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Modelling and Simulation of Dual Active Bridge Converter Using MATLAB/Simulink

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Abstract: Conventional DC–DC converters have been widely used in power electronic systems, but their limitations such as lack of galvanic isolation, reduced efficiency at higher power levels, and restricted bidirectional power flow have driven the need for more advanced converter topologies. To address these challenges, the Dual Active Bridge (DAB) converter which is a DC-AC-DC converter has emerged as an effective solution due to its high efficiency, inherent isolation, and flexible control of power transfer. This paper presents the modeling and simulation of a DAB converter using MATLAB. The performance of the system is analyzed under different phase-shift conditions to evaluate power transfer characteristics and Total Harmonic Distortion (THD). Phase-shift modulation is employed to regulate both the direction and magnitude of power flow between two DC sources. Simulation results indicate that the harmonic distortion present in the inductor current waveform decreases with an increase in phase-shift angle up to a optimal point , resulting in improved waveform quality and enhanced converter performance and beyond that optimal point harmonic distortion slightly increases. The study demonstrates that the DAB converter is a reliable and efficient solution for modern power electronic applications, particularly in energy storage systems and bidirectional power conversion.

Keywords: Dual Active Bridge (DAB), Bidirectional Converter, Phase Shift Modulation, Total Harmonic Distortion (THD), MATLAB/Simulink.

I. INTRODUCTION

As renewable power sources including solar and wind gains deeper penetration, and energy storage systems rapidly evolve, current-day power systems are becoming more flexible and efficient in their design. These innovations demand power electronics converters that can produce and consume a bidirectional power flow in an efficient and reliable manner. Under these conditions converters have to be efficient in different load conditions and ensure stable operation and reduce losses [1], [7].

Although traditional DC to DC converters are extensively applied in various applications, they have a number of limitations. They are the lack of galvanic isolation, low efficiency at high power levels, and less flexibility in control. Moreover, non-modular converter topologies are usually based on hard-switching methods, which add switching losses and decrease the total efficiency. These limitations render them less adapted to the modern applications like energy storage systems and electric vehicles, in which it is necessary to have an efficient and bidirectional power transfer [2], [8].

To address these shortcomings, higher converter topologies have been designed of which the Dual Active Bridge (DAB) converter has been found to be one of the best solutions. The DAB converter is a two-way full-bridge circuit with two active circuits linked together with a high-frequency transformer, which allows the transfer of power in both directions and electrical isolation. This is because a high-frequency transformer would be used not only to guarantee safety but also to enable the reduction of the size of the magnetic components and hence a more compact system design will be provided [3], [9].

The DAB converter has some notable benefits that could make it useful in current power electronic systems. It facilitates effective bidirectional flow of power especially in the areas where the power is needed like battery energy storage systems where disposal and charging of power is needed. The flow of the power may be simply regulated by changing the phase difference between two converter bridges, which does not require any extra complicated circuitry [4], [10]. The other notable benefit of the DAB converter is that it can work on soft switching conditions. This characteristic greatly minimizes switching losses as compared to traditional hard-switched converters, enhancing the overall efficiency and minimizing thermal stress on power electronic components. Consequently, the system reliability and life are increased [5], [11]. Moreover, a high-frequency transformer is present, and it offers galvanic separation between the input and output of the converter. This enhances safety of the system and allows it to operate at various voltage levels. The operation at high frequencies also makes the transformer smaller, which adds to the compact and lightweight design. Also, the modular design of the DAB converter can be easily scaled to higher power levels, and it can thus be integrated into systems, like electric vehicles, renewable energy systems, and DC microgrids [3], [6], [12].

The DAB converter has also a rapid dynamic response which means that it can readily adjust to the changes in load and working conditions. Phase-shift modulation can also be used to gain a simple and effective control strategy to control the direction and magnitude of power flow. This is used to guarantee a stable operation even in transient conditions and enhance the overall system performance [4], [5], [13].

