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Operation of Current-fed Dual Active Bridge DC-DC Converters for Microgrid

A. Geetha, N.P. Subramaniam, R. Gnanadass

Abstract: ***Dual Active Bridge (DAB) is an isolated bidirectional DC-DC converter, which comprises two full bridge converters linked through a high frequency transformer. It has low stresses and permits high frequency performance because of the soft-switching. All the switches in the converter achieves the turn ON & OFF during Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) to minimize switching loss. Generally, DAB is classified as two types, namely, voltage-fed and current-fed variants. At light load conditions, soft-switching is not realized in case of voltage-fed DAB topologies. The application of current-fed DAB converters is to reduce the losses at the time of switching under light load conditions and improves the efficiency. This paper describes the various topologies of voltage-fed and current-fed DAB used for different applications in microgrid and fuel cell energy generation system by using the simulation. The performance of voltage-fed and current-fed DAB with snubber-less converters are also demonstrated and their effectiveness are validated.***

Index Terms: ***Bidirectional, Current-fed Converter, Dual Active Bridge, Microgrid.***

I. INTRODUCTION

Proliferation of distributed energy resources (DER), renewable energy sources (RES) and energy storage systems (ESS) in modern power networks has enhanced an idea of microgrid concept. Distribution power grid approaches do not support RES and DERs in an efficient way as microgrids. Comprising of distribution grid with renewable energy sources like PV, Wind, etc., is said to microgrid [1],[2]. Due to renewable energy sources in islanded microgrid drifts towards an inverter based system from a rotational generated dominated system, but inverter dominated generation does not provide any mechanical inertial response.

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It leads to frequency instability and microgrid reliability and stability point of view, voltage regulation is also necessary [3]. Therefore, for frequency stability and for voltage regulation, p-f droop and Q-V controllers [4] are employed in the control system of standalone microgrid generates the reference voltage for the system respectively.

The power flow of traditional grid is naturally unidirectional from the generator station to consumers.

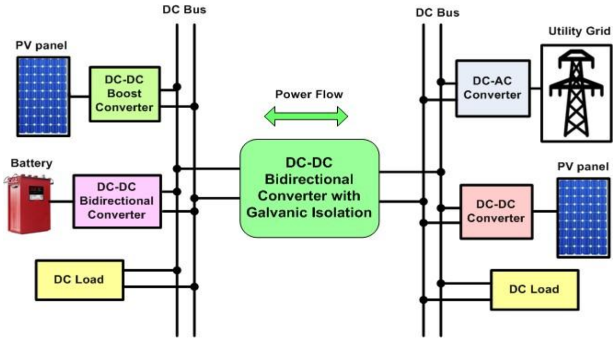

Fig. 1 Typical Structure of Microgrid using CFDAB Converter

In microgrid, most of the sources are RES, they are unpredictable due to the inherent features of PV [5] or wind type of inputs. Therefore, the flow of energy is not always in one direction, hence for consumer loads, an ESS with bidirectional converter is essential to get suitable power [6] with the use of bidirectional DC-DC converters. Commonly each distributed energy resources connect to microgrid through unidirectional converter, while each energy storage devices usually connected to microgrid through bidirectional DC-DC converter. Bidirectional converters interface between RES and ESS. They have applications such as Microgrids, Hybrid Vehicles, UPS, Distribution [7].

As of earlier literatures, due to isolation between source and load side, bidirectional converters can be categorized into isolated and non-isolated type of converters [8],[9]. But non-isolated (i.e.,) basic converters of buck or boost form are unidirectional in nature due to switches without having diode. Therefore, instead of using these types of devices, make it as bidirectional by placing a reverse diode is connected parallel to a power semiconductor switches like MOSFET or IGBT. But on the contrary, non-isolated converters are produce high EMI noise problems, not suitable for microgrids i.e., high power applications but suitable for low to medium power levels and difficult to implement multiple output topologies [10]. The structure of microgrid is presented in the Fig. 1 and the isolated bidirectional converter is crucial component in the system.

Further it acts as interface between two buses due its nature of bidirectional power flow. So, isolated bidirectional converters are more suitable option for integrated with RES & ESS [11]. The intuition of this paper is to categorize the isolated converters and to analyze their performance under different operating condition using simulation.

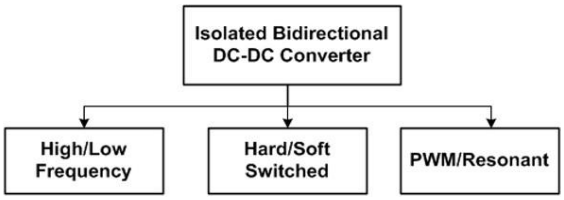

Fig. 2 Classification of Bidirectional Isolated Converter

II. CATEGORIES OF ISOLATED DC-DC CONVERTER

In high power applications, isolation between input and output side is necessary with the intention of personal safety and operation of the protection systems. In addition, proper design and optimization of various stages, voltage matching is required. All these can be achieved by using an isolation transformer in a power electronic circuitry, thus isolated converters [12] are best suited for these applications. Based on the performance, bidirectional isolated converters can be divided into low/high frequency, hard/soft switched and Pulse-Width Modulated (PWM)/resonant types converters as shown in Fig. 2.

