuses on implementing SPS and EPS control methods to an Isolated Bidirectional Full-Bridge DC-DC Converter (IBDC). A comprehensive review of the IBDC's operating modes and the EPS's control concept is included in this study. **Findings:** In comparison with EPS, SPS control is limited by a smaller operating range, higher power loss, and higher circulating current. Conversely, EPS exhibits benefits such as decreased back power flow, increased Zero Voltage Switching (ZVS) range, and decreased current stress. These conclusions are supported by the simulation results, which show that EPS control outperforms SPS in terms of operational stability, harmonics, and efficiency. Under the SPS control at different phase shift minimums, THD is 15.06%; whereas, for EPS it is 12.90%. **Novelty:** This study demonstrates how EPS outperforms SPS in DAB converters, providing better operational range, THD, and efficiency.

Keywords: Isolated Bidirectional Full-Bridge DC-DC Converters (IBDCs); Dual Active bridge (DAB); Single Phase Shift (SPS); Extended Phase Shift (EPS); Current Stress; Power Transmission

1 Introduction

Nowadays, DC-DC converters are playing a vital role in Distributed Generation Systems (DGS). Due to the increasing demand for Renewable Energy Sources (RES), many converters have been proposed by researchers for the integration of different generation sources. Proposed converters are of different types like ac-ac, ac-dc, dc-ac, dc-dc converters⁽¹⁾. For the power distribution among different generation sources and

Energy Storage System (ESS). Many Bi-Directional Converters (BDCs) have been proposed; which are interfaced between the generation system and Energy Storage System (ESS) as shown in Figure 1. It shows these BDCs are placed between high voltage buses i.e., different generation sources, and low voltage buses i.e., Energy Storage System (ESS) like batteries, supercapacitors or flywheels, etc.⁽²⁻⁴⁾

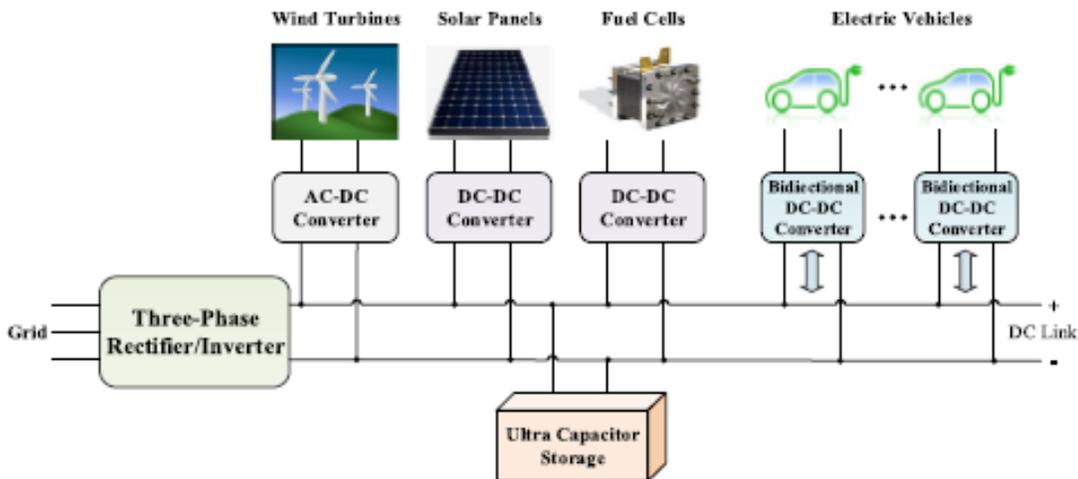


Fig 1. Application of IBDCs for different applications

These BDCs are classified as non-isolated and isolated type⁽⁵⁾. Non-isolated type dc-dc converter (NBDC) is provided with no galvanic isolation whereas Isolated type dc-dc converter (IBDC) is provided with galvanic isolation. This galvanic isolation for IBDC provides flexibility and different safety standards. IBDCs are advantageous due to their wider operating range, high voltage conversion ratio, etc. Among all BDCs, Dual Active Bridge (DAB) is most common which is used where power balancing is required. Two active bridges connected with a High-Frequency Transformer (HFT) and a series inductor (L) combine to form traditional DAB as shown in Figure 2^(6,7). Key features of DAB are galvanic isolation, high power density, wide ZVS range, high reliability, and bidirectional energy flow. V_p & V_s are equivalent voltage of bridges H_1 & H_2 respectively and L is leakage inductance^(8,9).

