ELECTRIC VEHICLE ON-BOARD CHARGER USING AN ISOLATED MULTIPORT DC-DC CONVERTER

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ABSTRACT
The normal engines that burn fuel can be replaced with electrical vehicles (EVs). A battery-connected isolated DC/DC converter along with an AC/DC power-factor correction (PFC) converter constitute the usual grid-connected EV chargers. It is possible to utilize the isolated DC/DC converter as a bidirectional converter to supply electricity to the grid during peak hours. Wide input and output voltage ranges are necessary for the DC/DC converter to function efficiently due to the voltage fluctuates greatly throughout the EV battery charging process. The full-bridge and half-bridge topologies of the bidirectional dual-active-bridge (DAB) converter are analyzed in this article. Zero-voltage-switching (ZVS) is no longer achievable under light-load conditions. Therefore, to increase the overall efficiency of the DAB converters, a switching control strategy that emphasizes variable frequency and duty-cycle (VFD) is proposed for light loads. Simulation results validate this technique reliability.

Keywords:
Zero-voltage-switching, Dual-active-bridge converter, Bidirectional DAB converter, Electrical vehicle, Variable frequency and duty-cycle.

INTRODUCTION
The demand for new environmentally friendly electrical vehicles (EVs) as a substitute for conventional internal combustion engines that run on gasoline is growing recently due to carbon dioxide (CO2) emissions, excessive fossil fuel exploitation, greenhouse effects and the severe consequences of global warming.

An isolated DC/DC converter coupled to the battery to offer both galvanic isolation and voltage control, and a grid-connected AC/DC power-factor-correction (PFC) converter for power quality enhancement and harmonic regulation, serve as a typical EV charger. Resonant LLC converters are a good option for grid-to-vehicle (G2V) unidirectional chargers that use DC/DC conversion [1], [2].

When energy demand is high, such as during peak hours, bidirectional vehicle-to-grid (V2G) chargers supply electricity to the grid. To assist stabilize the power grid during peak hours and enable battery charging during off-peak hours, the bidirectional chargers interact with the energy system [3], [4]. The literature discusses quite a few bidirectional DC/DC converters [5]– [7]. The two most crucial features of an effective EV charger that are discussed in the articles are efficiency and power density. There have been proposals for both isolated and non-isolated DC/DC converters [8], [9]. But for EV battery chargers, galvanic separation is crucial [10].

The most popular bidirectional isolated DC/DC converters found in plug-in EV chargers are the resonant CLLC and dual-active-bridge (DAB) converters, which come in both full-bridge and half-bridge topologies [11], [12]. These converters basic characteristics that render these appropriate for

EV applications include proper galvanic isolation, a soft switching control method, high power density, high efficiency across a broad range of output power and bidirectional power transfer [13].
For isolated, high-power, bidirectional DC/DC applications, resonant full/half bridge CLLC converters are appropriate [14]. The primary-side switches can achieve zero-voltage-switching (ZVS), while the secondary-side rectifier switches can achieve zero-current-switching (ZCS). The magnetizing inductor (Lm) current must be adequate to fully charge and discharge the switches output capacitors (Cout) during the dead-band period in order to guarantee the ZVS of the primary-side switches in various outputs [11]. However, the CLLC converter is not suitable for EV chargers, it can function flawlessly under changing load and constant output voltage situations. Additionally, the converter needs a complex control technique, and the gain is non-linear with the load.
The isolated high voltage and power density of bidirectional isolated DC/DC full and half-bridge DAB, FBDAB and HFDAB converters across a broad output power range allow them to be widely employed in EV charging applications [11], [15]. Nearly linearly correlated with phase-shift, the bidirectional DAB converter gain is proportionate to the load. The DAB converters thus benefit from simpler driving circuitry and control technique in comparison to CLLC resonant converters.
The primary and secondary side switches in DAB converters can function in ZVS conditions. However, in light-load conditions, the DAB converters can experience ZVS. The voltage fluctuates significantly throughout the EV battery charger charging process, therefore bidirectional DC/DC converters feature a vast input/output voltage range depending on the demands of the electric vehicle [16]. Therefore, in EV charger applications, it is crucial to provide an acceptable level of efficiency throughout an extensive range of output voltage/power.
In order to address the aforementioned drawbacks of the bidirectional DAB, converters used in EV chargers and achieve high efficiency under both light and heavy loads, the present research proposes a hybrid control approach that combines variable frequency and duty-cycle (VFD) control mode for light loads with ZVS control mode for heavy loads. The ZVS cannot be reached to offer overall maximum efficiency, hence the advised VFD control approach is only employed under moderate loads. For an in-depth study of both FBDAB and HBDAB converters utilizing the proposed control approach, the hybrid control method is applied to both full bridge and half bridge 1kW isolated bidirectional DAB converters. The simulation results are then compared and studied.

