Comparative Study of Dual Active Bridge Isolated DC to DC Converter With Single Phase Shift And Dual Phase Shift Control Techniques

Bhimisetty Manoj Kumar[1], Anupam Kumar[2], Dr. A.H.Bhat[3], Dr.Pramod Agarwal[4]
[1]M.tech Scholar, [2]Ph.D Scholar, [3]Associate Professor, [4]Professor
[1,2,3]NIT Srinagar, [4]IIT Roorkee
[1]kumarmanoj220@gmail.com, [2]kanupam310@gmail.com, [3]bhatdee@nitsri.net, [4]pramgfee@iitr.ac.in

Abstract— **Increased demand of battery energy storage systems, has increased the need of bidirectional DC-DC converters with galvanic isolation. For high power density, compact size, less weight and low cost, Power Conversion Systems with High Frequency tie connection are most likely be preferable. Dual Active Bridge (DAB) Isolated Bidirectional DC-DC converter (IBDC) is the core circuit of High Frequency Power Conversion Systems. Most common topology of dual active bridge converter has two full bridge converters connected through a high frequency transformer. Bi-directional power flow capability, high power density, high efficiency, innate soft switching, low number of passive components and galvanic isolation are some attributes of DAB attracting industry. This paper discusses the application of Dual Active Bridge (DAB) Isolated Bi-directional DC-DC (IBDC) converter in Uninterrupted Power Supplies (UPS), also compares the Dual Phase Shift (DPS) control with the Single Phase Shift (SPS) control in parameters like voltage, current and VA stress, and inductor peak current. The MATLAB & SIMULINK simulation results for both charging and discharging mode are shown for closed loop control of the two control strategies viz., SPS and DPS control using PI controller by varying the load in two steps.**

Keywords— **Dual active bridge converter, bi-directional power flow, Single Phase Shift (SPS), Dual Phase Shift (DPS), closed loop control, PI controller, switch stress, inductor peak current, UPS.**

I. INTRODUCTION

Because, of the high performance of Dual Active Bridge DC-DC converter it has become more popular from the last decade of the 20th century. To maintain the voltage at the dc buses i.e., voltage boost and buck operations, power flow from dc voltage bus to the energy storage element and vice-versa DABs have become very widespread at power electronics and industrial applications such as, DC-Micro Grid [1], Hybrid Electric vehicles [2] industry, Aero space energy storage system [3], uninterrupted power supplies (UPS) [4] and many power applications which require an intermediate energy storage system. Fig: 1 shows the application of Dual active bridge converter in uninterrupted power supplies (UPS). In UPS application to charge and discharge the low voltage battery from and to high voltage DC bus DAB is used as interface.

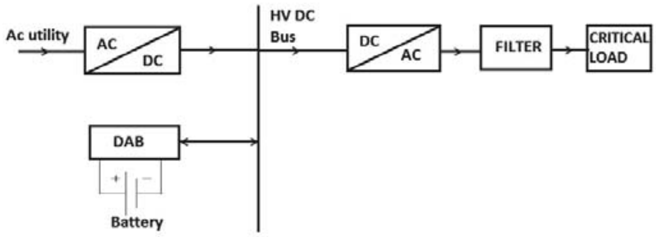

Fig: 1 Isolated Bi-directional DAB DC-DC converter in UPS

In SPS control strategy [5], phase shift is maintained between the primary voltage and the secondary voltage of the high frequency transformer, such that power flow direction can be controlled. Performance and steady state operation, closed loop control, inductor selection [6], ZVS [7] operation for conventional control strategy i.e., SPS has been discussed by researchers. DPS control strategy [8] has two degrees of control i.e., equal inner phase shift between the cross connected switches of both the bridges and outer phase shift between the primary and secondary voltage of the high frequency transformer. Various control strategies of DAB with high frequency link power conversion systems [10] are discussed in literature

In this paper, circuit operation, design, and comparison of switch stress, inductor peak current and closed loop operation[9] for step load variation are discussed. Two control strategies viz., single phase shift and dual phase shift, are compared and respective waveforms are shown. By extensive simulation studies in MATLAB & SIMULINK, the above control strategies are tested and results are obtained.