As a result of these benefits, the DAB converter has been extensively researched and utilized in multiple applications, such as energy storage systems, electric vehicle powertrains, and integrating renewable energy. A number of studies have been devoted to the modelling, controlling and optimization of performance of the DAB converter to improve its efficiency and dynamism in various operating conditions [1], [2].

This paper models, simulates and analyzes the performance of the Dual Active Bridge (DAB) converter in MATLAB/Simulink. The behaviour of the converter is tested with varying phase-shift conditions but with special focus on the power transfer behaviour and harmonic behaviour of the inductor current waveform.

II. DUAL ACTIVE BRIDGE CONVERTER

A. Basic Structure

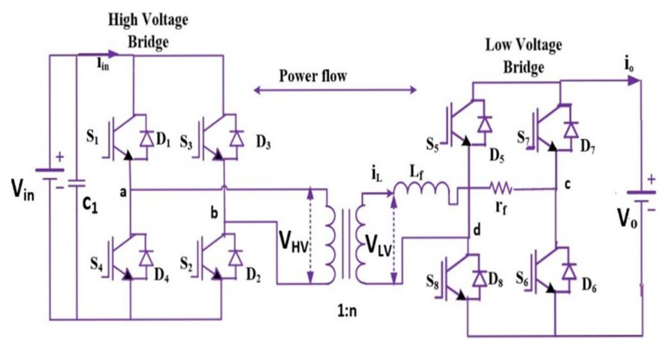

Fig. 1. Dual Active Bridge Converter

The Dual Active Bridge converter consists of two full-bridge converters (primary side and secondary side) and an isolation transformer of high frequency with a coupling inductor. The main bridge is linked to the high voltage DC supply and the secondary bridge to the low voltage DC supply.

B. Principle of operation

In dual active bridge (DAB) topology, two bridges operates based on phase shift modulation, such that both high voltage and low voltage bridges create square wave voltages of same frequency. Power flow takes place due to the phase shift between these two voltages. If high voltage side voltage leads secondary side voltage, then power will be transferred from the high voltage to low voltage side whereas, for opposite case the power flow gets reversed. Working of DAB topology in one switching cycle can be better understood through various operating stages, shown in Fig. 2 to Fig. 5. These figures show the conduction path and currents flowing within the circuit while power is being transferred from one side to another.

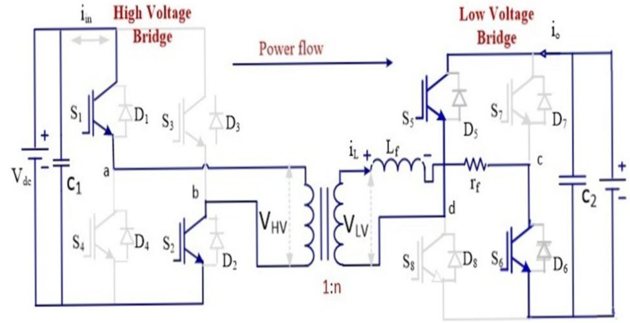

Fig. 2. Forward power transfer (HV to LV) — Switching state 1

While transferring power in forward manner from high voltage to low voltage side as shown in Fig. 2 and Fig. 3, high voltage side bridge generates a leading square wave voltage compared to the low voltage side bridge. For this condition, high voltage side switches (S1 and S2) and corresponding low voltage side switches get turned ON/OFF in a way to establish a positive voltage across inductor. Consequently, there will be a positive inductor current I_L, thus the energy will be transferred from the high voltage side to the low voltage side using a high frequency transformer.

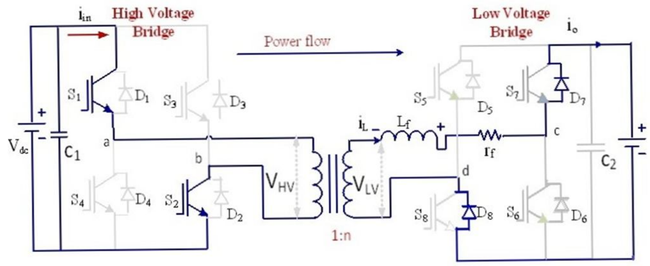

Fig. 3. Forward power transfer (HV to LV) — Switching state 2

At the switching state changeover during the same cycle, as shown in Fig. 3, the polarity of the applied voltage to the inductor changes while the current maintains its direction due to the property of the circuit inductor. As a result, continuous current and soft-switching take place.