Principles of EV Charging FBDAB and HBDAB Converter Operation

The solitary bidirectional FBDAB and HBDAB converters are depicted in Fig. 1 respectively. The DAB converter can be designed with either a full or half bridge topology. The FBDAB converter benefits from a number of control strategies, notably [17]– [19]:

- Single-phase-shift (SPS)
- Enhanced phase-shift (EPS)
- Dual-phase-shift (DPS)
- Triple-phase-shift (TPS)

Although the HBDAB converter has many benefits, including low weight, small size, straightforward drive circuitry and low cost, the SPS control method is the only control strategy available for it [11]. In the present study, bidirectional FBDAB and HBDAB converters for EV applications are reviewed and contrasted, and an ideal hybrid control strategy is implemented utilizing both ZVS and VFD control techniques.
The grid-to-vehicle (G2V) mode waveforms of the DAB converter using the single-phase-shift (SPS) control mechanism are displayed in Fig. 2. All MOSFET gate voltages (SQ1–SQ8) are shown in Fig. 2. The transformer primary-side voltage, transformer secondary-side voltage, inductor current, inductor voltage, and output current waveforms are denoted as Vpri, Vsec, iL, VL and io, respectively. At primary and secondary side bridges, the result is a phase shift of ts=DTs/2. Dis represents the switches duty-cycle ($0<D\leq0.5$) and Ts is the switching time.

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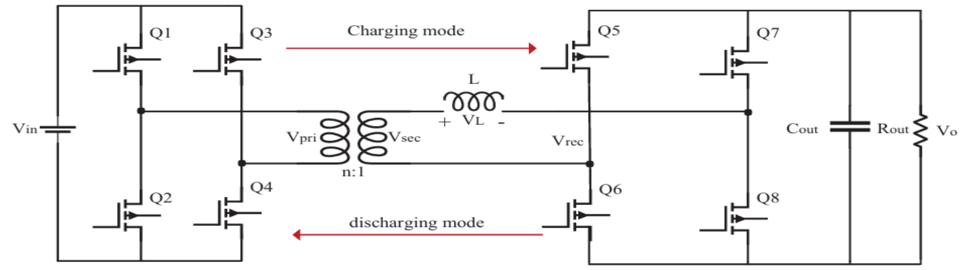

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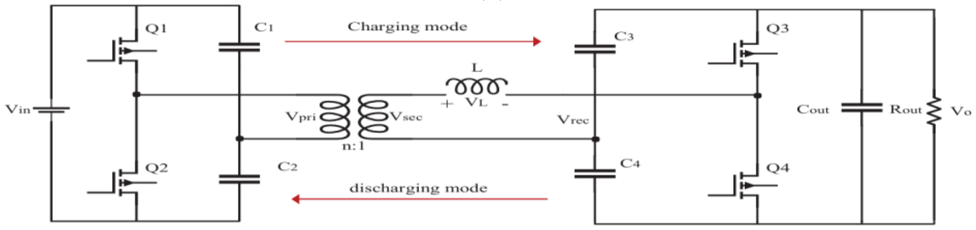

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Fig.1. isolated bidirectional converters for DC/DC (a) FBDAB and (b) HBDAB.