II. System Modeling and Description

The circuit topology of single phase dual active bridge dc-dc converter is shown in Fig:2, the switches in the primary bridge (H1) are represented as S1 and S2 in one leg, D1 and D2 are their respective anti-parallel diodes, in the same way S3 and S4 are the switches in the second leg, D3 and D4 are their respective anti-parallel diodes. Similarly, the switches in the secondary bridge (H2) are represented as Q1 and Q2 in one leg, M1 and M2 are their respective anti-parallel diodes, in the same way Q3 and Q4 are the switches in the second leg, M3 and M4 are their respective anti-parallel diodes. As shown in the fig it consists of two full bridge converters connected through a high frequency transformer. Inductor (L) represents the primary side leakage inductance and the secondary leakage inductor referred to the primary side.

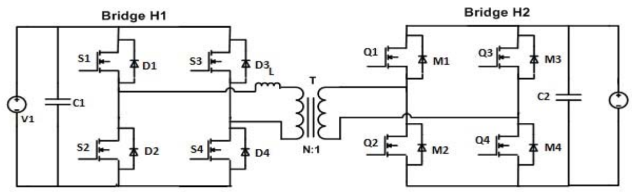

Fig: 2 Schematic diagram of single phase dual active bridge converter

The switches are controlled by control pulses of 50% duty ratio. High frequency square wave voltages are available at the terminals across the HF transformer; power flow direction is from the leading voltage side to the lagging voltage side of the transformer, such power flow direction is controlled by controlling the phase shift.

1. a Single Phase Shift (SPS)

The waveform for single phase shift control is shown in Fig:3 for charging mode.

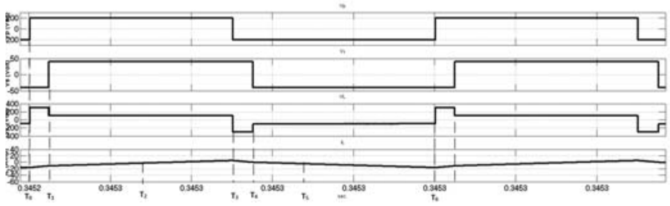

Fig: 3(a) Primary voltage (b) secondary voltage (c) inductor voltage (d) Inductor current for charging mode of SPS control.

Similarly the waveforms can be seen in Fig: 4 for discharging mode.

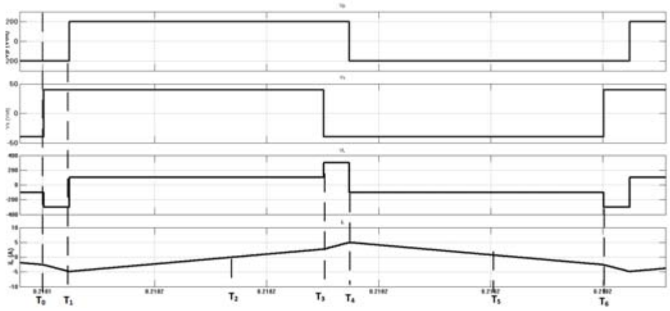

Fig: 4(a) Primary voltage (b) Secondary voltage (c) Inductor voltage (d) Inductor current for discharging mode for SPS control.

The conduction table showing conduction of various devices in charging as well as discharging mode is shown in table I (a) and table I (b).

Table I (a)

Conduction table for charging mode of SPS control

Time Interval	Conducting devices in Primary Bridge	Conducting devices in Secondary Bridge
T_0-T_1	D1 & D4	M2 & M3
T_1-T_2	D1 & D4	Q1 & Q4
T_2-T_3	S1 & S4	M1 & M4
T_3-T_4	D2 & D3	M1 & M4
T_4-T_5	D2 & D3	Q2 & Q3
T_5-T_6	S2 & S3	M2 & M3

Table I (b)

Conduction table for discharging mode of SPS control

Time Interval	Conducting devices in Primary Bridge	Conducting devices in Secondary Bridge
T_0-T_1	S2 & S3	Q1 & Q4
T_1-T_2	D1 & D4	Q1 & Q4
T_2-T_3	S1 & S4	M1 & M4
T_3-T_4	S1 & S4	Q2 & Q3
T_4-T_5	D2 & D3	Q2 & Q3
T_5-T_6	S2 & S3	M2 & M3

Furthermore, the waveforms of the primary voltage & secondary voltage across the high frequency transformer, inductor current, sending end current and receiving end current are shown in Fig:5 and Fig:6 for charging as well as discharging mode respectively. In charging mode, the negative input current shows that current is being taken out of primary side source, while positive output current shows that current is being dumped into the secondary side source. While in discharging mode the positive input current shows that current is being dumped in primary side source and negative output current shows that current is being taken out from the secondary side source.