A. High/Low Frequency Converters

High efficiency is one of the most advantage of low frequency converters because it has reduced losses i.e., turn-on and off losses, magnetics, passive elements, filter and power losses. However, the converters have limitations of high cost and density, greater transformer size and it is suitable for low power applications. High frequency converters have advantages of low cost, small size, light weight, cheapest cost and neglects the oscillated waveforms of voltage and current [13], [14]. But they have difficulties of hard-switching, the large current and voltage stress, high EMI leads to more dv/dt and di/dt losses [15], [16]. Therefore, for improving the efficiency of the converter, it requires modulation technique, auxiliary transition circuit and resonance needs to enhance soft-switching.

B. Hard/Soft Switched Converters

In literatures [17], Soft-switching can minimize the switching losses by adding special circuitry [18], resonant converters and modulation techniques are used to increase the efficiency [19]. In the papers [20], [21], use of auxiliary circuits to improve soft-switching. However, converter efficiency decreases because it increases the cost, elements count and size. Coupling inductor [22], [23] with interleaving [24] converters introduces to achieve ZVS. But these papers have a difficulty in control point of view and also have a problem with the size and cost for the same power rating. In this literature [25], it introduces a bidirectional converter operating with phase-shifted control, which can realize ZVS for the input side switches. However, hard switching occurs at the output side turned-on states. In [26], a different isolated DC-DC converter with soft-switched method compares and presented, in which active clamped current-fed converter can provide ZVS over a wide source voltage fluctuation at full load. However, it not supported ZVS at low load conditions.

C. PWM/Resonant Converters

Pulse Width Modulation (PWM) converters are hard-switched converters, they provide high power density, ease of control and fast transient response, but increased frequency of switching, these properties are improved in [27]. However, more switching losses and EMI noise are increased due to the high frequency. So, it is mandatory to reduces the switching losses through additional circuits called snubbers [28]. Series and parallel combination of RC/RCD and active/passive circuits are the types of snubbers. Resonant converters are used to eliminate the switching losses [29]. It can control the output voltage by controlling the switching frequency and is called variable frequency control. In this control, switching frequency controls the resistance of the resonant components connected between the converter and load. However, at reduced load conditions series resonant converters have a problem with voltage control. Parallel resonant converters have the circulating current leads to low efficiency at low loads. Combination of both series and parallel resonant converters have a suitable choice to offer good efficiency from the huge load to reduced load. For the earlier decades, several ZVT and ZCT PWM converters introduce resonant snubbers with traditional PWM converters to merge the features of both techniques [30]-[32]. Because of a resonance, the turn on or off process of these converters take place under soft-switching during a short period. So, most of the time, it acts as a normal PWM converter. But the Pulse width modulation has a least time duration in the switching process due to the operation of the passive snubbers [33], [34].

III. TOPOLOGY SELECTION

The arrangement of isolated bidirectional converter consists of an isolation between the converter A and converter B using a transformer with high frequency as given in the Fig. 3. Generally, the operating principle of a transformer is only with ac quantities, so it needs the DC-AC converter to be placed at both the terminals. Since the energy transfer in this system is in both directions, the DC-AC converters involved here must be of bidirectional power flow. Also, these converters are like buck or boost mode of action of the non-isolated converters.

The major topologies of isolated bidirectional converter are flyback [35], [36], current-fed push-pull and bridge type converters [37], [38], in these converters except bridge type converter, other topologies have low voltage and power rating.This paper has interested to prefer bridge type converter (i.e.) Dual Active Bridge converter owing to its power rating and flexible in their application and the most suitable option of isolated bidirectional converters. Table I shows the comparison of the topologies of isolated converter based on voltage and power rating [39]. The comparison clearly illustrates that the DAB converters possess high voltage rating up to 1kV moreover, with high power handling capability.

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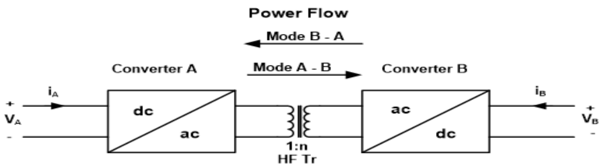

Fig. 3 Construction of Bidirectional Isolated DC-DC Converter

Table. I Comparison Between Different Isolated Bidirectional Converters

Major Topologies of Isolated bidirectional Converter	Voltage Capacity	Power Capacity
Flyback with bidirectional Converter	<100V	<500W
Push-Pull with bidirectional Converter	100-400V	<2kW
Half-Bridge Converter	<400V	<2kW
Full-Bridge Converter (DAB)	>400V	>2kW

