Analysis and Implementation of a DAB DC-DC Converter for OBC Application with Wide Output Voltage Range

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***Abstract*— In this paper, a bidirectional DC-DC converter is designed and analyzed for On-board charger (OBC) application that requires high power, and wide voltage range. The Dual Active Bridge (DAB) converter is an excellent choice for high-efficiency, high-power density, and bidirectional operation. The rated power of the DAB converter is 11kW and the specified output voltage range is 450V ≤ V_{dc} ≤ 850V. Hybrid modulation scheme using single-phase-shift (SPS) and dual-phase-shift (DPS) control is proposed to reduce RMS current, conduction losses in the higher voltage level, and achieve zero voltage switching (ZVS)-on of all the switches under wide battery voltage range. ZVS turn-on of all main switches at different voltage gain has been analyzed in detail. The simulation and experiments results are presented in this paper to verify the analysis and design of an 11kW converter prototype operating in the full ZVS range.**

***Index Terms*—DAB, DC/DC Converter, OBC, Wide voltage range.**

I. Introduction

Recently, increasing concerns on environmental issues and clean energy are prompting the introduction of electric vehicles (EVs). There are a wide variety of Battery Electric Vehicles (BEVs) in the market, each with its own charging time and range. Although being more eco-friendly and cheaper than internal combustion engines (ICE), the long charging time and range concerns of EVs remain major challenges to mass adoption [1]. Several isolated bidirectional dc-dc converters have been studied and proposed in recent years. The design targets of power electronics for EV charging systems include efficiency improvement, achieving high power density, and overall cost reduction of the power converter. The high-power, high voltage electric vehicle (EV) charging system has been actively investigated recently to reduce the charging time [2].

There are a wide variety of DC-DC converters that are used according to their power density. For power conversion applications which require bidirectional power flow, galvanic isolation, soft-switching, the dual active bridge (DAB) is the preferred topology due to its various advantages [3]. In order to control power transfer, various control techniques are reported in literature [4]. The DAB converter, on the other hand, can be operated most efficiently when the input to output ratio (V_{in}/V_o) is close to the transformer turns ratio n [5] [6]. In terms of current stress, SPS modulation control is only effective when the voltage gain is unity. The DPS control on the other hand, provides flexibility in power and control along with reduction in reactive power with two control degrees of freedom in terms of inner and outer phase shift ratios [7]. However, different selections of phase shift results in different peak of the inductor current. As the battery voltage varies during the whole charging range, the peak of the inductor current increases due to the mismatch of the voltage on the primary and secondary sides. The performance of the wide voltage range operation depends on the modulation control techniques such as dual-phase-shift, triple-phase shift and PWM control.

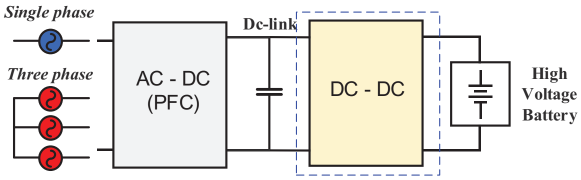

Fig. 1. EV On-board Charger block diagram

The commercially available OBCs have a two-stage structure of a power-factor correction (PFC) converter for harmonic reduction, followed by a dc-dc converter for output control and electrical isolation. Fig. 1 depicts a typical structure of an OBC, which consists of a PFC stage and a DC-DC stage. This paper deals with the design of the DC-DC stage of such a system, with specific emphasis on achieving high power-density and efficiency, as discussed in [8]. The focus and contribution of this work is to analyze the performance and implementation of the converter for wide output voltage range operation that can be used for OBC application due to its advantages of bidirectional power flow, Zero-voltage switching turn-on of the main switches, reduction in RMS current and high-power density. The rest of the paper is organized as follows. The proposed control for wide voltage operation of the DAB converter using hybrid control in wide voltage range are summarized in Section 2. Converter design considerations with comparison is shown in Section 3. In Section 4, the performance of the DAB converter is presented by experimental results. The obtained results shows that the DAB converter achieves high efficiency operation in a wide output voltage range. The final section depicts conclusion.