To control these DABs mainly two methods are used first is Traditional Pulse Width Modulation (PWM) method and other is phase-shift. Into traditional PWM control, diagonal switches of H-bridge (H_1) are turned ON to convert high voltage V_p from DC to AC into H-bridge (H_2) $Q_1 - Q_4$ are turned OFF but current conducts through $M_1 - M_4$ which converts voltage from AC to DC; this led to power transfer from V_p side to V_s side and for vice versa switches states are exchanged. Despite its easy and simple control approach its dynamic performance is poor also its operating range is limited these disadvantages are overcome by the phase shift control method; into phase shift control diagonal switches of bridge H_1 (S_1, S_4) and bridge H_2 ($Q_1 - Q_4$)⁽¹⁰⁾.

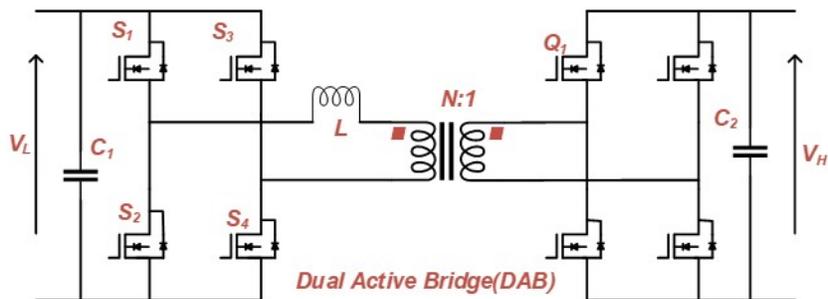


Fig 2. Conventional DAB

One of the popular control methods for the DABs is single-phase shift (SPS) control. For the SPS, the diagonal switch of bridges is phase shifted with a 50% duty cycle for both bridges of DAB. Voltage transfer and direction of power are controlled by varying the phase shift ratio between the bridge H_1 and H_2 i.e., V_p and V_s respectively. SPS has many advantages which include high dynamics, low inertia, and simplicity of application with effective output. The issue with SPS is, that it cannot work under zero voltage switching (ZVS) due to power flow control is dependent on the transformer’s leakage inductance. Also, large circulating power is produced when the transformer ratio is not unity which increases RMS and peak currents; due to this power loss increases, and overall efficiency is reduced. During power backflow for the SPS, it depends on the leakage inductance of the transformer but for the forward power flow it results in high circulating power. To eliminate the drawback of SPS new method Extended Phase Shift (EPS) is proposed. Into EPS one more degree of freedom is added by introducing a phase shift provided between the bridges i.e., H_1 & H_2 . It is advantageous over SPS due to many reasons like smaller circulating power, reduced current stress, improved ZVS & transmission power range, and backflow power (BFP). The paper is organized as follows: DAB is discussed in Section I and the SPS control and EPS control and their implementation are discussed in Section 2. The results and comparative approach are elaborated in section 3. Finally, the conclusion of the study is expressed in section 4.

2 Methodology

2.1 Single Phase Shift (SPS)

For the Single Phase Shift, switches are selected at 50% of the duty cycle and phase shifted diagonally i.e., (S_1, S_4 , or $Q_1 - Q_4$). The primary bridge (H_1) & secondary voltage (H_2) output voltages are V_p and V_s respectively. These voltage waveforms are of two levels. This phase shift also decides different parameters like energy transfer, power flow control, and ZVS range. For sustained ZVS under wide input voltage duty cycle needs to be adjusted of DAB which may lead to higher ripples in current^{(11) (12) (13) (14)}. Power transmitted under SPS control is expressed as:

$$P = \frac{V_p V_s}{2\pi f_{sw} L} \sin(\delta) \tag{a}$$

where

- V_p is the output rms voltage of the primary bridge (H_1)
- V_s is the output rms voltage of secondary voltage (H_2)
- L is inductance
- f_{sw} is switching frequency
- δ is phase shift.