Initially, only MOSFETs Q1 and Q4 are active on the main side of Fig. 2. MOSFETs sQ5 and Q8 are conducting in the secondary side rectifier bridge. At the beginning, the inductor current is negative; at t1, it becomes positive. This indicates that MOSFETs Q1, Q4, Q5, and Q8 are activated via ZVS. The insufficient energy stored in the inductor L prevents the ZVS from being reached under light loads. The inductor current is initially positive under low load conditions and turns negative at t1, indicating that ZVS is not attained. When the inductor voltage is halved, the waveforms of the HBDAB converter are comparable.

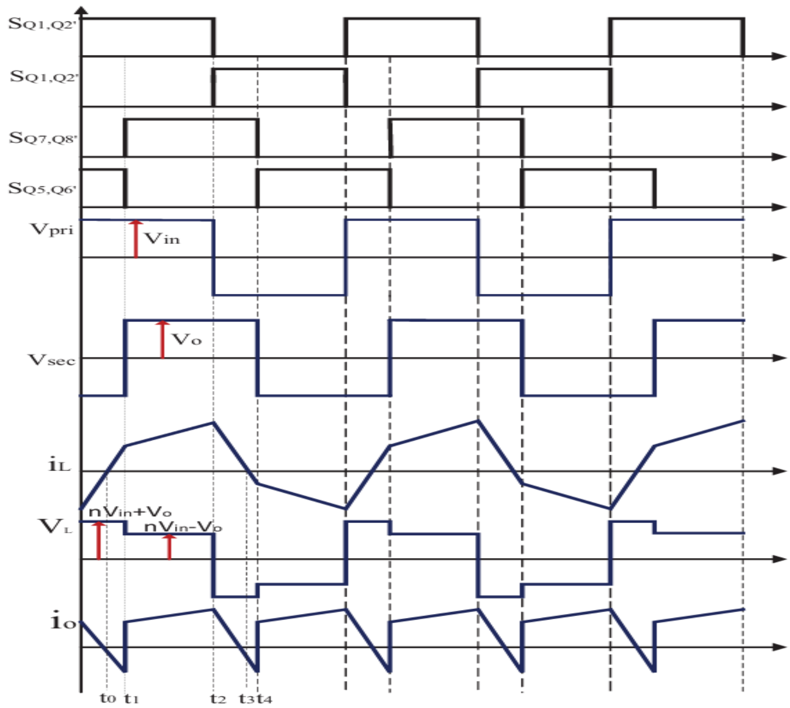

Fig.2. DAB converter waveforms in G2V charging mode.

Range of Zero Voltage Switching:

The following formula can be used for calculating the FBDAB and HBDAB gain in the G2V charging mode [11]:

$$G_{G2V,FBDAB} = \frac{V_0}{V_{in}} = \frac{R_0 D}{2nf_s L}(1-D) \qquad (1)$$

$$G_{G2V,HBDAB} = \frac{V_0}{V_{in}} = \frac{R_0 D}{8nf_s L}(1-D) \qquad (2)$$

where, accordingly n is the transformers turn-ratio, fs is the switching frequency, Vin is the input voltage, Ro is the output load and Vo is the output voltage. The ZVS requires its iL waveform contain a positive amount at t1 and a negative amount when t < t0. The ZVS can be reached in areas which satisfy the following criteria for both FBDAB and HBDAB converters [11]:

$$\begin{cases} D \geq \frac{G_{DAB}-1}{2G_{DAB}} & G_{DAB} \geq 1 \\ D \geq \frac{1-G_{DAB}}{2} & G_{DAB} \leq 1 \end{cases} \quad (3)$$

The ZVS can be attained in DAB converters with GDAB=1/n, according to (3). The DAB converter is unable to achieve the ZVS at low loads, when the duty-cycle is less. In order to reduce the significant switching losses, a different control method is to be implemented. The various control strategy zones for the FBDAB and HBDAB converters obtained from (3) are displayed in Fig. 3.