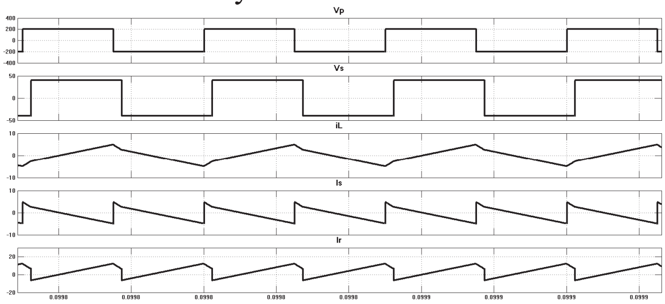

Fig: 5(a) primary voltage, (b) secondary voltage, (c) inductor current, (d) Sending end current, (e) receiving end current for charging mode.

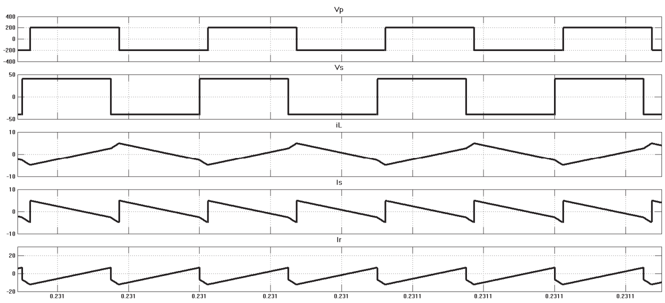

Fig: 6(a) primary voltage, (b) secondary voltage, (c) inductor current, (d) Sending end current,(e) receiving end current for discharging mode.

b. Dual Phase Shift (DPS)

Unlike SPS control, we maintain two phase shifts in DPS control along with outer phase shift (D2) between primary and secondary voltages we also provide equal inner phase shift (D1) between cross switches of a bridge in both H-bridges. Each phase shift should be less than the half switching period as well as sum of the phase shifts should be less than the half switching period. The voltage wave forms across the primary and secondary sides of the HF transformer are three level waveforms with equal inner phase shift. The waveforms for DPS technique in charging and discharging mode are shown in Fig: 7 and Fig: 8.

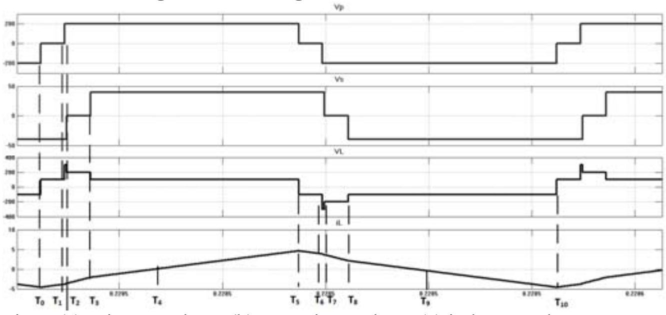

Fig: 7 (a) Primary voltage (b) secondary voltage (c) inductor voltage (d) inductor current for charging mode.

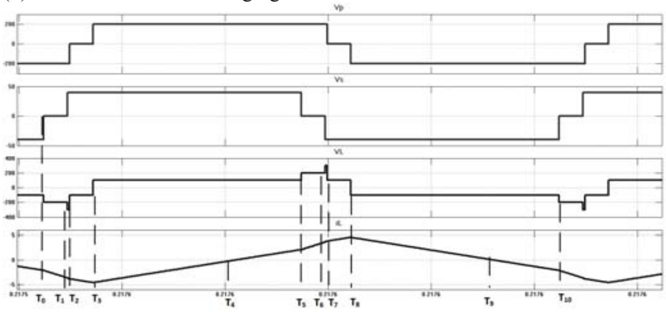

Fig: 8 (a) Primary voltage (b) secondary voltage (c) inductor voltage (d) inductor current for discharging mode.