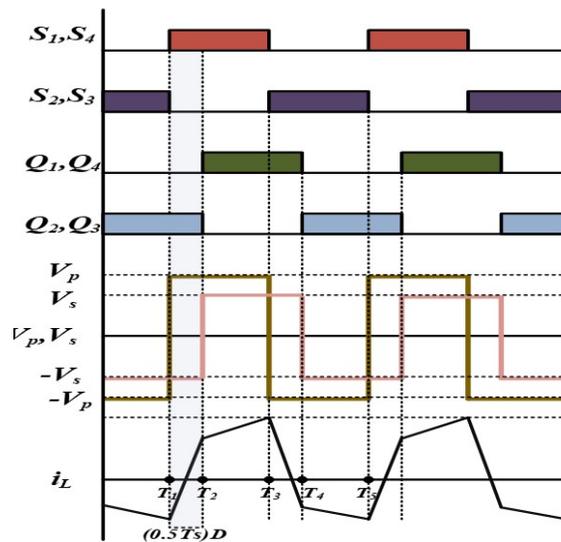


Fig 3. Switching pattern under SPS of different switches, V_p , V_s & i_L

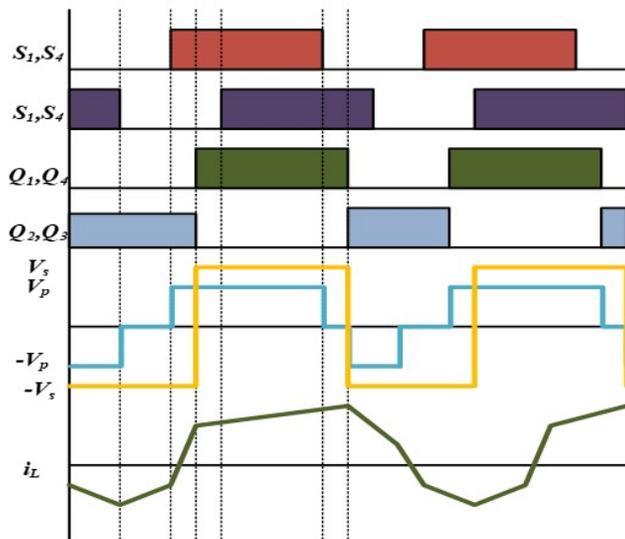


Fig 4. Switching pattern under EPS of different switches, V_p , V_s & i_L

Figure 3 shows the switching pattern of different switches i.e. (S_1, S_4, Q_1, Q_4), voltage of bridge H_1 & H_2 , and inductor current (i_L).

2.2 Extended Phase Shift (EPS)

EPS modulation provides a wider ZVS range at a medium power level, less back power flow, and less current stress^(15,16). At normal power levels, SPS performs better than EPS for a wider voltage range for DAB. Switching under EPS control is provided between the diagonal switches of bridges i.e., (S_1, S_4 or Q_1, Q_4) named as inner phase shift (δ_{in}), and another phase shift is provided between both bridges i.e., V_p & V_s named as outer phase shift (δ_{out})⁽¹⁷⁾⁽¹⁸⁾⁽¹⁹⁾. As a result of the provided phase shift V_p & V_s are three level voltage as shown in Figure 4. Power under EPS control is expressed as:

$$P_{EPS} = \frac{nV_s V_p}{4L f_{sw}} [\delta_{in} (1 - \delta_{in} - 2\delta) + 2\delta (1 - \delta)] \tag{b}$$

where

- V_p is the output rms voltage of the primary bridge (H_1)
- V_s is the output rms voltage of secondary voltage (H_2)
- L is inductance
- f_{sw} is switching frequency
- δ_{in} is the inner phase shift.

2.3 Implementation of Single Phase Shift (SPS)

Figure 5 shows the switching and output waveform of the Dual Active Bridge (DAB) under Single Phase Shift (SPS).

Table 1. Simulation parameter for the Dual Active Bridge (DAB) under SPS & EPS

Parameter	Unit
Bridge Voltage (H_1)	24V
Bridge Voltage (H_2)	120V
Inductance	0.2mH
Turns Ratio	5
Switching Frequency	10kHz

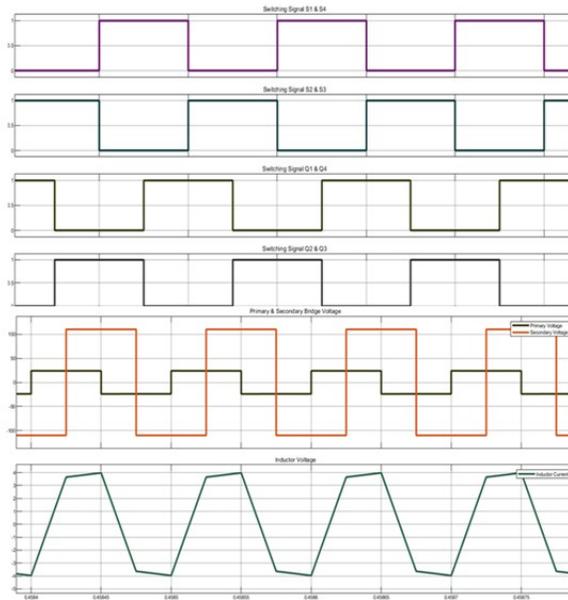


Fig 5. Switching pattern and output waveform of V_p , V_s & i_L under SPS

2.4 Implementation of Extended Phase Shift (EPS)

Figure 6 shows the switching and output waveform of the Dual Active Bridge (DAB) under Extended Phase Shift (EPS).