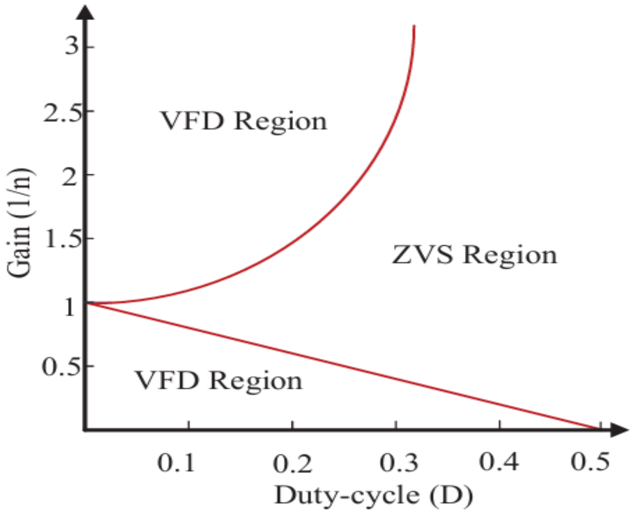

Fig.3. Various areas of the proposed FBDAB and HBDAB converter control technique.

Proposed Light-Load VFD Control Techniques

A vast output voltage range is necessary for EV chargers. Therefore, in order to prevent saturation, magnetic components as transformers and inductors should be appropriately established. The transformer maximum flux density (Bm) can be computed using the formula [20]:

$$B_m = \frac{D}{f_s}\frac{V_{in}}{4A_eN_{pri}} \quad (4)$$

In this case, Ae is the transformer cross-sectional area, Npri is the number of primary windings turns and Vin is the fixed 500V DC connection. (4) states that the only factors influencing the maximum flux density are D and fs. In the non-ZVS zone, the transformer maximum magnetic flux density (Bm) is regulated to be 0.1T across all of its outputs. The VFD control mode in the non-ZVS area is therefore to set both fs and D so that, when the output voltage is changed, the D/fs ratio remains constant and, consequently, the maximum magnetic flux density remains unchanged. The design specifications are the frequency and duty-cycle maximum and minimum. The gain equations (1) and (2), respectively, can be used to determine the duty-cycle of HBDAB and FBDAB converters. Considering a linear connection between D and fs, the corresponding frequency is determined so that the D/fs ratio remains constant. For a linear connection between switching frequency (fs) and duty cycle (D), the line equation approximates this:

$$\frac{f_s - f_{s,max}}{D - D_{max}} = m \quad (5)$$

The DAB converter responds to variations in the output voltage in the non-ZVS area by operating in variable frequency and duty cycle (VFD) control mode. The new duty-cycle is computed from (2) and (1) each time the output voltage is changed in the VFD control mode and the ZVS cannot be reached. Switching frequency can be calculated using (5) and the new duty-cycle. The ratio D/fs will remain constant after determining D and fs using gain equations and (5). As switching power loss and frequency depend on a linear connection, the DAB converter switching power loss is significantly decreased when the VFD control technique is deployed.

SIMULATION RESULTS

Mode of G2V Charging:

Table I displays the design features and requirements. In G2V mode, the output range is 200V to 420V, the gain is 0.7/n − 1.5/n, and Vin is a set value of 500V. In the ZVS domain, the switching frequency for both V2G and G2V modes is set at 170 kHz.

Mode of V2G Discharging:

The Vin and Vo ranges in vehicle-to-grid (V2G) mode are 350–420V and 500V, respectively. The gain of the DAB converter is affected by the transformer turns ratio n in both the V2G and G2V modes, correspondingly. As regulate the power flow in V2G/G2V modes and fully capitalize on the ZVS area, the turns ratio is set to 1.5.