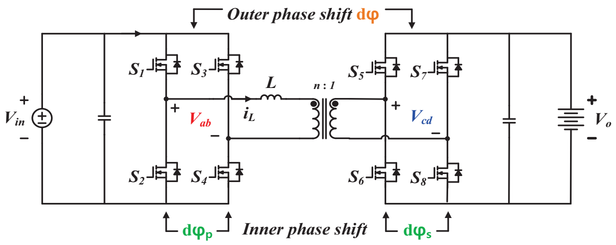

Fig. 2. Circuit schematic of a DAB converter

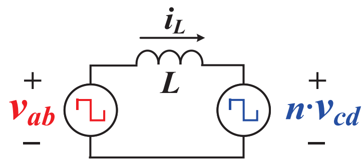

Fig. 3. Equivalent circuit of a DAB converter

II. Proposed Control Method for Wide Voltage Operation

A. Hybrid SPS and DPS control for securing ZVS over wide voltage range.

The full-bridge DAB converter shown in Fig. 2 consists of two full bridges interfaced through a high-frequency transformer (Leakage inductance as an energy transfer element) enabling power flow in both directions. Each bridge is controlled with constant duty cycle (50%) to generate a high-frequency square wave voltage at its transformer terminals $(\pm V_i, \pm V_o)$ [4].

To realize the zero-voltage switching (ZVS) for all the eight switches within a wide-output-power range, control modulation such as SPS and DPS has been used. SPS is the most commonly used control. The SPS method indicates that the voltages generated at the primary and secondary (which is referred to primary side) of the High-frequency (HF) transformer is phase shifted by φ where the positive value of φ corresponds to charging / forward mode and negative value of φ is for discharging / reverse mode. This technique is simple and easier to implement in closed loop as only one control variable is there which is $\varphi = D/\pi$. In SPS control, the phase-shifts relationship is expressed as shown in (1). Larger circulating current can be observed during the power transmission, which is also known as reactive power. To reduce or even eliminate the reactive power, the DPS control was developed [9].

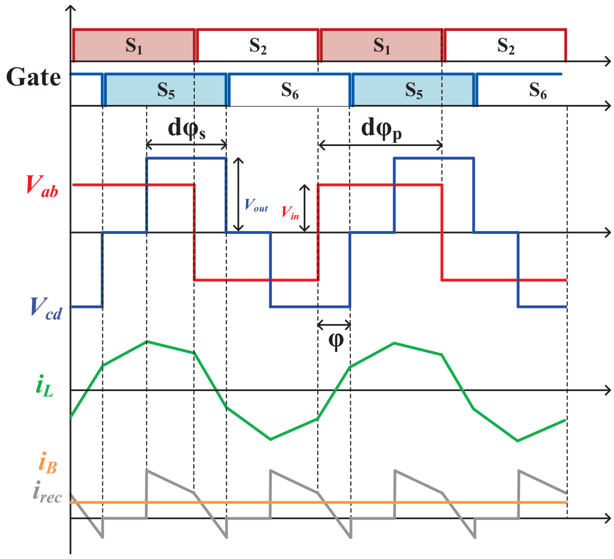

Fig. 4. DPS operation key waveforms

$$P = \frac{n \cdot V_i V_o}{2 f_s L} \phi(1-\phi) \tag{1}$$

$$i_{L(rms)} = \sqrt{\frac{\int_0^{T_S/2} i^2{}_L(t)\,dt}{T_s/2}} \tag{2}$$

It is difficult to operate the converter efficiently especially at light loads [10]. To increase the overall efficiency of a DAB converter, reactive power and the RMS value of the inductor current should be msinimized within the ZVS constraints. Minimizing the RMS value of the inductor current is of the important factor to reduce losses. The RMS value of the inductor current is expressed as shown in (2).

