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Dual Active Series Resonant Bridge Converter for Energy Storage Systems

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Abstract- In this work a simulation study of Dual-Active Bridge (DAB) and Dual-Active Bridge Series Resonant Converter (DBSRC) is done for a certain input voltage and load demand. The DAB topology utilizes a resonant network to reduce the magnitude of bridge currents, switches and copper losses. A comparative study of existing converter topologies is simulated and efficiencies are compared to demonstrate the DBSRC is more efficient than DAB topology. The design of converters are done and simulated using PSIM to verify the effectiveness of the DBSRC in comparison to DAB and the results are presented to validate the same.

Keywords—resonant converter, DAB, DBSRC.

I. INTRODUCTION

In order to realize power distribution between energy generation systems and storage systems, bidirectional converters play vital role compared to traditional DC-DC converter circuits, this converter has many advantages such as electrical isolation, easy to realize soft switching control, high reliability, bidirectional energy flow and key feature for permitting flexible interfacing to energy storage devices. So these converters have become popular due to increasing applications in renewable energy generation and hybrid electric vehicles. When Dual Active Bridge converter operated in high frequency for fast charging and discharging cause high conductive losses.Bidirectional power flow capability is a key feature of DAB dc–dc converters, permitting flexible interfacing to energy storage devices. Although the DAB converter has an inherent soft-switching technique, it is limited to a reduced operating range depending on voltage conversion ratio and output current. In renewable energy dc-supply systems, batteries are usually required for back-up power to electronic equipment. Their voltage levels are typically much lower than the dc-bus voltage. Therefore bidirectional converters for charging/discharging the batteries are required.

For high-power applications, bridge-type bidirectional converters have become an important research topic over the past decade. Need for control of intermediate bus voltage, so a non-isolated second stage is required to regulate the intermediate bus voltage while the proposed DAB SRC provides electrical isolation and high voltage step, [1]. For a constant switching frequency optimized ac-link transformer is modeled with limited dynamic voltage operating range and constant power capability. And effect on transformer size by resonant capacitor has negative influence on converter characteristics, [2].

The concept of Dual Phase Shift control for the time sequence between the gate signals of diagonal semiconductor switches used at starting process to reduce high inrush of current, [3]. Comparative study on voltage fed and current fed full bridge, dual active full bridge and series resonant DAB converter with clamped capacitor voltage. Efficiency of Dual Active Full Bridge and resonant converter in both forward and reverse mode of operation is discussed in, [4]. Resonant network to minimize the reactive power requirement of the converter and reduces the magnitude of bridge currents and therefore switch, copper losses. The control scheme is equal to PWM while maintaining the phase shift between the bridges fixed at +90º or -90º to regulate the direction of power flow, [5].

The other category of bi-directional converters with current-fed full bridge on the low voltage side converters have reduced RMS switch and transformer current values at the expense of higher voltage ratings of the switches. To protect switches from over voltages, which is occurring due to energy stored in the transformer inductance and the DC choke an additional circuitry is needed. To manufacture an efficient high current DC choke is difficult so we go for voltage-fed topologies which are considered to be advantageous over the current-fed topologies with respect to reliability and cost of the converter. For increasing power level, a dual full-bridge configuration is adopted usually, and its high side and low side are typically configured with boost type and buck type topologies, respectively. The major concern of these studies include reducing switching loss, reducing current and voltage stresses, and reducing conduction loss due to circulating current. This is a drawback for applications that operate mainly with variable or low loads as the overall converter efficiency is reduced. To perform the power conversion with high efficiency and to reduce the size of transformer and filter components, high frequency operation of the converter is desirable. An attractive alternative for a high frequency dc-to-dc converter is the use of a resonant converter. These converters typically make use of high frequency resonant (LC) circuits. These circuits may be operated either at switching frequency below/above the resonant frequency. The operation of the circuit above resonance is preferred compared to below resonance for any type regarding to the fact of a basic resonance principle that the operation above resonance is in the lagging power factor region of the basic resonance curve.