IV. DUAL ACTIVE BRIDGE CONVERTER

A. DAB Circuit Configuration

The researchers introduce the name called as" Dual Active Bridge" because, the converter structure uses bridge type inverter and rectifier configuration [40]. This topology has low device stresses, no extra reactive components and uses a high frequency transformer to provide galvanic isolation between two active bridges of the dual active bridge converter, it permits high frequency performance because of soft-switching (i.e.) at zero voltage occurs at all the semiconductor devices over a wide range. The transformer leakage inductance is the main component in the power transfer between source & load and used as an energy storage element. In the time of turn-off instant, the voltage spikes in the switches are minimized, hence it verifies soft-switching. The filter capacitors at the input and output side are also seen the reasonable ripple current level. DAB converter uses a phase-shift control technique. The angle between two bridges adjust to control the amount of power flow in both the direction. When the phase-shifted angle is +ve, the converter transfers power from V_{in} to V_{out} and while the angle is -ve, it transfers energy from output to input. But for a wide range of source voltage and load power, phase-shift modulation has

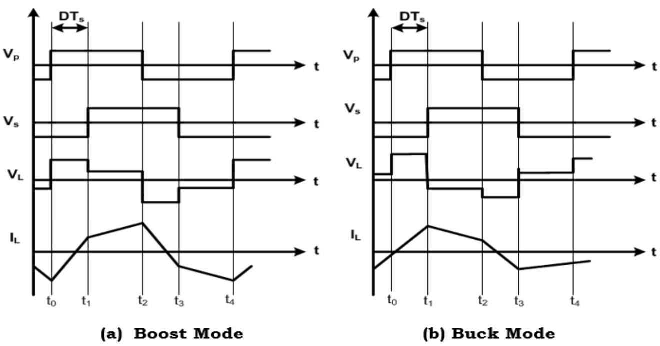

Fig. 4 Basic Waveforms of CVFDAB Converter

difficult to operate [41], [42]. The average power equation of basic topology of dual active bridge converter is

$$P_o = \frac{V_o V_{in}\, \delta(\pi - \delta)}{2\pi^2 n f_s L_{lk}} \tag{1}$$

$$V_o = nV_{in} \tag{2}$$

Where,

V_o & V_{in} are output and input voltages

Phase shift ratio, $d = \frac{\delta}{\pi}$

δ = Phase - shift angle

L_{lk} = Leakage/Discharge inductance of a high frequency transformer

f_s = Switching frequency and

n = Turns ratio of transformer.

Fig. 4 shows basic waveforms of buck and boost mode of CVFDAB converter based on phase shift angle. The leakage inductance, phase shift angle and power rating of the converter are related by the equations 1 and 2. Bidirectional Isolated DC-DC Dual active bridge is classified as voltage-fed and current-fed DAB and by improving soft-switching of DAB, they can be further divided into many topologies as shown in Fig. 5.

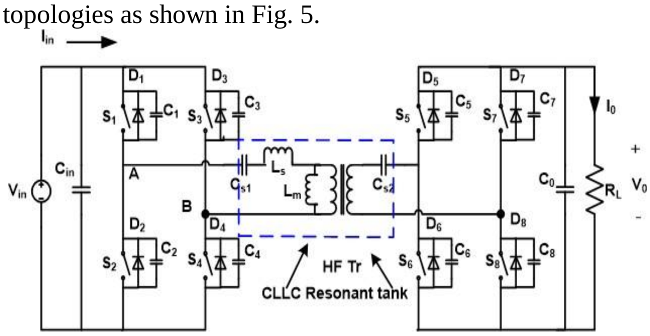

Fig. 5 Topologies of DAB Converter

B. Voltage-fed DAB Converter

The voltage-fed dual active bridge has two bridges, the primary switches, (i.e.) input side are operated in fixed gating pattern, while, secondary side switches, (i.e.) output side are in the controlled mode, by making a phase difference between the source and load side voltages of the transformer as shown in Fig. 6. Therefore, the output voltage regulation is achieved even if presents of line and load variation. As all primary active switches are better operated with switching at zero voltage, input voltage must be greater than the output. It can achieve when the input current lags the primary voltage, so that all primary switches come in ZVS. Likewise, the secondary aspect switches come in ZVS once the secondary current leads the voltage.