The conduction table showing conduction of various devices in charging as well as discharging mode is shown in table II (a) and table II (b).These tables are obtained from Fig:7 and Fig:8.

Table II (a)

Conduction table for charging mode of DPS control

Time Interval	Conducting devices in Primary Bridge	Conducting devices in Secondary Bridge
T_0-T_1	S2 & D4	M2 & M3
T_1-T_2	D1 & D4	M2 & M3
T_2-T_3	D1 & D4	M2 & Q4
T_3-T_4	D1 & D4	Q1 & Q4
T_4-T_5	S1 & S4	M1 & M4
T_5-T_6	S1 & D3	M1 & M4
T_6-T_7	D2 & D3	M1 & M4
T_7-T_8	D2 & D3	M1 & Q3
T_8-T_9	D2 & D3	Q2 & Q3
T_9-T_{10}	S2 & S3	M2 & M3

Table II (b)

Conduction table for discharging mode of DPS control

Time Interval	Conducting devices in Primary Bridge	Conducting devices in Secondary

		Bridge
T_0-T_1	S2 & S3	M2 & Q4
T_1-T_2	S2 & S3	Q1 & Q4
T_2-T_3	S2 & D4	Q1 & Q4
T_3-T_4	D1 & D4	Q1 & Q4
T_4-T_5	S1 & S4	M1 & M4
T_5-T_6	S1 & S4	M1 &Q3
T_6-T_7	S1 & S4	Q2 & Q3
T_7-T_8	S1 & D3	Q2 & Q3
T_8-T_9	D2 & D3	Q2 & Q3
T_9-T_{10}	S2 & S3	M2 & M3

Furthermore, the waveforms of the primary voltage & secondary voltage across the high frequency transformer, inductor current, sending end current and receiving end current are shown in Fig: 9 and Fig: 10 for charging as well as discharging mode respectively.

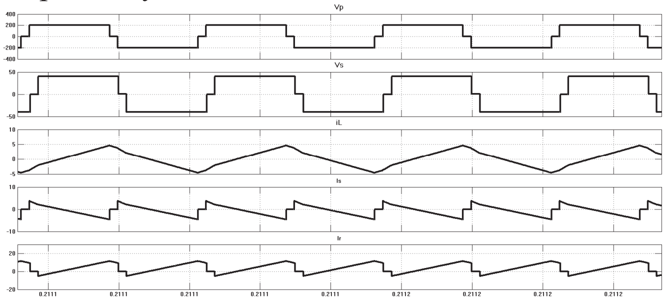

Fig: 9(a) primary voltage, (b) secondary voltage, (c) inductor current, (d)sending end current, (e) Receiving end current for charging mode.

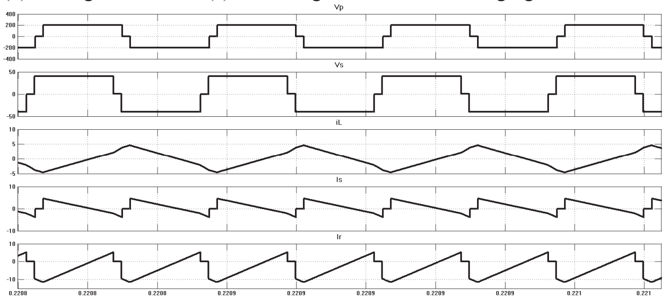

Fig: 10(a) primary voltage, (b) secondary voltage, (c) inductor current, (d)sending end current, (e) Receiving end current for discharging mode.