II. DC-DC CONVERTER TOPOLOGIES

A. *Dual Active Bridge Converter Topology*

A DAB topology, Figure 1, is a common choice for bi-directional dc/dc converters when high input to output voltage ratio and high output power level are considered. It consists of two full-bridge converters interconnected by a high frequency transformer that provide isolation between the dc- buses and reduces the voltage difference applied to the tank inductor. Some other advantages of this converter are soft switching capability, which is dependent of the converter operating range, absorption of the parasitic inductances in the tank inductance, lower component number and device voltage stress. The DAB converter shown in Figure 1 consists of two full-bridge circuits connected through an isolation transformer and a coupling inductor *L*, which may be provided partly or entirely by the transformer leakage inductance. The functionality of the circuit configuration and the purpose of discrete elements used in the DAB is already dealt in [3].

The DAB is a four-quadrant DC-DC bidirectional isolated converter which consists of high frequency transformer and two H-bridges converters (where one always operate in rectification mode, and the other one -in inversion mode). Introduced inductor on the low voltage side of converter leads to reducing current ripples. High value of operating frequency leads to significant reduction of designed planar transformer and inductor sizes. Full-bridge voltage-fed converters are used at both sides of the isolation transformer and the control is performed based on soft-switched phase-shift strategy. In its basic form, the diagonal switching pairs in each converter are turned on simultaneously with 50% duty cycle and with 180 degrees phase shift between two legs to provide a nearly square wave ac voltage across transformer terminals.Principle of operation of the DBSRC. The symmetry of circuit configuration enables it to handle bidirectional power flow. The output can be from another dc source for bidirectional power flow or a resistive load with capacitive filter for unidirectional power flow only. Figure 2 shows the configuration of dc/dc DBSRC. Two full bridges are connected through a series *LC* resonant tank and a HF transformer.

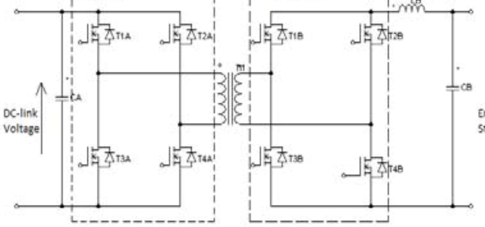


Figure1. Schematic diagram of the DAB dc-dc converter

The bidirectional dc-dc converter circuit scheme is a two-quadrant converter containing only standard MOSFET or IGBT switches. The two bridges have phase shift and all switches work with 50% duty cycle. The *LC* resonance frequency is set lesser than the switching frequency, thus, the converter works only in continuous current mode.

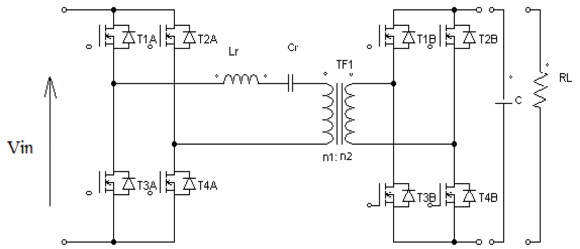


Figure 2. DAB series resonant converter

The amount of power transfer is controlled using the phase-shift angle, whereas, the power flow direction is dependent on the polarity of phase shift. Also, only a small variation of the phase shift is needed to regulate the output from full load to almost no load. The leakage inductance of the HF transformer is used as part of resonant inductance. The resonant tank has series capacitor which helps in blocking the dc current component arising from any asymmetry in device drop etc., which prevents the transformer from saturation [6].

B. *Resonant cicuit analysis for DBSRC*

The resonant inductance L_r is a part of parasitic inductance of the transformer. The effective impedance offered by the parasitic inductance to power flow is reduced by including the resonant capacitor C_r and exciting the tank with a voltage waveform V_{in} having frequency close to the tank resonant frequency. When a circuit operated above resonant frequency it offers ZVS which is preferred for a MOSFET based inverter.