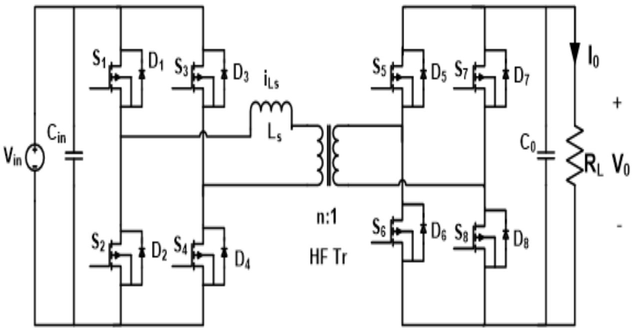

Fig. 6 Conventional Voltage-fed DAB (CVFDAB) Converter

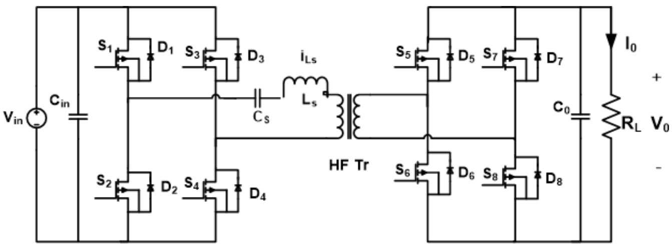

Fig. 7 Voltage-fed DAB with Series Resonant DC-DC Converter

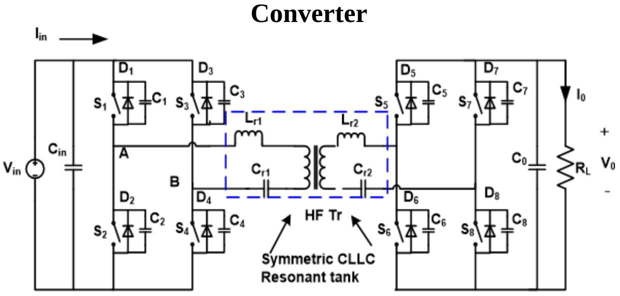

Fig. 8 Voltage-fed DAB with CLLC Resonant Converter

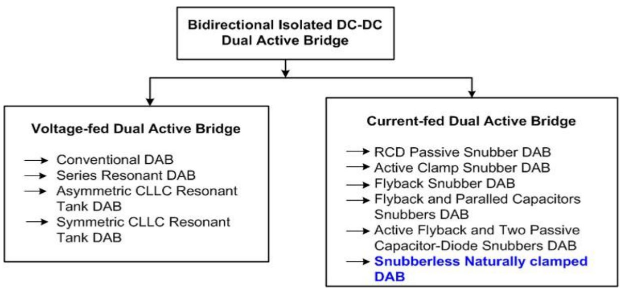

Fig. 9 Voltage-fed DAB with Symmetric CLLC Resonant DC-DC Converter

In Fig. 6 the traditional DAB of two active bridges [42] operate with switching time at the constant and variable switching frequency however DAB with the series resonant converter as in Fig. 7 is barely work with the amendment in switching time. The basic DAB has the highest total power losses once operated with constant switching frequency and with variable switching frequency owing to high RMS values of transformer and switch currents. Using DAB with the series resonant converter reduces the above drawbacks. However, the transformer turns ratio of each topologies are smaller [43]. Similar to the series resonant converter, voltage-fed DAB with asymmetric and symmetric CLLC resonant converters [44] have proposed to achieve the wide variation of voltage gain as shown in Fig. 8 and Fig. 9. In these topologies operate with modulation technique having variable frequency and power semiconductor devices drive with a 50% duty cycle. Symmetric CLLC resonant circuit has ZVS capability for input, good commutation ability for output side switches, power conversion operation and efficiency are the same as other power flow directions. So, those topologies do not allow the proper use of the isolation transformer over a wide range of source and output voltages, moreover smaller turns ratio produces more RMS current values on secondary and leads to high power losses [15, 42]. But, voltage-fed dual active bridge converters have several limitations:

(i) Large peak and circulating current in the devices.

(ii) Low efficiency with voltage and load variation due to high conduction losses, particularly for low voltage high input current applications.

(iii) Voltage conversion ratio is high leads to poor performance.

(iv) Higher value of transformer leakage inductance will cause higher duty cycle loss, need to increase transformer turns ratio.

(v) The inductance in transformer and the diode parallel capacitance resonates.

(vi) Lack of soft-switching with fluctuations of the input and load especially at low load conditions.

C. Current-fed DAB Converter

The above-mentioned limitations of voltage-fed DAB converter are eliminated in case of current-fed DAB converter. However, it requires snubbers to avoid stresses across the switches. Generally, DC-DC current-fed DAB converter comprises of two bridges made up of active switches with a boost inductor and a capacitive output filter. Based on the snubber circuit employed in the current-fed DAB converter, it classified into six topologies. They are RCD passive snubber, active clamp snubber, flyback snubber, flyback and parallel capacitors snubbers, active flyback & two passive capacitor-diode snubbers and snubberless naturally clamped current-fed DAB converter. In Fig. 10 shows the Current-fed DAB with RCD passive snubber circuit which helps to put down the voltage spikes and current difference between boost inductor & discharge inductor of the isolation transformer. In addition, reducing the power rating for a voltage clamping snubber significantly and enabling the use of a basic passive clamped snubber [26]. Comparison of voltage-fed and current-fed DAB with RCD passive snubber have presented in [28]. It clearly presents about the DAB with RCD snubber to provide low current and voltage stresses. However, the capacitor discharges through the resistor at higher output voltage and leads to increases the circulation loss.