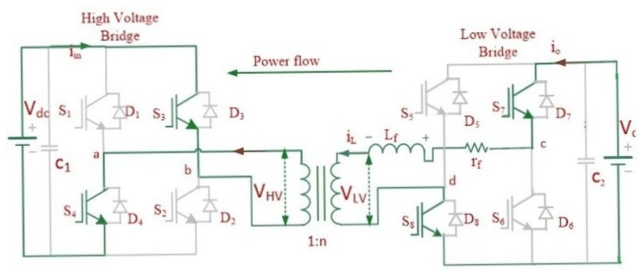

Fig. 4. Reverse power transfer (LV to HV) — Switching state 1

In the case of reverse power transfer as in Fig. 4 and 5, the low voltage bridge leads the high voltage bridge. Corresponding switching order makes the polarity of the voltage across the inductor reversed so that the inductor current becomes negative; therefore, the power will be transferred from the low voltage side to the high voltage side.

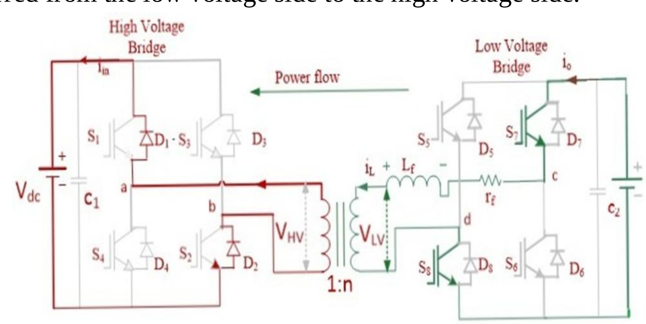

Fig. 5. Reverse power transfer (LV to HV) — Switching state 2

When the operation moves on to Fig. 5, there is a reversal of the voltage applied to the inductor, unlike in the former stage. However, the current in the inductor does not change its direction. Again, like forward mode, a number of switching intervals can take place in each cycle, and hence, the energy will be transferred continuously through the inductor current.

The transitions between these switching states are the main reason behind creating the inductor current wave form and affecting the transfer of power. The level of the phase shift will determine the average current that is passing through the inductor, affecting the transferred power.

C. Power Transfer Equation

The power transferred in a DAB converter is given by:

$$P = \frac{nV1V2}{\omega L}\left(1 - \frac{\phi}{\pi}\right)$$

where

$V1$= Primary DC Voltage

$V2$= Secondary DC Voltage

L= Inductance

ϕ= Phase shift angle

n=Transformer turns ratio

III. MATLAB/SIMULINK MODEL

A. Simulation Setup

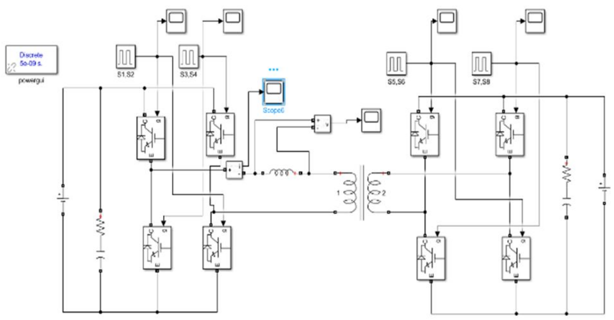

Fig. 6. Simulation Diagram of Dual Active Bridge

The DAB converter is simulated in MATLAB/Simulink with the following parameters:

TABLE I
DESIGN SPECIFICATIONS OF THE PROPOSED DIAGRAM OF DUAL ACTIVE BRIDGE

Parameter	Value
Primary Voltage (V_{HV})	400 V
Secondary Voltage (V_{LV})	300 V
Switching Frequency	100kHz
Transformer Ratio	1:1
Inductance	0.001H

The model has the full-bridge operation switching pulse generation, precisely modeled high-frequency transformer with a coupling inductor and blocks of voltage and current measurements to thoroughly analyze the performance of the transformer.