Parameters which have been transferred to primary side are represented by the superscript " ' ". All the equations are normalized with the base values

$$V_B = V_i\,, \qquad Z_B = R'_L\,, \qquad i_B = \frac{V_B}{Z_B} \qquad (1)$$

where V_i is the input voltage and the converter gain is defined as ratio of the output dc voltage to the supply voltage

$$M = \text{converter gain} = \frac{V'_o}{V_i} \qquad (2)$$

Relation between fs and fr is defined as normalized switching frequency

$$F = \frac{\omega_s}{\omega_r} = \frac{f_s}{f_r} \qquad (3)$$

The resonant tank has a natural frequency determined by Lr and Cr, where f_s = switching frequency $=\omega_s/(2\pi)$ and

f_r = resonant frequency $= \frac{1}{2\pi\sqrt{L_r C_r}}$

The parameter Zc called the characteristic impedance of the tank is defined as

$$Zc = \sqrt{\frac{L_r}{C_r}} \qquad (4)$$

For the converter with a load resistance R_{load}, the load factor of the converter Q, is defined as

$$Q = \frac{Z_c}{R_{load}} \qquad (5)$$

The objective of the design is to achieve soft switching for all the switches (ZVS which is preferred) for high efficiency (lower resonant current), specified range of full-operation, and small tank size. It is hard to select a design point to fulfill all objectives for a converter with varying input and output voltages. This paper depends on the converter gain for the priority to realize soft switching. To keep the soft switching operation of all the switches maximum gain is selected.

III. SIMULATION RESULTS

A. *Simulation Results of DAB converter*

Figure 3 shows the simulation model which was done in PSIM software and consist of high frequency transformer with winding ratio 5:4, DAB block and two H-bridges A and B respectively. Figure 4 and 6 show simulation results for buck and boost modes. These figures show the voltages and currents generated by the two H-bridges, V_{HV} on the HV side and V_{LV} on the LV side, the device currents on the HV side i_1 and device current.

The power circuit is simulated by PI-controller. The advantages of both P-controller and I-controller are combined in PI-controller. The proportional action increases the loop gain and makes the system less sensitive to variations of system parameters. The integral action eliminates or reduces the steady state error.

For buck mode when power flow is from HV side to LV side. In this mode HV side acts as source and LV side acts as the load. The switches are controlled to conduct at 50% duty cycle and there is some delay between the diagonal switches to reduce the voltage. The expected values are V_{HV} = 30V, V_{LV} = 24V, I_{in} = 0.8A, I_0 = 0.8A.

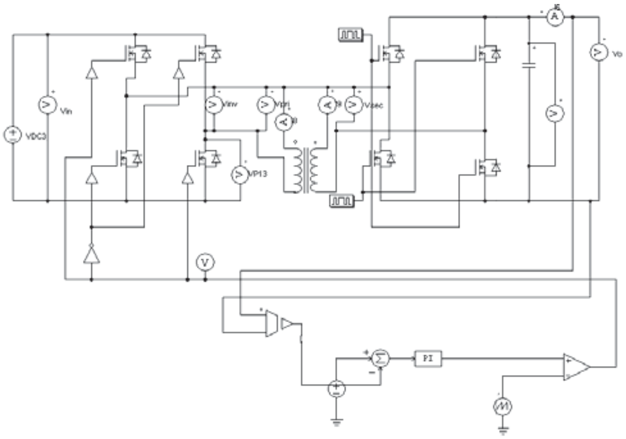
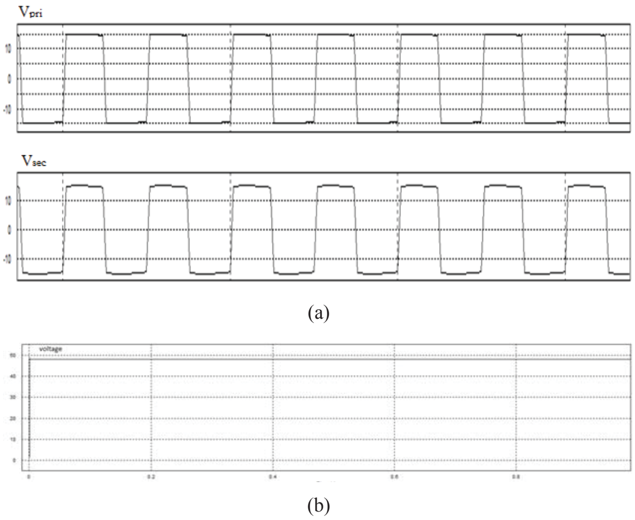