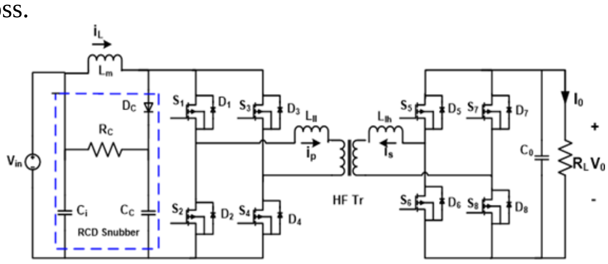

Fig. 10 Current-fed DAB with RCD Passive Snubber DC-DC Converter

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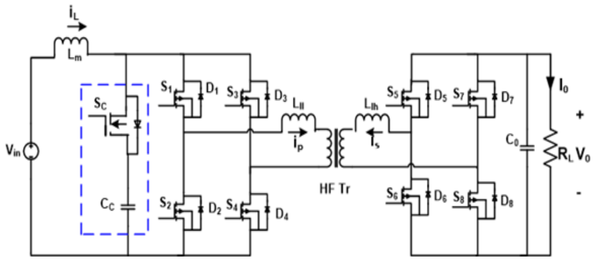

Fig. 11 Current-fed DAB with Active Clamp Snubber DC-DC Converter

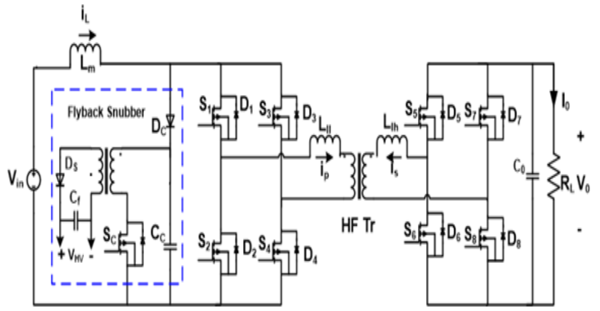

Fig. 12 Current-fed DAB with Flyback Snubber Converter

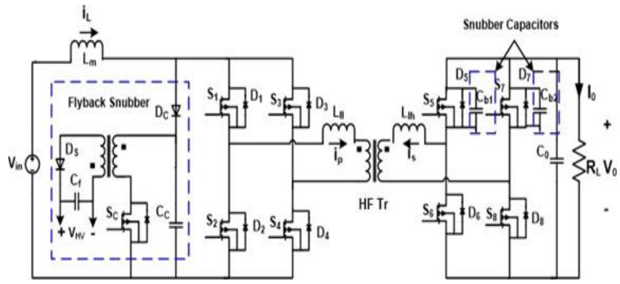

Fig. 13 Current-fed DAB with Flyback and Parallel Capacitors Converter

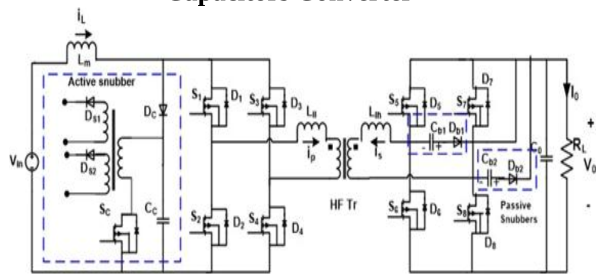

Fig. 14 Current-fed DAB with Active Flyback and Two Passive Capacitor-Diode Snubber DC-DC Converter

On the other hand, DAB with active clamp snubber has been proposed as shown in Fig. 11 [45, 46]. It improves the conversion efficiency slightly under full load condition compared with passive snubber. However, the current spikes of the main switches increase due to the flow of resonant current in devices. According to [46], flyback snubber introduces with a DAB converter as shown among the Fig. 12, it recycles the stored energy within the capacitor and regulates the clamping capacitor voltage, so it can clamp the voltage to a certain level slightly greater than the primary voltage of static device. Since the current does not circulate through the active switches, minimizes their current spikes under full load condition. It reduces the voltage stress made due to the difference currents between the input and discharge inductance. In addition, during start-up period, control of flyback snubber avoids the inrush current using precharging the high side capacitor. However, voltage spikes at turn off power semiconductor devices, switching losses are increased. According to the paper [45], the authors propose two buffer parallel capacitors added with the rectifier side as illustrated in Fig. 13. It can also ignore the limitations as explained above, but with the help of capacitors, it works under ZVS and ZCS of all devices. However, EMI noise and turn on or off losses have increased owing to buffer capacitors can resonate with discharge inductance of the isolation transformer, once it operates in buck mode. Using two capacitor-diode snubbers overcome the above to supplement the active flyback snubber as represented in Fig.14.

This topology eliminates high current and high voltage stresses on the main switches from hard switching at turn-on and turn off transitions. It also avoids the voltage spike caused by the two difference currents (i.e.) discharge inductance and input inductance currents. It achieves soft-switching on both the bridges. However, under low load condition, lack of ZVS turn-on in buck mode. Current-fed converters have the merits over voltage-fed converters for applications such as very small diode ringing, lower turns ratio of high frequency transformer, absence of duty cycle loss, lower pulsating current at the input, and easier current control ability. However, it needs passive and active clamp snubbers to absorb switch turn-off voltage stress. At light load conditions, snubbers with RCD have large current spikes in the switches lead to low efficiency while in case of active clamp, reduces boost capability.