Table I

Parameters for Proposed DAB DC/DC Converters

Parameters	**Symbol**	**Value**
Input Voltage	V_{in}	500V
Output Voltage	V_{out}	200-420V
Nominal Output Power	P_{out}	1KW
Maximum Frequency	f_{max}	170kHZ
Minimum Frequency	f_{min}	100kHZ
Maximum Duty Cycle	D_{max}	45%
Turns Ratio	n:1	1.5:1
FBDAB inductor	L_{FBDAB}	90µH
HBDAB inductor	L_{HBDAB}	20µH

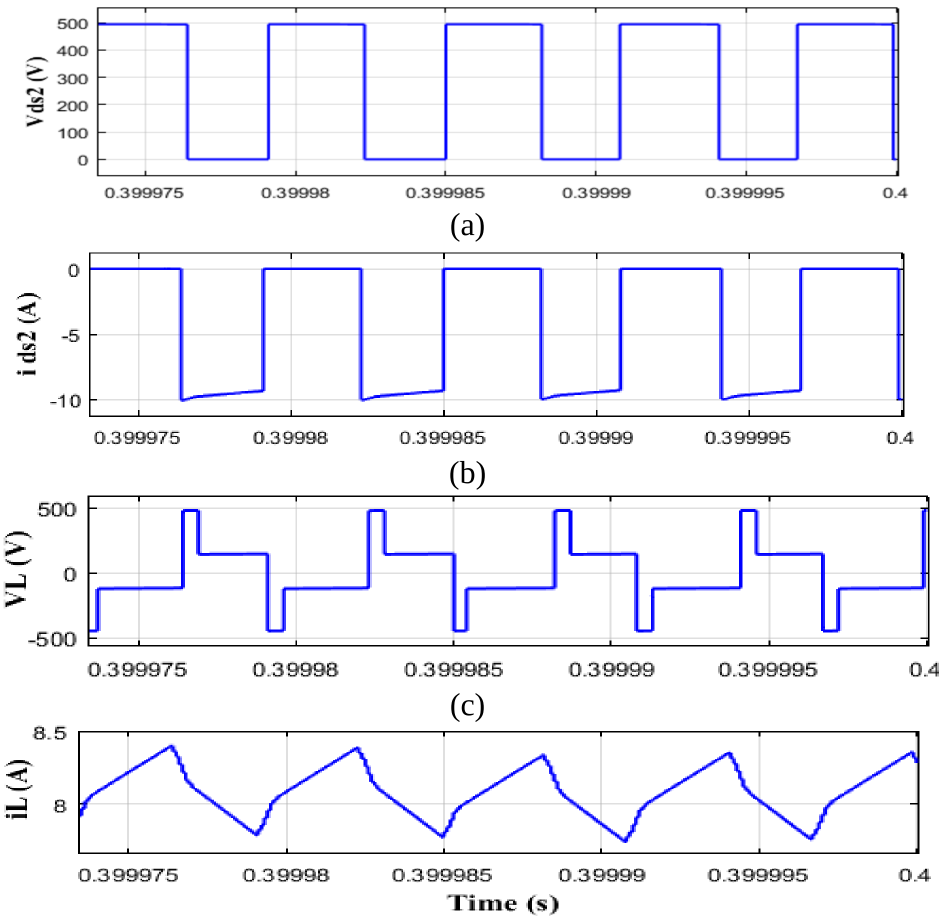

Fig.4. Simulation results of the proposed FBDAB converter (a) drain-source voltage of Q2, (Vds2) (b) drain-source current of Q2, (ids2) (c)Inductor voltage, (VL) (d) Inductor current, (iL).

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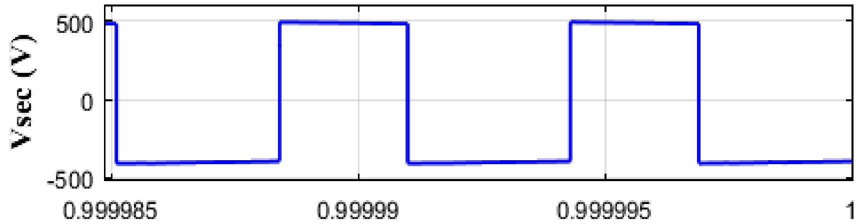
The FBDAB waveforms in G2V mode at Vo=300V, fs=170kHz and D=0.4 are shown in Fig. 4. The ZVS is used to turn on the switches in Fig. 4d. Each gain minimal duty-cycle required to reach the ZVS can be computed using (3). The duty cycle is lowered to produce the appropriate gain during light load conditions and the converter is no longer able to reach the ZVS.