Figure 3. Closed loop diagram of buck mode of DAB converter



(a)

(b)

Figure 4. Simulation results of DAB for buck mode for V_{HV} = 30V,V_{LV} = 24V

(a) voltage across primary and secondary windings of transformer
(b) output voltage.

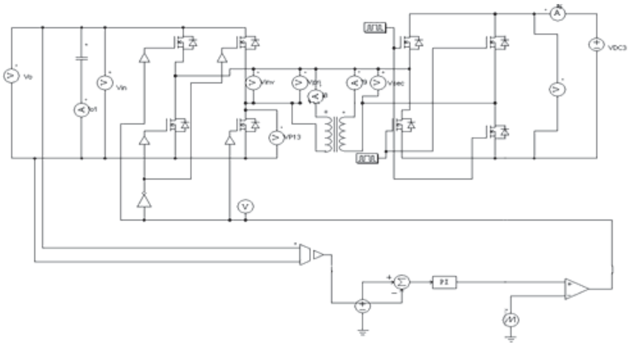


Figure 5. Closed loop diagram of boost mode of DAB converter

For boost mode when power flow is from LV side to HV side. In this mode LV side acts as source and HV side acts as the load. The switches are controlled to conduct at 50% duty cycle and there is some delay between the diagonal switches to decrease the voltage. The predicted values are V_{HV} = 37.5V, V_{LV} = 30V, I_{in} = 25.7μA, I_0 = 32.9μA. Finally all the parameters given obtained from theoretical calculation and simulation are given in Table I. It is seen that all the values are matched closed to each other.

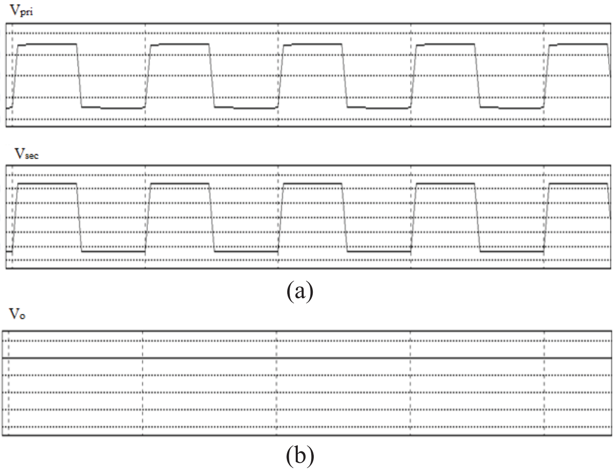


Figure 6. Simulation results of DAB for boost mode for V_{HV} = 24V, V_{LV} = 30V,
(a) voltage across primary and secondary windings of the transformer
(b) output voltage.

B. Simulation Results for DAB series resonant converter

The converter designed is simulated with a integrated circuit emphasis (PSIM) software.