In the paper [47], the researchers realize ZCS using the discharge inductance and the parasitic capacitance of the high frequency transformer results in ignoring the use of snubbers circuit. A new CFDAB converter without snubber as illustrated in Fig. 15. This converter allows turn off at ZCS in the primary switches naturally with lack of passive and active clamp snubbers. Therefore, minimizes the switching losses due to ZCS of inverter side and ZVS of rectifier side and it also allows high frequency switching operation with lower magnetics. It shows better efficiency compared to current-fed active clamp and dual half-bridge converters. The current-fed DAB acts as an isolated boost converter in forward direction and the converter acts as a voltage-fed full bridge dc-dc converter in reverse direction. Standard phase shift modulation (PSM) can be employed to achieve soft-switching with relatively low circulating current. Fig. 16 shows typical waveforms of CFDABSNC, the pulses of input switch pairs (i.e.,) S1,4 & S2,3 are working with a duty ratio of 80% and phase displaced by 180o. Secondary switches of two diagonal pairs (i.e.,) S5,8 & S6,7 are same pulses but operating with a duty ratio of 20%. The primary diagonal pairs S1,4 and secondary diagonal switch pairs S6,7 are phase-shifted with an angle of δ and vice versa. The design equations are given as follows,

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Table. II Simulation Parameters of CVFDAB and CFDABSNC

Component	CVFD AB	CFDABSNC
Input voltage (V_{in})	12 V	12 V
Output voltage (V_{out})	288 V	288 V
Switching frequency (fs)	100 kHz	100 kHz
Rated output power (Pout)	1 kW	250 W

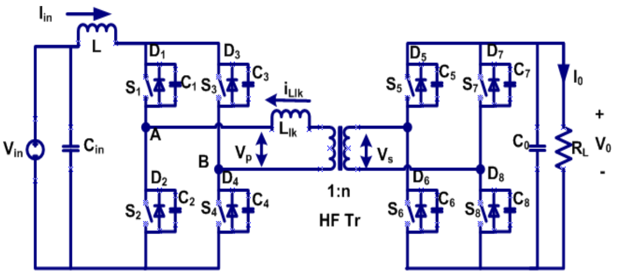

Fig. 15 Current-fed DAB with Snubber-less naturally Clamped DC-DC Converter (CFDABSNC)

Output voltage,

$$V_{out} = \frac{0.5nV_{in}}{(1-D)} \quad (3)$$

Discharge inductance of the high frequency static device,

$$L_{lk} = \frac{V_{out}(D-\frac{1}{2})}{2nI_{in}f_s} \quad (4)$$

Boost inductor, $L = \frac{V_{in}(D-\frac{1}{2})}{\Delta I_{in}f_s}$ (5)

At light load conditions,

Output voltage,

$$V_{out} = \frac{0.5nV_{in}}{(1-D-D')} \quad (6)$$

Where,

$$D' = D - \frac{1}{2} - \frac{2nI_{in}L_{lk}f_s}{V_{out}} \quad (7)$$

D = duty cycle of primary switches

V. SIMULATION RESULTS AND DISCUSSION OF CVFDAB AND CFDABSNC CONVERTERS

PSIM 9.0.3 Software package is employed to simulate the above mentioned two converter topologies. The parameters of simulated converters are listed in Table II. They operated with modulated output side and regular switching time at input side. According to the simulation results of CVFDAB as shown in Fig. 17, as all primary active switches are better operated with zero voltage switching, input voltage must be greater than the output voltage under every supply and load conditions. This can be achieved when the primary current lags the primary voltage, so that all primary active switches come in zero voltage switching. Likewise, the secondary side switches come in zero voltage switching when the secondary current leads the secondary voltage as shown in Fig. 18. In Fig. 19, the voltage across primary and secondary side switches are phase shifted by an angle δ and current and voltage of the leakage inductance of transformer as shown in Fig. 20.

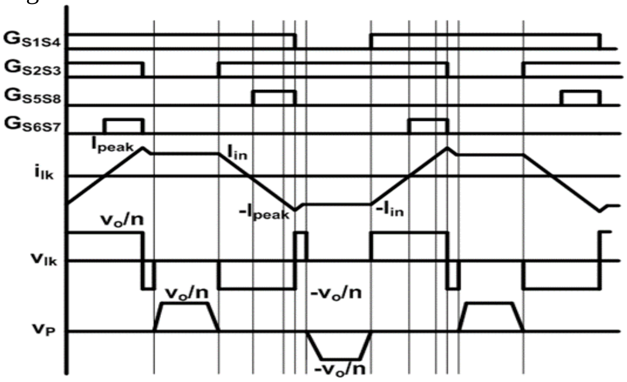

Fig. 16 Pulse Waveform of CFDABSNC Converter

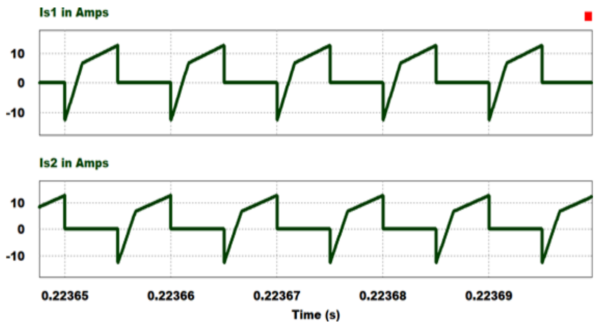

Fig. 17 Current Responses through Primary Switches I_{S1} and I_{S2} of CVFDAB Converter

