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A Bidirectional DC-DC Converter using Soft Switching and Resonant Converter

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Abstract - A proposed bidirectional dc-dc converter and Resonant Converter Transformer-based circuit topologies are commonly employed in conventional bidirectional converters, and soft-switching techniques, including zero-voltage switching (ZVS) or zero-current switching (ZCS), are frequently applied to mitigate switching losses. Unfortunately, the use of more than four switches and several diodes in these transformer-based schemes increase production costs and reduce conversion efficiency. In this work, a coupled-inductor bidirectional converter scheme utilizes four power switches to achieve the goal of bidirectional current control. The high step-up and step-down ratios enable a battery module current with a low voltage to be injected into a high-voltage dc bus for subsequent utilization. Experimental results based on an 800-W prototype are provided to verify the effectiveness of the proposed bidirectional converter. Since the techniques of voltage clamping, synchronous rectification and soft switching are utilized in the proposed circuit topology, and the corresponding device specifications are adequately fulfilled, the proposed converter can provide highly efficient bidirectional power conversion in a wide range on the low-voltage side.

Keywords: Bidirectional converter, Coupled inductor, Step-up, Step-down, High-efficiency

I. INTRODUCTION

The development of bidirectional dc-dc converters has recently become increasingly important for clean-energy vehicle applications because battery-based energy storage systems are required for cold starting and battery recharging. Bidirectional converters transfer power between two dc sources in both directions. However, back-up power from the battery is supplied using a bidirectional converter, which is employed in many uninterrupted power supplies (UPS), the front-end stage for clean-energy sources, and dc motor drivers circuits. The dc back-up energy system typically consists of numerous low-voltage-type batteries. Although series strings of storage batteries can provide a high voltage, slight mismatches or temperature differences cause charge imbalance when the series string is charged as a unit [1]. Charge equalization cycles must be employed to correct this imbalance; however, conventional approaches to this process stress batteries, shorten their life, and are limited to a low capacity power. The current extensive operation of batteries in parallel strings is based on the desire of enhancing the redundancy of the power supplied by a battery, and the problems caused by series strings of storage batteries can be alleviated [2]. However, output voltage remains low in this parallel connection configuration. Therefore, a highly efficient bidirectional dc-dc converter with high voltage diversity is a key component for batteries connected in parallel. Bidirectional dc-dc converters with transformer-based structures are the most common topologies [3] −[5], and soft-switching techniques are generally applied to reduce corresponding switching losses. These mechanisms with isolated transformers have high conduction losses because four to nine power switches are required. Many applications call for high step-up converters that do not require isolation [6], such as the front-end converter with dual inputs. Accordingly, practical implementation is complex and costly.

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Switched-capacitor dc-dc converters [7]−[9] have attracted much attention as an alternative method for providing bidirectional power flow control. However, increased switching loss and current stress are the critical drawbacks, and the primary challenge is to design a circuit that has few switch devices and capacitors. Generally, the bidirectional converter in the UPS must generally boost 48V to 400V, which is appropriate for eightfold step-up voltage gain. Zhao and Lee [6] developed a family of highly efficient, high step-up dc-dc converters by adding only one additional diode and a small capacitor. This capacitor can recycle leaked energy and eliminate the reverse-recovery problem. In this approach, the magnetic core can be regarded as a fly back transformer and most energy is stored in the magnetic inductor. Inaba et al. [10] introduced a two-quadrant pulse-width modulation (PWM) chopper-type dc-dc converter that uses a coupled inductor. In this technique, only three switches were needed to achieve bidirectional power flow. Although an additional snubber capacitor was utilized successfully to clamp spike voltage, a 250V voltage-rated switch was employed in a low-voltage (36V) side circuit, resulting in considerable conduction loss because a switch with a high () DSONR was used. Coupled inductors with a low-voltage-rated (80V) switch and a passive regenerative snubber circuit [11] was adopted to achieve high-voltage gain with a 400V output voltage; this gain is superior to that in [6]. Unfortunately, the non-isolation topologies in [6], [11] only control unidirectional power flow. Moreover, bidirectional dc-dc converters with transformer-based structures are not suitable for use in power sources with wide voltage variations because magnetizing currents are difficult to manage, large copper losses occur on the low-voltage side (LVS), and all energy is transferred from the large core. Therefore, the number of devices must be minimized and good transformer performance ensures the high-efficiency of a bidirectional converter.