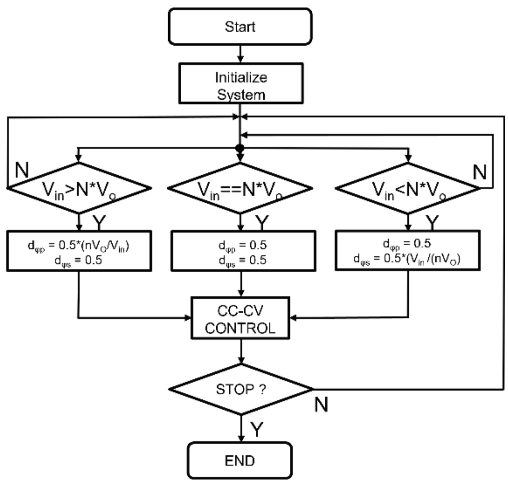

Fig. 5. Hybrid DPS and SPS Control Algorithm Flowchart

TABLE I
COMPARISON AND CHARACTERSTICS OF ISOLATED DC-DC CONVERTERS IN EV CHARGERS

	Modulation method	Control variable variation	Operation	Other
LLC [12]	Frequency modulation	Complex	Unidirectional	Sensitive to resonant components' tolerance
Phase-shift Full Bridge	PWM modulation	Simple	Unidirectional	No tolerance sensitive component
CLLC [11]	Frequency modulation	Complex	Bidirectional	Sensitive to resonant components' tolerance
DAB (in this paper)	Phase shift modulation + variable DC link control	Simple	Bidirectional	No tolerance sensitive component

The control algorithm is illustrated in Fig. 5. Firstly, after the initialization step the voltage reference is used to control and determine the voltage state of V_{in} and V_o. According to voltage gain **(*Mv*)** **(**V_{in}==nV_o, $V_{in}>nV_o$, $V_{in}<nV_o$) the duty of both primary and secondary sides are fixed or changed. The CC-CV control based on charging profile is executed and charging is completed.

The comparison between various isolated dc-dc topologies is summarized in Table I. Due to the simple control variable variation and no tolerance with sensitive components, the DAB converter with proposed hybrid SPS and DPS control is most suitable for wide voltage range application. Other topologies such as LLC and CLLC are complex to design due to sensitive tolerance to its resonant components [13].

B. ZVS range analysis

In SPS modulation, the square wave form with constant duty cycle (50%) at the primary and secondary side is the simplest way to regulate the power. When the voltage gain is not equal or far from one, DAB converter can lose ZVS easily which results in hard switching. Compared with the conventional SPS control, there are two independent parameters to manipulate the energy flow in the DAB with the DPS control.

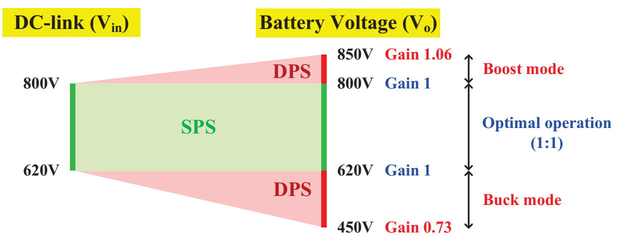

Fig. 6. Voltage gain for wide output voltage operation

In DPS control, the power flow is controlled not only by the phase shift between the primary and secondary voltages (outer phase shift) but also the phase shift between legs in the primary and the secondary H-bridges (inner phase shift). The DPS control can decrease the current stress, improving efficiency [6]. Fig. 4 shows the buck and boost mode region, when the converter cannot operate at ZVS over wide voltage variation which results in power loss and its efficiency is greatly reduced. From the analysis, it is noted that the converter achieves ZVS when the voltage gain (*Mv)* is not equal or far from 1. At the buck region i.e., V_o < V_{in} and boost mode region i.e. V_o > V_{in}, when the converter cannot operate at ZVS which results in power loss. Based on the analysis in Fig. 7, the converter can also achieve ZVS when the voltage gain varies. When the voltage gain (*Mv)* in buck mode is less than 1, dφp is decreased to achieve ZVS. Likewise, dφs is decreased, as the *Mv* in boost mode is higher than 1.