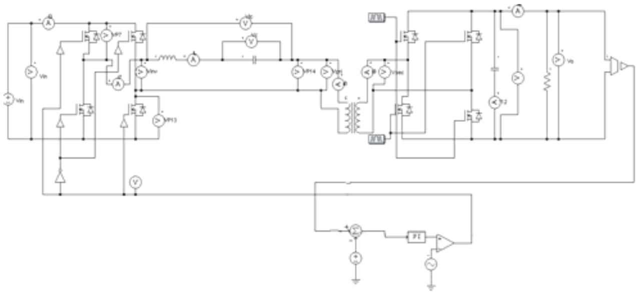
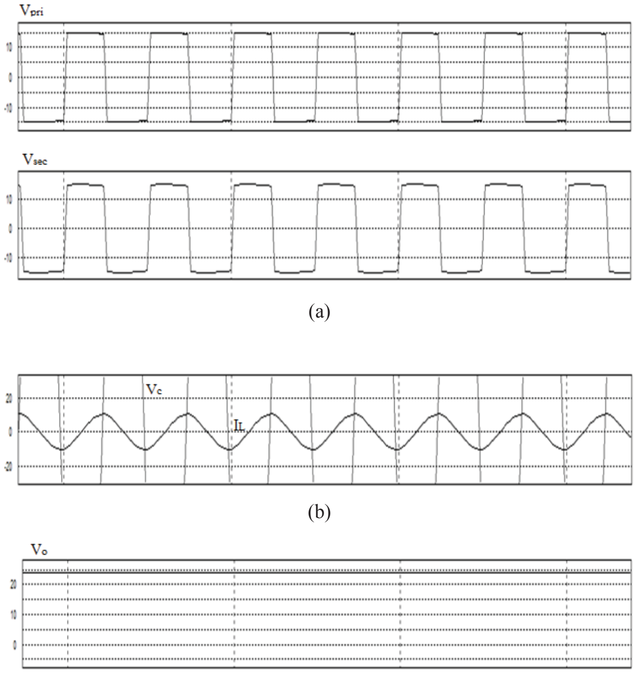


Figure 7. Closed loop diagram of buck mode of DBSRC converter

To deliver the required power with regulated output voltage certain value of phase shift between the gating signals of two HF bridges is needed. The waveforms obtained for the buck mode is illustrated in Figure 8. The primary converter works in ZVS condition since M = 0.89 < 1.The secondary converter is found working in diode rectifying mode.

There is no circulating current in the secondary side as all the power is being transferred to the secondary side during all the time in each switching period. This shows the design point is located at the soft switching boundary point of secondary bridge which delivers maximum power. In Figure 8.(b) the voltage across the capacitor Cs is shown as sinusoidal due to resonance.



(a)

(b)

(c)

Figure 8. Operation in buck mode (Vi = 30V, Vo = 24V) (a) voltage across primary and secondary windings of transformer, (b)voltage across capacitor and current through inductor, (c) output voltage waveforms.

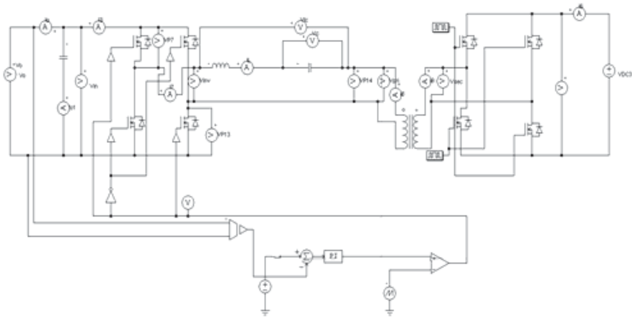
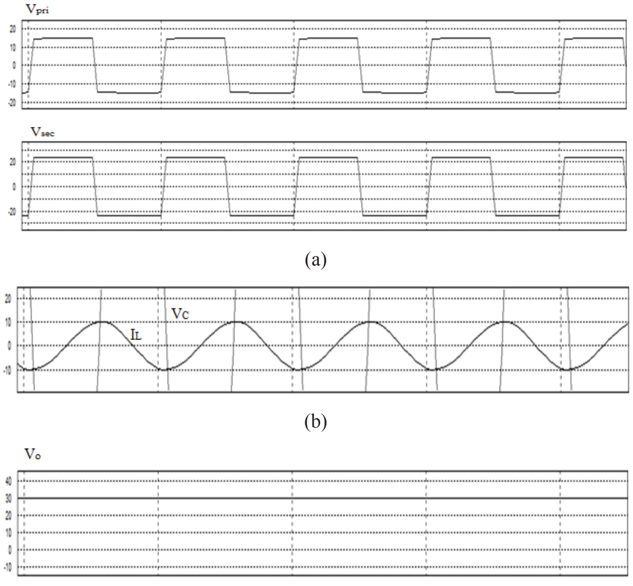


Figure 9. Closed loop diagram of boost mode of DBSRC converter.