B. Control Strategy

Phase Shift Modulation (PSM) is used to control power flow. Increasing phase shift increases the amount of power transfer and decreasing phase shift reduces the amount of power transfer. This approach offers effective and efficient two-way functioning.

IV. SIMULATION RESULTS AND ANALYSIS

A. Waveform Analysis

The performance of the DAB Converter is analyzed based on four different phases, including lag, moderate lag, intermediate high phase shift lag, more lag, and leading phase situations. The analysis involves the voltage across the inductor, inductor current, and the Total Harmonic Distortion (THD) of the current waveform.

Lag Condition (ϕ=36°)

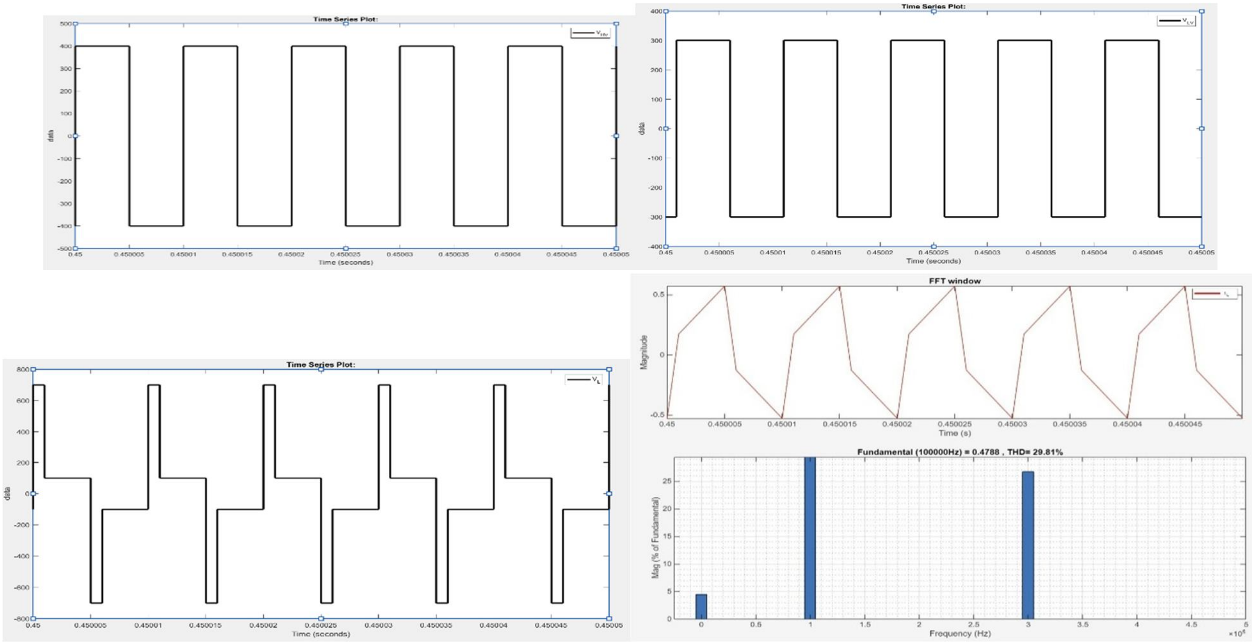

Fig. 7. Waveforms of $V_{HV,}$ $V_{LV,}$ V_L and I_L (36°Lag) with THD

Here, the low voltage side is 36° behind the high voltage side. Therefore, there is a slight phase angle that leads to a little overlap of the voltages across the two bridges. As a result of this small overlap, there are sharp transitions on the inductor current waveform, leading to harmonics. In this case, the THD percentage value is 29.81%, showing that the waveforms have a poor form. Despite the fact that power flows from the high voltage side to the low voltage side, there is some efficiency loss.