III. CONTROL ALGORITHM

The power flow equations for both the control strategies in terms of phase shift (D) in case of SPS control; inner phase shift (D1) and outer phase shift (D2) in case of DPS control are shown:

In SPS control the power flow equation is given by

$$P = \frac{NV1V2}{2 * fsw * L} D(1 - D) \qquad (1)$$

Where,

V_1 =Primary side voltage

V_2 =Secondary side voltage

N =Transformation ratio of isolation transformer

D = Outer phase shift between the two bridges

f_{sw} =Switching frequency

L = Leakage inductance of primary plus referred value of secondary leakage inductance on primary side.

$$C1= (\Delta I_L T_{sw})/8\Delta V_o \qquad (2)$$

C1 =Input side capacitor value

ΔI_L=Peak to Peak ripple in inductor current

T_{sw}=Total time period= $(1/f_{sw})$

ΔV_o= Peak to Peak ripple in output voltage

$$C2 =(I_o D\, T_{sw})/ \Delta V_o \qquad (3)$$

C2 =Output side capacitor value

I_o =Output current value

ΔV_o= Peak to Peak ripple in output voltage

In DPS control the power flow equation is given for different modes, one of the modes is $0<D_1<D_2<1$

$$P = \frac{NV1V2}{2 * fsw * L}\left[D2(1 - D2) - \frac{D1^{\wedge}2}{2}\right] \qquad (4)$$

Where,

V_1 =Primary side voltage

V_2 =Secondary side voltage

N = Transformation ratio of isolation transformer.

D_1=Inner phase shift in primary and secondary bridges

D_2=Outer phase shift between primary bridge voltage and secondary bridge voltage

f_{sw} =Switching frequency

L =Leakage inductance of primary plus secondary leakage inductance referred to primary side.

The controller schematic diagram is shown below for closed control operation,

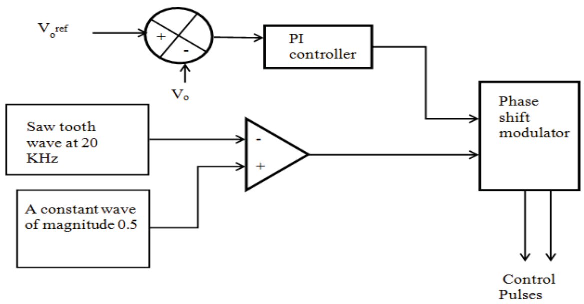

Fig: 11 closed loop controller of dual active bridge converter.

As shown in above Fig: 11, in closed loop control of dual active bridge converter, initially the output voltage is compared with the required reference voltage and the error is feed to the PI controller. Pulses are generated by comparing a high switching frequency saw tooth waveform with a constant magnitude signal. Both the pulses and PI controller output are given to the phase shift modulator to generate gating pulses for the converter. This closed loop controller is used for both control techniques only difference is the various phase shifting done through phase shift modulator.

IV.SIMULATION STUDIES

The dual active bridge converter is simulated using MATLAB/SIMULINK and SimPowerSystem software. The system parameters are specified in table III.

Table III
Systems parameters

	SPS	DPS
V_{in}(Input voltage)	200V	200V
V_{out}(Output voltage)	40V	40V
C1(Input capacitor)	100μF	100μF
C2(Output capacitor)	3000 μF	3000 μF
L(Leakage inductor)	130 μH	130 μH
N(Tranformer ratio)	200:80	200:80
Rout(load resistance)	10Ω to 5Ω	10Ω to 5Ω

SPS

A variable load that varies at .1sec which varies from 4 Amps to 8Amps, whose simulation result load voltage and load current are shown in Fig: 12; in which output voltage is maintained constant at 40V irrespective to the load variation. Also the switch stress is shown in table IV along with efficiency. Waveform for primary voltage, secondary voltage, inductor voltage, inductor current, input side current and output side current are shown earlier.

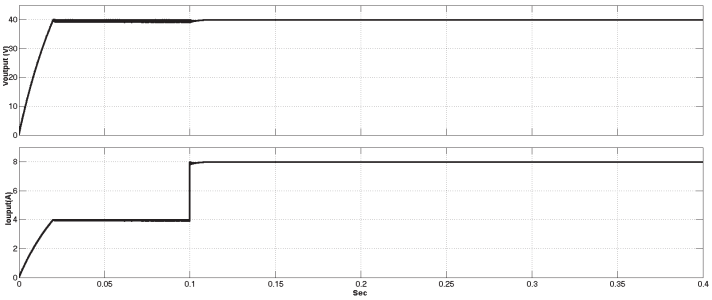

Fig: 12 Load voltage (V) and load current(Amp) vs time(sec) for SPS

Table IV
Performance of DAB using SPS

Switch stress(primary side switch)	556.6VA
Switch stress(secondary side switch)	264.1VA
Inductor peak to peak current	22.1A

DPS

A variable load that varies at .1sec which varies from 4 Amps to 8Amps, whose simulation result load voltage and load current are shown in Fig: 13; in which output voltage is maintained constant at 40V irrespective to the load variation. Also the switch stress is shown in table V along with efficiency. Waveform for primary voltage, secondary voltage, inductor voltage, inductor current, input side current and output side current are shown earlier.