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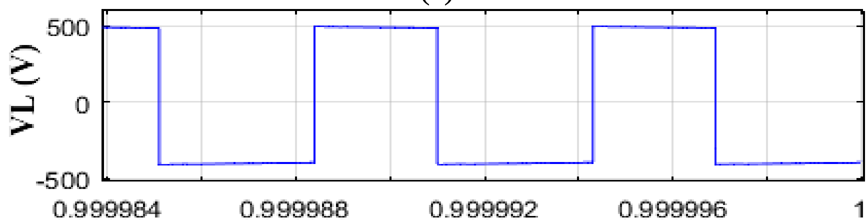

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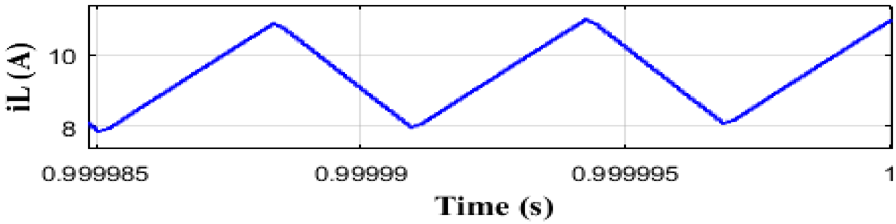

(c)

At light load conditions, the FBDAB converter runs at Vo=60V with an output power of 50W, as shown in Fig. 5. The duty-cycle is 0.35 and the converter gain is 0.25/n. As a result, the converter operates in a non-ZVS area. As seen in Fig. (5), the ZVS is lost in Q2 of the FBDAB converter. ZVS is therefore nearly difficult to perform for every switch and under light loads, an alternative control strategy must to be taken into consideration. This study VFD control approach enables increased efficiency at light loads.

The G2V and V2G modes of HBDAB and FBDAB converters respective efficiency ranges from 50W to full load. The VFD control mode is utilized in the non-ZVS zone shown in Fig. 3 as both DAB converters drop the ZVS at minimal load. Furthermore, the half-bridge architecture offers greater efficiency at light loads than the FBDAB converter since it uses fewer MOSFETs and driving components and offers a lower switching power loss. Nevertheless, the half-bridge architecture experiences increased current strains, necessitating a higher current rating for the switches. The following are the two control approaches provided:

- The proposed strategy for controlling variable frequency and duty-cycle (VFD) (fs=100−170kHz).
- Conventional DAB converters employ the fixed frequency (FF) control approach, where fs = 170 kHz. [11]

When light loads prevent the ZVS from being accomplished, the fixed frequency (FF) control mechanism is employed in typical DAB converters [11]. Using a set frequency of 170 kHz, SPS controls the switches in this control approach. However, because the converter is not receiving enough power to discharge the MOSFETs output capacitors, the switches are unable to reach the ZVS. As a result, the proposed VFD control approach offers much greater efficiency at minimal load.

CONCLUSION

In this electrical vehicle battery charging applications, the study presented an ideal hybrid control approach for bidirectional dual-active-bridge (DAB) converters with both full-bridge and half-bridge topologies (FBDAB and HBDAB) throughout an extensive output power range. Two control modes should be combined, according to the control method put forth by this article:

- For large loads, use the single-phase shift (SPS) control technique in conjunction with zero-voltage-switching (ZVS) mode.
- At minimal load, it operates in variable frequency and duty-cycle (VFD) mode.

The VFD mode is utilized in light-load conditions, where the ZVS cannot be realized because there is not enough energy flowing in the circuit, whereas the ZVS with SPS control mode offers the ZVS in medium to high output voltages, where the ZVS can be attained. When the VFD control mode is used and no auxiliary components were used, the DAB converter's efficiency at light loads greatly improved.

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