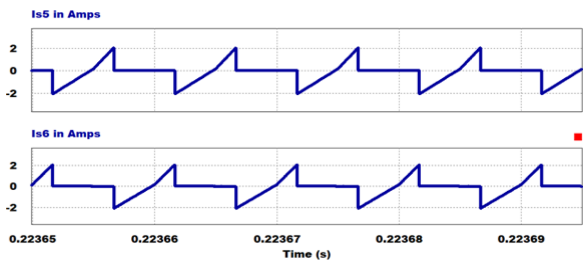

Fig. 18 Current Responses through Primary Switches I_{S5} and I_{S6} of CVFDAB Converter

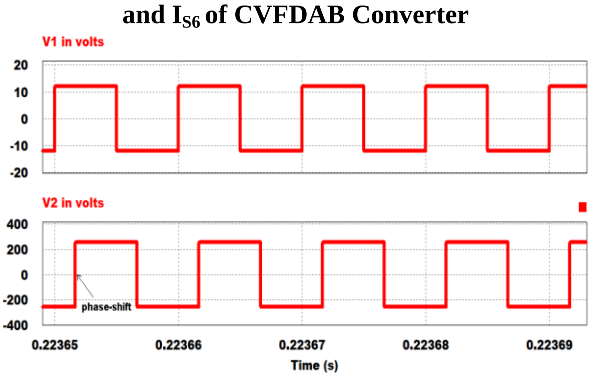

Fig. 19 Voltage Responses across the Primary V_1 and Secondary V_2 switches of CVFDAB Converter

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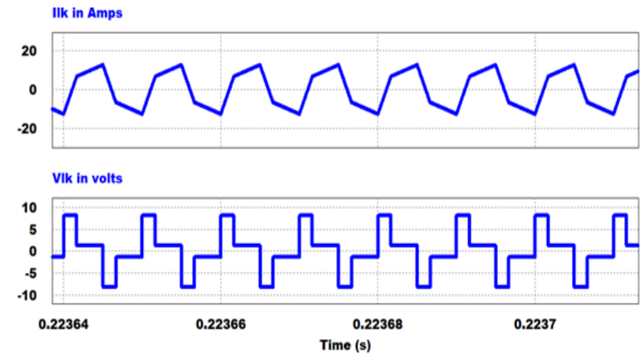


Fig. 20 Current and Voltage Responses of Discharge Inductance I_{lk} and V_{lk} of CVFDAB Converter

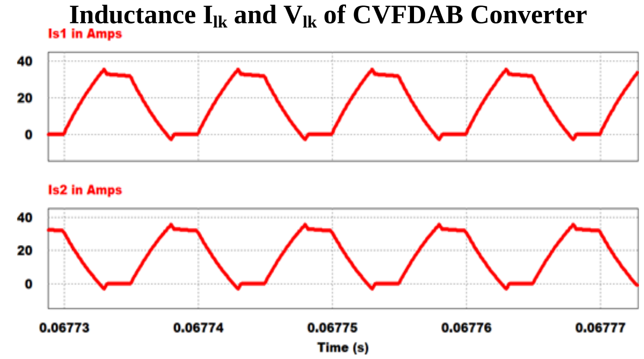


Fig. 21 Responses of Current through Primary Switches I_{S1} and I_{S2} of CFDABSNC Converter

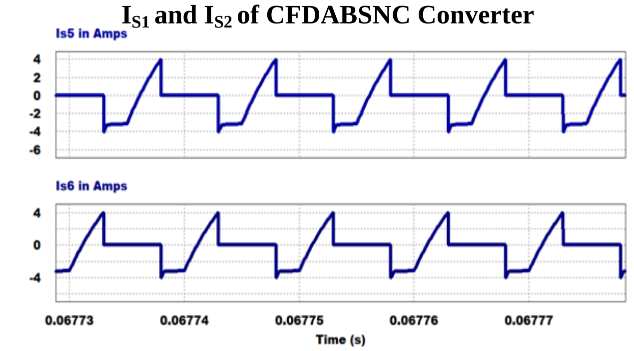
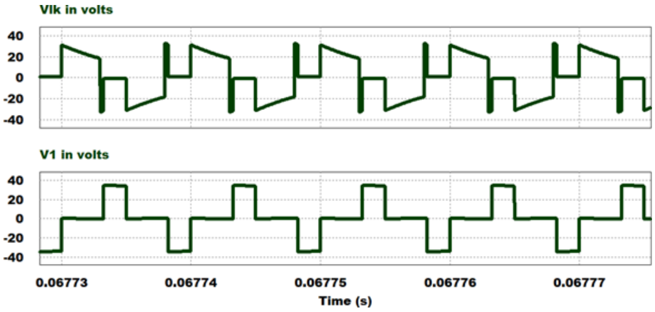