Moderate Lag (ϕ=90°)

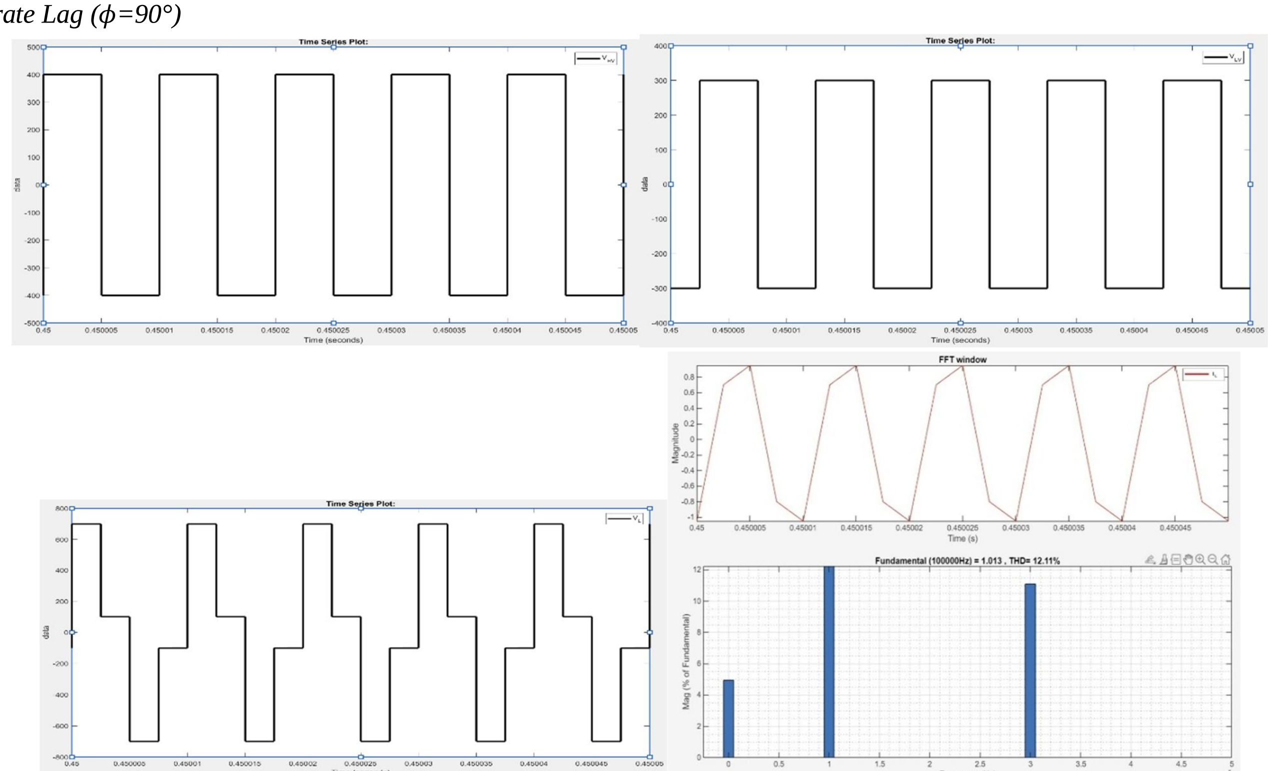

Fig. 8. Waveforms of $V_{HV,}$ $V_{LV,}$ V_L and I_L (90°Lag) with THD

As the angle of phase shift increases to 90°, there will be better overlapping between the two bridge voltages. In addition to the above factors, the inductor current waveform becomes smoother. Harmonic content is reduced in the inductor current waveform, which in turn causes the total harmonic distortion to reduce to 12.11%, indicating improved waveform quality. This condition represents a balance between power transfer capability and harmonic performance.