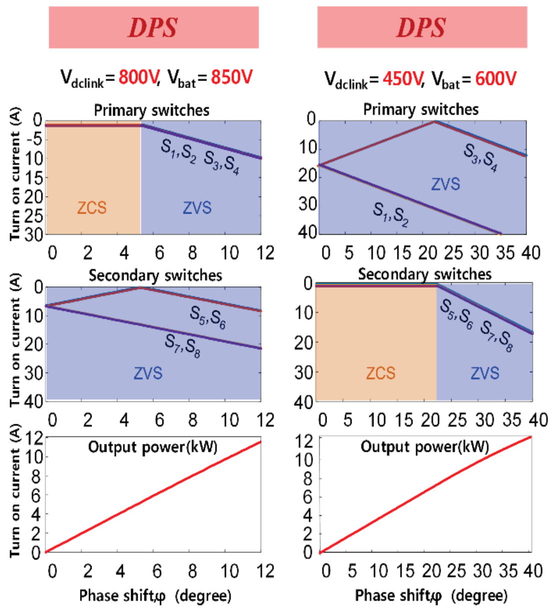

Fig. 7. ZVS range analysis of the DAB converter

For any DC-DC converter to operate at maximum efficiency, it is necessary to operate converter at ZVS under wide voltage range. In order to get exact analytical ZVS performance, it is necessary to include various parameters of such as transformers, inductors, dead time and switch output capacitance. The analyzed ZVS profile is simulated based on the charging profile of the converter as shown in Fig 7. The turn-on current of the primary side switches and secondary side switches is analyzed according to the given output power and phase shift degree.

III. DESIGN CONSIDERATIONS

In high power application converter, every part of the system must be studied in care. First, determine the voltages V_{in} and V_o, P_{rated} rated power and f_s switching frequency according to the application. Now, based on the voltage conversion ratio that $Mv = nV_0 / V_{in}$, the turns ratio of the transformer n can be determined, as well as the maximum voltage conversion ratio. The leakage inductance determines the power transfer capability. In terms of the selection of the semiconductors, it is characterized with simulation to determine their losses (conduction and switching) as a function of current. For this converter, 1200V SiC MOSFETs are selected. The Silicon Carbide technology is appropriate to consider in an OBC application.

The switching and conduction losses of the MOSFET are calculated and measured using simulations tools. The results and graph given in the manufacturer datasheet are often far from our case because the parameters are more environmentally dependent and values differs from each operating point. Therefore, to analyze accurately simulation using PLECS model is selected.

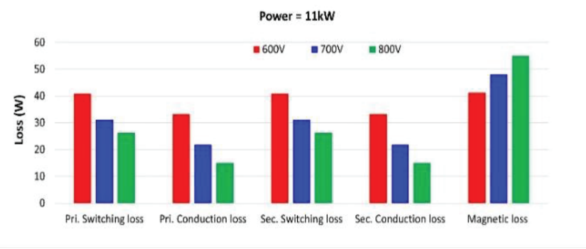

Fig. 8. Loss distribution calculation according to voltage

IV. EXPERIMENTAL RESULTS

Table II shows the designed parameters of a 11kW bidirectional DAB converter. The experimental results are shown mainly using DPS control when the *Mv* varies. The RMS current of the transformer is reduced, and soft-switching turn-on is achieved in optimal, buck and boost operations. Fig 9 and Fig 10. shows the experimental result of the converter operated in wide voltage range at V_{in}=620 and V_o=450V. $V_{ds,S8}$ is the drain to source voltage of secondary side switch S8, V_{ab} and V_{cd} are the square wave voltage generated at the primary and secondary side, I_L is the leakage inductor current and I_O is the output current.