Figure 10. Illustrates the waveforms for boost mode, the voltage level showing the power flows back from secondary side to primary side. The switches on the secondary converter works in ZCS turn-off and primary side converter work in ZVS turn-on.



(a)

(b)

(c)

Figure 10. Operation in boost mode (Vi = 24V, Vo = 30V) (a) voltage across primary and secondary windings of transformer, (b) voltage across capacitor and current through inductor, (c) output voltage waveforms.

Finally the comparisons of all the parameters from simulation for conventional DAB and resonant DAB converter are given in Table 1. It is seen that the actual phase shift angle does not match reasonably from theoretical calculation and simulation values. The major deviations of compared values is explained as: Due to presence of dead band between gating signals the phase shift of the gating signals is not exactly the same as the phase shift of two actual square wave voltages V_{AB} and V_{CD} and is similar to the effect of different soft-switching conditions of two bridges, which is similar to the effect of dead-band on steady state operation of DAB. The additional factor that influences the actual phase shift is the effect of snubber. With different types of snubber on two sides of the HF transformer for different commutation conditions could result in different rising and falling rate of V_{AB} and V_{CD} which affect the actual phase shift.

TABLE- 1 Comparison Parameters For The Converters

PARAMETERS	**DAB CONVERTER**	**RESONANT DAB CONVERTER**
Input voltage	**30V**	**30V**
Input current	**0.8A**	**0.9A**
Output voltage	**23.16V**	**24.17V**
Output current	**0.9A**	**1A**
Power input	**24W**	**27W**
Power output	**20.8W**	**24.17W**
Efficiency	**86.8%**	**89.5%**

Two different topologies are discussed, conventional DAB and resonant DAB for the energy storage system. Experimental results of a 24W prototype DAB, operated under various conditions, have also been presented to demonstrate the improved performance of the converter. Results indicate that the resonant DAB topology has lower bridge currents and, consequently, offers higher efficiency over a wider supply voltage and load range in comparison to conventional DAB topologies. Simulation results for the 24W prototype of DBSRC is operated at various conditions have been improved the performance of the converter at wide range of power and dc supply voltages. By comparing the results of both the converters it has been observed that using DBSRC topology minimizes the reactive power required to the converter over the entire load range. The resonant network which includes the leakage inductance of the isolation transformer reduces the magnitude of bridge currents and switch and copper losses is 86.8% efficient which is higher than the conventional one with 89.5% efficient.

IV. CONCLUSION

In this paper conventional DAB and DBSRC are compared to assess the effectiveness of the system for application towards energy storage system. Simulation results for the 24W capacity DAB and DBSRC is presented in this paper. The converters are operated with 30V dc input voltage. By analysing the results of both the converters it has been observed that using DBSRC topology improves the efficiency of the system when used with energy storage systems. It is also evident from the Table -1 that the resonant network which includes the leakage inductance of the isolation transformer reduces the magnitude of bridge currents, losses in switch and copper windings. The use of zero-voltage and zero-current switching increases the converter efficiency. Some of the application of the said converter includes the following: There is configuration that involves a wind-hydro hybrid system electronically interfaced by a dual bi-directional converter with dc-link section augmented with a battery energy storage scheme. In such configuration, hybrid system converter control can be such that, the excess power generated can be stored in battery units or deficit power generation can be overcome by meeting the demand due to energy stored in battery. Such battery augmented hybrid system can work in grid-tied mode as well exchanging power with grid.

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