Intermediate High Phase Shift Lag (ϕ=126°)

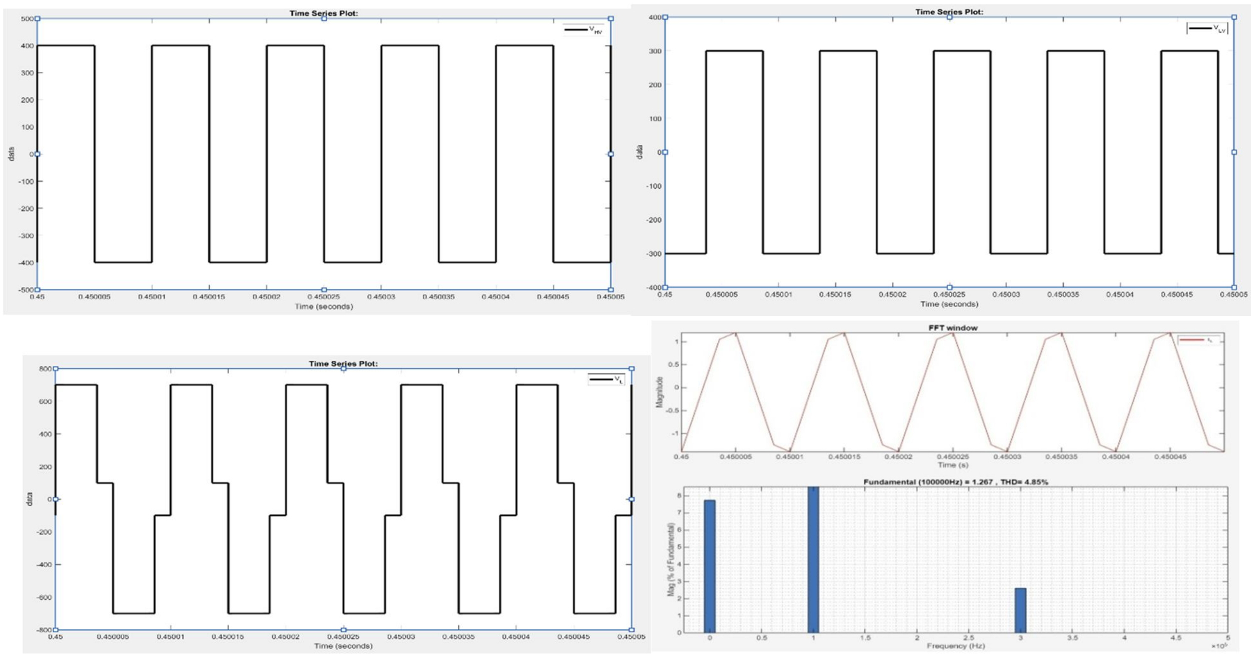

Fig. 9. Waveforms of $V_{HV,}$ $V_{LV,}$ V_L and I_L (126°Lag) with THD

Another condition is considered between moderate lag and more lag conditions, with a higher phase shift of 126°. Here, the overlap between the bridge voltages is more accentuated, and the inductor current is almost continuous. This leads to additional mitigation of harmonic distortion, and the THD is reduced to 4.85% (its lowest value). This case offers the best waveform quality of all cases, as well as optimal converter operation. This THD reduction is caused by a better continuity of the current and a lower amount of high-frequency components in the current waveform.

More Lag (ϕ=144°)