TABLE II
PARAMETERS OF DAB CONVERTER

Items	Value
Input Voltage (V_{in})	620V ~ 800V
Output Voltage (V_o)	450V ~ 820V
Rated Power	11kW
Switching frequency (f_s)	100kHz
Components	**Specifications**
MOSFETs	8 x IMBG120R030M1H
Capacitors	3 x C4AQNBW5250M3OJ
Transformer	2 x PQ 65/44, wire 0.12/250x2
Inductor	2 x PQ 60/52, wire 0.12/600
Gate Driver	8 x UCC5350MC

❖ Infineon Technologies SiC MOSFETs are used.

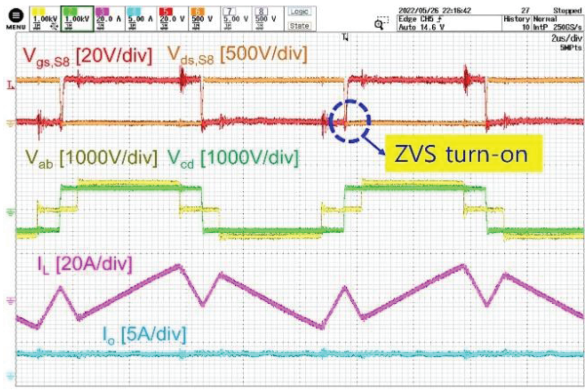

Fig. 9. Experimental waveforms of the DAB under DPS control at 2.2kW, Vin = 620V and Vo = 450V.

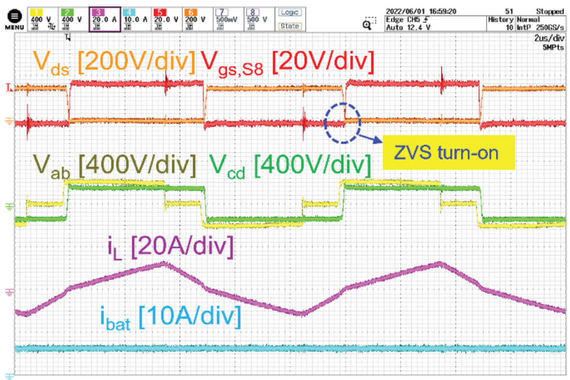

Fig. 10. Experimental waveforms of the DAB under DPS control at 875W, Vin = 200V and Vo = 145V

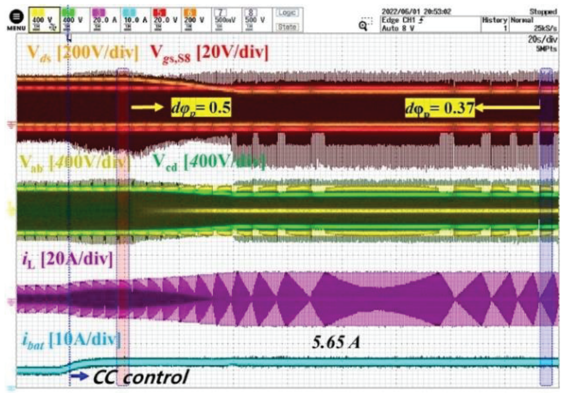

Fig. 11. Experimental waveforms showing transition from SPS to DPS control with CC control at Vin = 200V and Vo = 145V

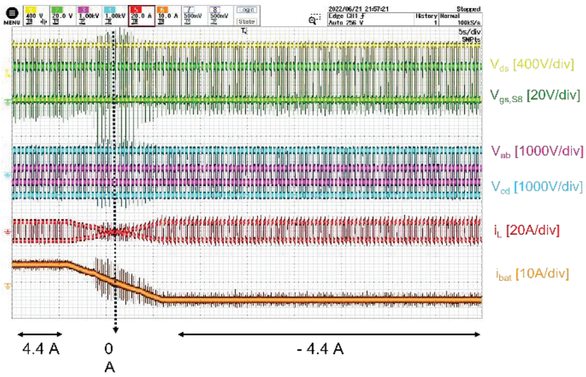

Fig.12. Experimental waveforms showing charging and discharging mode at Power=3kW.