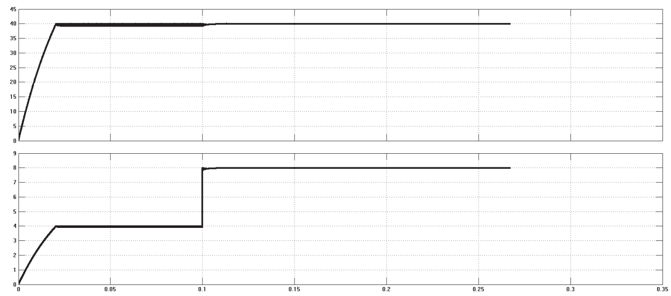

Fig: 13 Load voltage (V) and load current (Amp) vs time(sec) for DPS

Table V
Performance of DAB using DPS

Switch stress(primary side switch)	534.1VA
Switch stress(secondary side switch)	314.5VA
Inductor peak to peak current	19.5A

CONCLUSION

On observation of simulation results for the SPS control and DPS control of the DAB, it is observed that in DPS control switch stress is lower than that of SPS control in the primary side for same power transfer capacity. Even the inductor peak to peak current is less in DPS control than that of SPS control which reduces the transformer and inductor losses. In closed loop operation for both control strategies the output voltage is maintained constant irrespective of the load variation.

REFERENCES

[1] Biao Zhao, Qingguang Yu and Weixin Sun, "Extended-Phase-Shift Control of Isolated Bidirectional DC–DC Converter for Power Distribution in Micro grid", IEEE Transactions on Power Electronics, Vol. 27, No. 11, November 2012.

[2] Sangtaek Han and Deepak Divan, "Bi-Directional DC-DC Converters for Plug-in Hybrid Electric Vehicle (PHEV) Applications", IEEE Transactions, 2008.

[3] R.T.Naayagi, A.J.Forsyth and R.Shuttleworth, "Performance Analysis of Extended Phase-Shift Control of DAB DC-DC Converter for Aerospace Energy Storage System", IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), 2015.

[4] Narasimharaju B. L, Venkata Prahlad V, Ramanjaneya Reddy U, Vijay Babu K and P. Srinivasan, "Optimized Dual Active Bridge Bi-Directional DC-DC Converter for UPS Application", IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), 2014.

[5] R.T.Naayagi, N.E.Mastorakis, "Performance Verification of Dual Active Bridge DC-DC Converter", Recent Researches in Applications of Electrical and Computer Engineering.

[6] Xintao Guo, Jiuchun Jiang, Liyong Niu, Jingxin Li and Yanqing Qu, "A 10kW DC-DC System Based on a Bidirectional High-Frequency Isolated Dual Active Bridge DC-DC Topology", IEEE Transactions, 2011.

[7] R.T.Naayagi, A.J.Forsyth and R.Shuttleworth, "Performance Analysis of DAB DC-DC Converter under Zero Voltage Switching", IEEE 1st International Conference on Electrical Energy Systems, 2011.

[8] Myoungho Kim, Martin Rosekeit, Seung-Ki Sul and Rik W. A. A. De Doncker, "A Dual-Phase-Shift Control Strategy for Dual Active-Bridge DC-DC Converter in Wide Voltage Range", 8th International Conference on Power Electronics - ECCE Asia.

[9] H.Qin,.J.W.Kimball,"Closed-Loop Control of DC–DC Dual-Active-Bridge Converters Driving Single-Phase Inverters", IEEE transactions on power electronics, vol. 29, no. 2, February,2014.

[10] Biao Zhao, Qiang Song, Wenhua Liu and Yandong Sun, "Overview of Dual-Active-Bridge Isolated Bidirectional DC–DC Converter for High-Frequency-Link Power-Conversion System", IEEE Transactions on Power Electronics, Vol. 29, No. 8, August 2014.