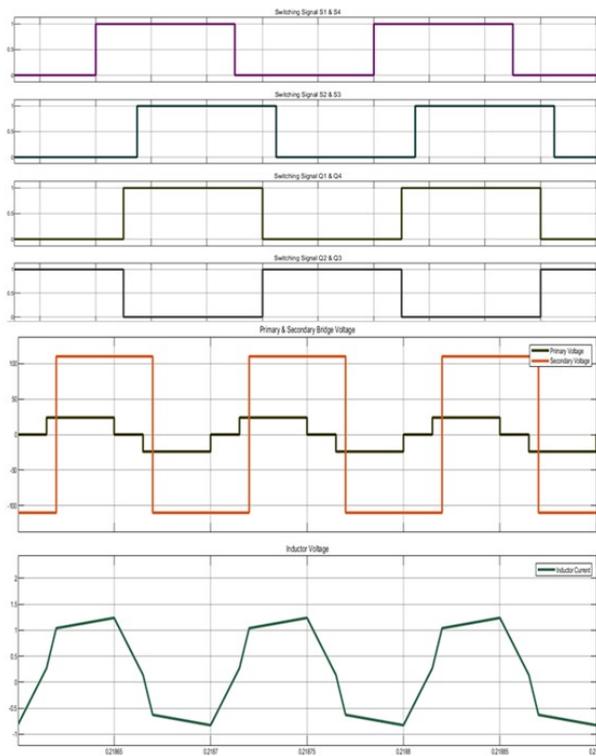


Fig 6. Switching pattern and output waveform of V_p , V_s & i_L under EPS

3 Results & Discussion

3.1 Comparison of Single-Phase Shift (SPS) & Extended Phase Shift (EPS)

shows the comparison of Harmonics under both phase shift methods i.e., Single Phase Shift (SPS) & Extended Phase Shift (EPS). For the comparison of Total Harmonics Distortion (THD) keeping the outer phase shift (δ_{out}) fixed and varying inner phase shift at different values⁽¹⁹⁾. From Table 2, it can be observed that the harmonics of a Dual Active Bridge (DAB) under Single Phase Shift (SPS) is greater when it is compared under the operation of Extended Phase Shift (EPS) whereas Figures 7 and 8 shows the plot of range of power transmission and efficiency of system with respect to the outer phase shift; for the analysis keeping 0.5 as fixed inner phase shift value and varying outer phase shift. From the plot, it can be analyzed that maximum power is transferred when the phase shift is equivalent to the value of 0.5 for both inner and outer phase shifts.

Table 2. Effect of SPS & EPS at different d

d	THD under SPS ⁽¹¹⁾	THD under EPS
0.1	15.38%	13.63%
0.2	15.78%	13.22%
0.3	15.06%	13.96%
0.4	15.91%	13.62%
0.5	15.38%	13.09%
0.6	15.45%	13.55%
0.7	15.78%	13.28%
0.8	15.93%	13.07%
0.9	15.94%	13.06%
1	15.10%	12.90%