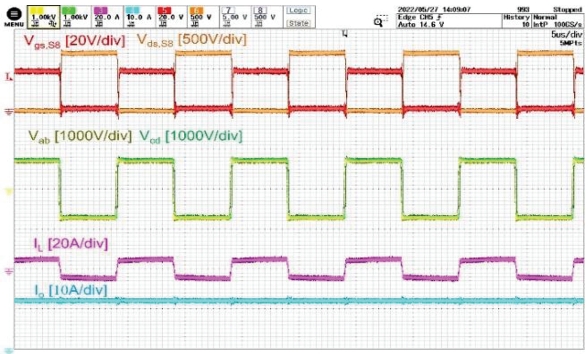

Fig. 13. Experimental waveforms showing charging and discharging mode at Vo = 800V and Power = 11kW.

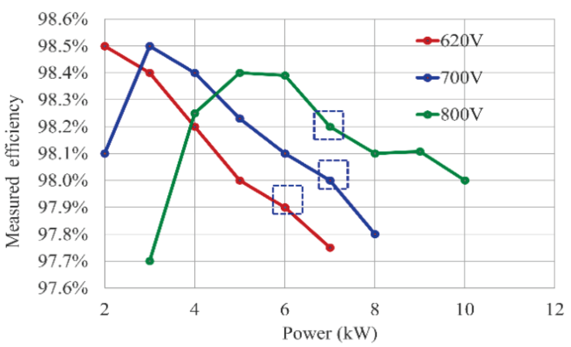

Fig. 14. Measured efficiency at Vo = 620V, 700V, 800V

Fig. 15. Measured efficiency at Vo = 800V (measured by T3000)

Fig. 11 shows the voltage and current waveform applied to the transformer using SPS and DPS control. It is clearly confirmed that with the change in dφp to 0.37, the converter can operate smoothly with good performance.

The experimental waveforms using SPS at optimal operation is shown in Fig. 13 as the primary and secondary sides switches can easily achieve ZVS. In the wide voltage operation, the key concern is to operate the converter with higher efficiency and low current stress which is possible using various modulation such as DPS and TPS control modulation. Based on the analysis, the converter performance is excellent at various operating points. Fig. 14 shows the measured efficiency at 98.10% when battery voltage is 800V and Fig. 15 shows the efficiency of the converter at different operating points of the converter.

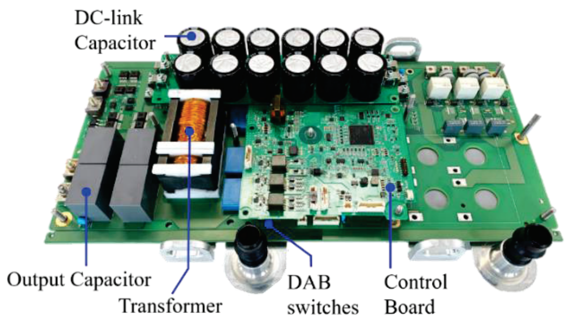

Fig. 16. Prototype of the converter

V. Conclusions

In this paper, authors designed a DAB based dc-dc converter securing zero-voltage switching considering the wide output voltage range. The zero-voltage switching of all main switches was analyzed in detail. The converter has been implemented with SiC MOSFET for EV OBC application. Optimized hybrid control method using SPS and DPS control has been used to reduce RMS current and achieve ZVS turn-on of all switches under wide battery voltage range. Moreover, the analysis and implementation demonstrated that overall higher efficiency could be achieved by adjusting the phase shift duty using SPS and DPS control depending on the operating point of the converter. The experiment results show the good performance of converter that can achieve high efficiency over 98%. The theoretical and practical analysis both verifies that the DAB converter can be used for OBC application.

Acknowledgment

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