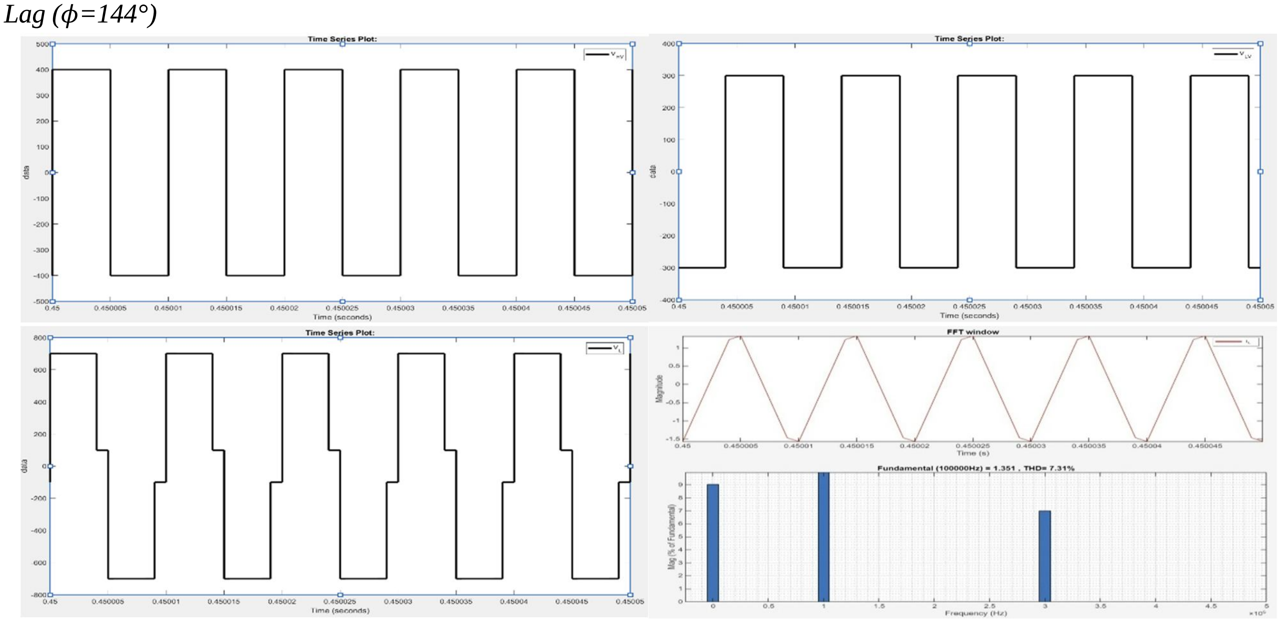

Fig. 10. Waveforms of $V_{HV,}$ $V_{LV,}$ V_L and I_L (144°Lag) with THD

In this case, the phase shift is increased to 144°. While the current waveform is still continuous, the effective power transfer mechanism starts to vary due to the high phase shift. The THD rises to 7.31% showing that at larger phase angles, harmonics might increase. It demonstrates that using excessively large phase shifts is not necessarily the best.

Lead Condition (ϕ=36°)