Fig. 22 Responses of Current through Primary Switches I_{S5} and I_{S6} of CFDABSNC Converter



Fig, 23 Responses of Voltage across Discharge Inductance V_{lk} and Primary Switches V_1 of CFDABSNC Converter

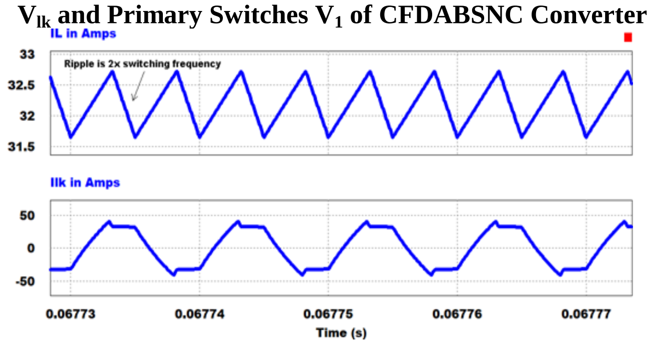


Fig. 24 Responses of Current through Input Inductor I_L and Discharge Inductance I_{lk} of CFDABSNC Converter

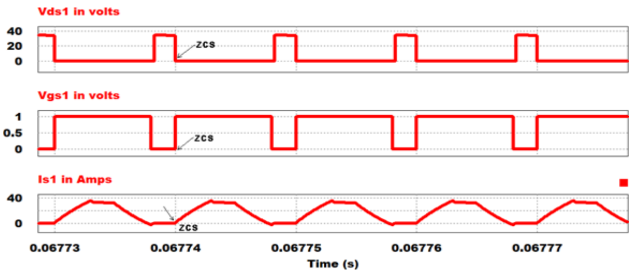


Fig. 25 Voltage & Current Responses of Primary Switch S_1

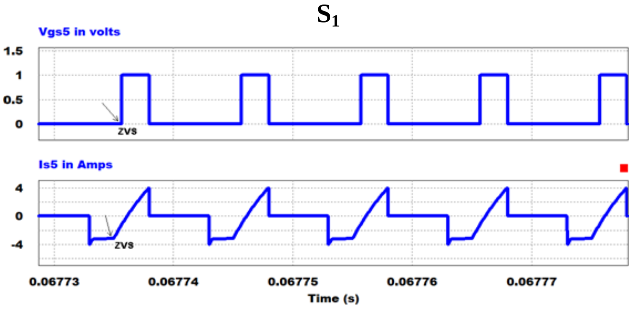


Fig. 26 Voltage & Current Responses of Secondary Switch S_5

From the simulation results of CFDABSNC converter, Fig. 21 and Fig. 22 illustrate the waveforms of current through, primary and secondary switches respectively and due to modulation signals these two opposite pairs of input and output sides are displaced by 180◦ with each other. They also show the current through reverse diodes in parallel with the power semiconductor devices. The switches s1 and s2 performs ZCS turn off because of modulation at output side, reverse diodes forward biased before the switches turned off as shown in Fig. 21. Fig. 22, clearly justifies ZVS of S5 and S6 switches, the reverse diodes across the switches conduct before the conduction of corresponding switches. Fig. 23 presents the voltage across leakage inductance, Vlk clearly validates the variations in ramps of the input current Ilk waveforms and voltage waveform V1 across the primary switches of the transformer is naturally held at Vo/n. In Fig. 24 shows transformer leakage inductance and inductor currents at the input, the ripple current of input inductor response IL is two times that of the switching frequency fs, leads to decrease in size. In, leakage inductance current waveform Ilk is continuous and has a small peak value beyond the steady value ensure ZCS turnoff due to continued conduction of reverse diodes across the corresponding switches. Fig. 25 and Fig. 26 demonstrate the voltage & current responses of input switch S1 and secondary switch S5 respectively. It clearly verifies ZCS turn off in the primary and ZVS turn on in the secondary side switches (as mentioned in the Fig. 25 and Fig. 26) without use of any snubbers. Therefore, this converter leads to higher efficiency compared to conventional topologies.

VI. CONCLUSION

This paper has discussed the various topologies of isolated DC-DC dual active bridge converters for microgrid applications. In soft-switching range of view, all the topologies have limitations even with the use of active and passive snubbers especially lack of soft-switching at light load conditions.

Current-fed DAB without snubber converter eliminates the above-mentioned problems. In this paper, both traditional VFDAB and current-fed naturally hold snubber-less DAB converter have simulated using PSIM 9.0.3 software package. From the simulation results, converter without snubber verify the commutation at zero current and natural voltage clamping of input side switches. Primary devices achieve ZCS and secondary devices achieve ZVS. Hence, switching losses reduces drastically. The modulation technique uses at the output side is simple to implement. Therefore, this topology is easy to interleave and extensible for a microgrid application.

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