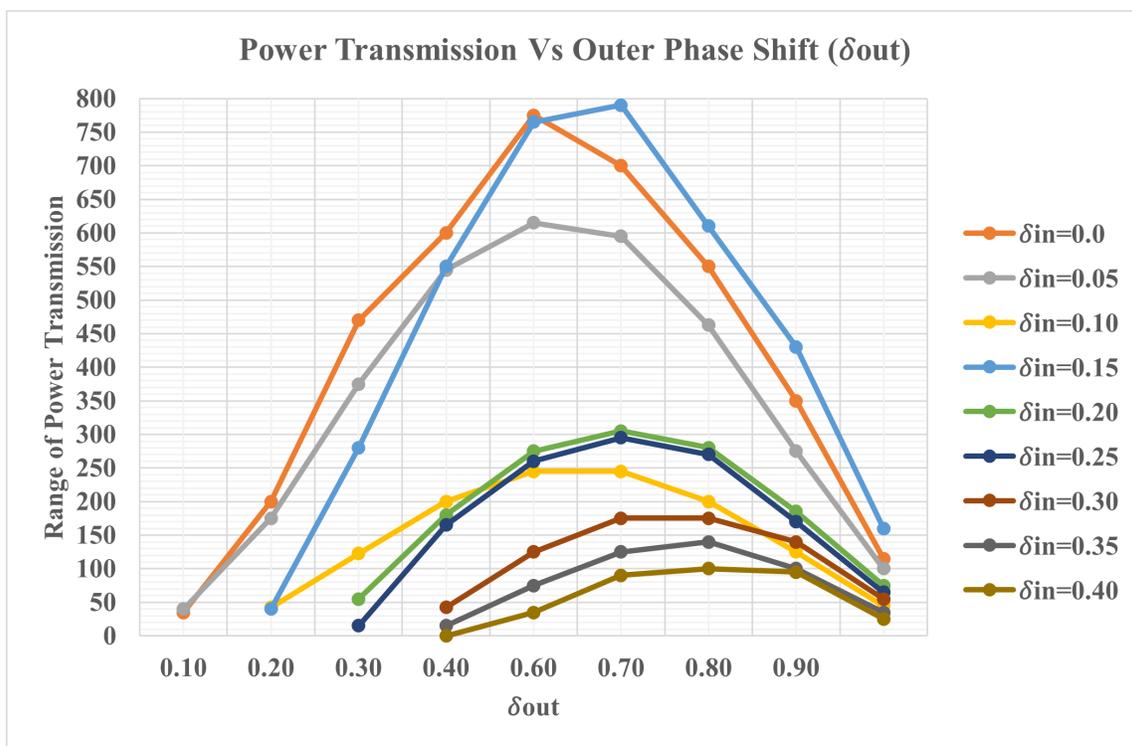


Fig 7. Variation of power transmission w.r.t (δ_{in}) & (δ_{out})

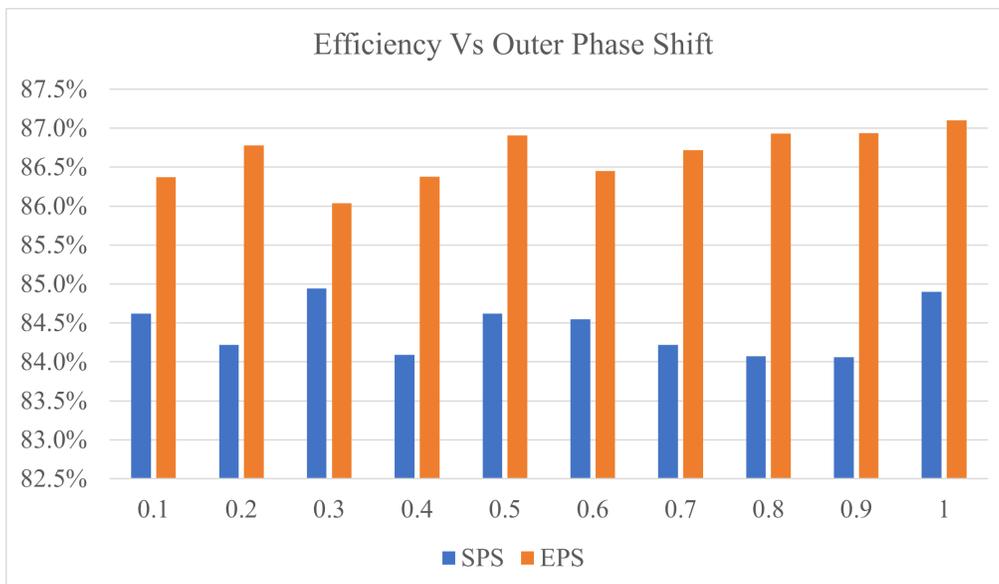


Fig 8. Variation of efficiency w.r.t (δ_{out})

4 Conclusion

DAB is one of the important converters to achieving power flow between the energy generation systems and Energy Storage Systems (ESS). In this study, EPS control is implemented for the controlling of power distribution to overcome fundamental drawbacks of SPS control of IBDC. Into SPS for different phase shifts minimum THD is 15.06% while compared with EPS it is 12.90%. Also, the following characteristics of EPS control methods are determined through analysis:

1. EPS improves and expands the range of power transmission and improves its flexibility as well.
2. By reducing circulating power, EPS minimizes conduction losses & improves system efficiency.
3. By implementing EPS overall reduction in switching losses & current stress.
4. EPS control is simple to understand and easy to implement.

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