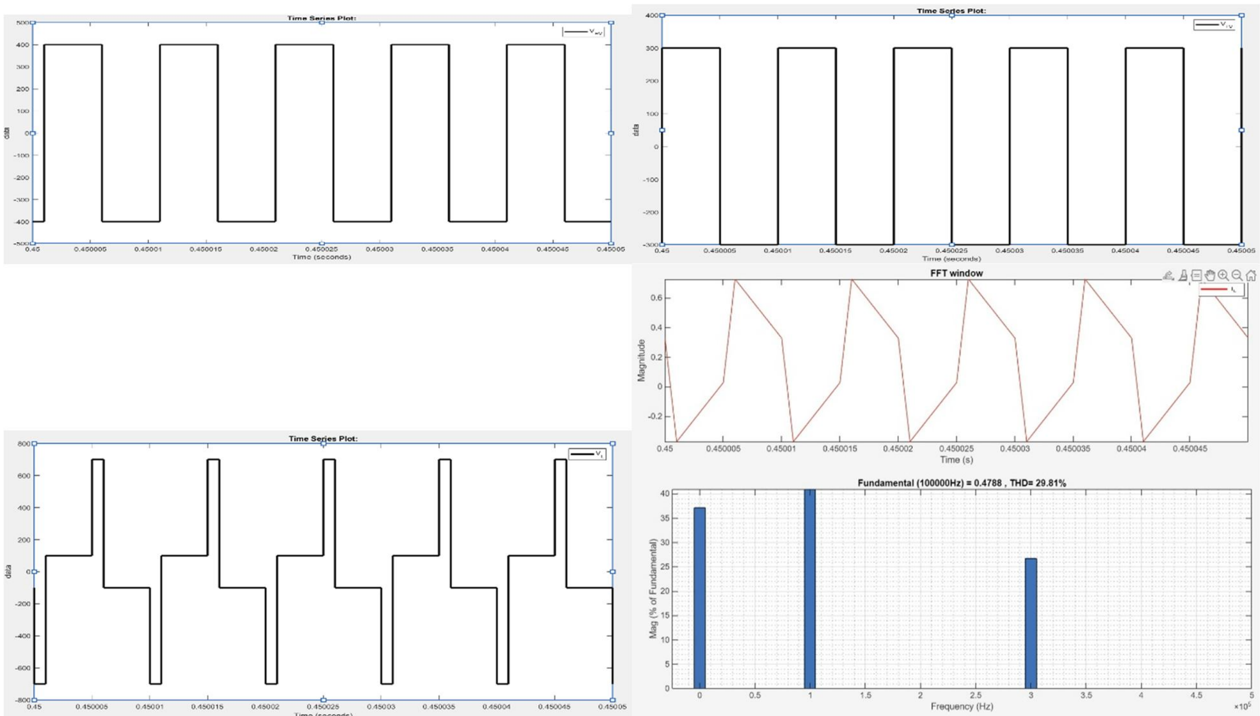

Fig. 11. Waveforms of V_{HV}, V_{LV}, V_L and I_L (36°Lead) with THD

The lead condition is when the low voltage side leads the high voltage side by 36° and power flows backwards. The waveform shape and Total harmonic distortion is same as in the lag condition but with a change in power direction.

B. THD Analysis

The system is tested under different phase-shift conditions:

TABLE II
THD ANALYSIS OF CURRENT WAVEFORM AT DIFFERENT PHASE SHIFTS

Condition	Phase Shift	Magnitude of Fundamental Component	THD%
Lag/Lead	36°	0.4788	29.8
Moderate Lag	90°	1.013	12.1
Intermediate High phase shift	126°	1.267	4.85(LOW)
More Lag	144°	1.351	7.31

C. Discussion

The graph demonstrates that the Total Harmonic Distortion (THD) reduces as the phase shift angle increases, i.e. there is an inverse correlation between THD and phase shift until an optimal phase shift is reached. The improvement in the converter performance with an increase in phase shift is due to improved current continuity and lower harmonic distortion. But, after the optimal point of 126°, it is observed that the THD starts to increase slightly due to the presence of extra circulating currents. It is also clear that the phase shift in the lead or lag mode produces similar harmonics for the same magnitude of phase shift. This confirms the fact that the harmonic distortion is not dependent on power flow direction.

V. CONCLUSION

This paper discusses about the modelling and simulation of aA Dual Active Bridge (DAB) converter using MATLAB/Simulink for bidirectional power transfer in various phase shift conditions. The converter's performance was assessed for different operating conditions in terms of inductor current waveform and Total Harmonic Distortion (THD). The simulation results show that the DAB converter can effectively provide the controllable bidirectional power transfer between the high-voltage and low-voltage sides. It was found that the harmonic distortion reduces with the increase in phase-shift angle due to better current continuity. The lowest THD (4.85%) was observed at an optimum phase shift of 126°, which indicates the best operating point for enhancing the waveform quality and the performance of the converter. After this, a slight rise in THD was noticed, suggesting that too much phase shift may lead to additional circulating currents. The findings also demonstrate that the harmonic distortion level is related to the magnitude of the phase shift, not the power flow direction, as the same level of harmonic distortion was observed for both lead and lag conditions with the same phase shift. Thus, the DAB converter is a potential solution for energy storage, DC microgrids, electric vehicles, and other emerging power electronic systems that need efficient bidirectional power converters.

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