This work presents a novel bidirectional converter with a coupled inductor, which uses only four switches to achieve high step-up and step-down functionalities. This circuit include soft switching, synchronous rectification, and voltage clamping to reduce switching and conduction losses caused by utilizing a low-voltage-rated device with a small $R_{DS\,(on)}$. The windings in the coupled inductor function as a bidirectional magnetic switch controlling energy release or storage. Since the slew rate of current change in the proposed coupled inductor is restricted by the leakage inductor, the current transition time to both sides easily facilitates soft-switching. The problems of saturation and imbalance of the magnetizing current for a variable voltage source are therefore eliminated. Moreover, a full copper film and few primary winding turns reduce the size, cost, and copper loss of the coupled inductor; the corresponding voltage gain, which is related to the turns ratio and duty cycle, is higher than that in previous work. The remainder of this paper is organized as follows. The converter operations and design considerations are described in Sections II and III, respectively. Section IV presents experimental results for a 24V/200V 800W power with 100-kHz switching frequency to validate the effectiveness of the proposed power conversion system. Finally, conclusions are given in Section V.

II. CONVERTER OPERATIONS

System has the following four parts circuit: an LVS, a clamped circuit, a middle circuit; and, a high-voltage side (HVS). The symbols used are as follows: V_L and V_H are the voltages at the LVS and HVS, respectively; L_P and L_S represent individual inductors on the primary and secondary sides of the coupled inductor (T_r), respectively, where the primary side is connected to a battery module; S1 and S2 are the low-voltage switch; and, S3 and S4 are the high-voltage switch. When power flows from the HVS to the LVS, the circuit works in buck mode to recharge the battery from the HVS or by absorbing regenerated energy. In the other power flow direction, the circuit works in boost mode to keep the HVS voltage at a desired level. The following assumptions simplify converter analyses. 1) All MOSFETs, including their body diodes, are assumed ideal switching elements. 2) The conductive voltage drops of the switch and diode are neglected. The converter design and analytical procedures in buck and boost modes are described in the following subsections.

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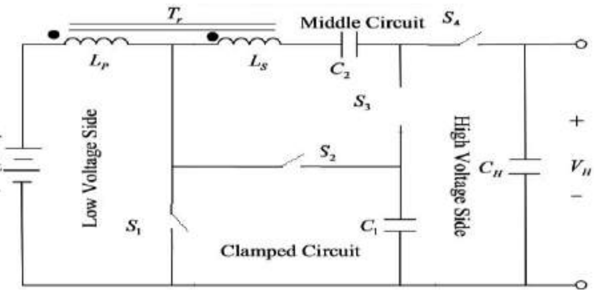

Fig. 1. System configuration of bidirectional converter

A. Buck Mode

Fig. 2 shows the characteristic waveforms of the proposed converter in buck mode. Fig. 3 shows the topological stages in one switching cycle. Fig. 3(a) is the equivalent circuit, including buck and boost modes, to define voltage polarities and current directions. The coupled inductor (T_r) can be modelled as an ideal transformer that has magnetizing inductors (L_{m1} and L_{m2}) and leakage inductors (L_{k1} and L_{k2}). The turn's ratio (N) and coupling coefficients (k) of this ideal transformer are defined as

$$N = N_2 / N_1 = \sqrt{L_{m2} / L_{m1}} \quad (1)$$

$$k_1 = L_{m1} / (L_{k1} + L_{m1}) = L_{m1} / L_P \quad (2a)$$

$$k_2 = L_{m2} / (L_{k2} + L_{m2}) = L_{m2} / L_S \quad (2b)$$

Where N_1 and N_2 are the winding turns on the primary and secondary sides of the coupled inductor (T_r), respectively. Because voltage gain is insensitive to the coupling coefficient and a clamped capacitor C1 is appropriately selected to completely absorb inductor energy leakage [10], [11], the coupling coefficient is simply set at 1 to obtain. $L_{m1} = L_P$, $L_{m2} = L_S$ and N= $\sqrt{L_S/L_P}$ via Eqs. (1) and (2).

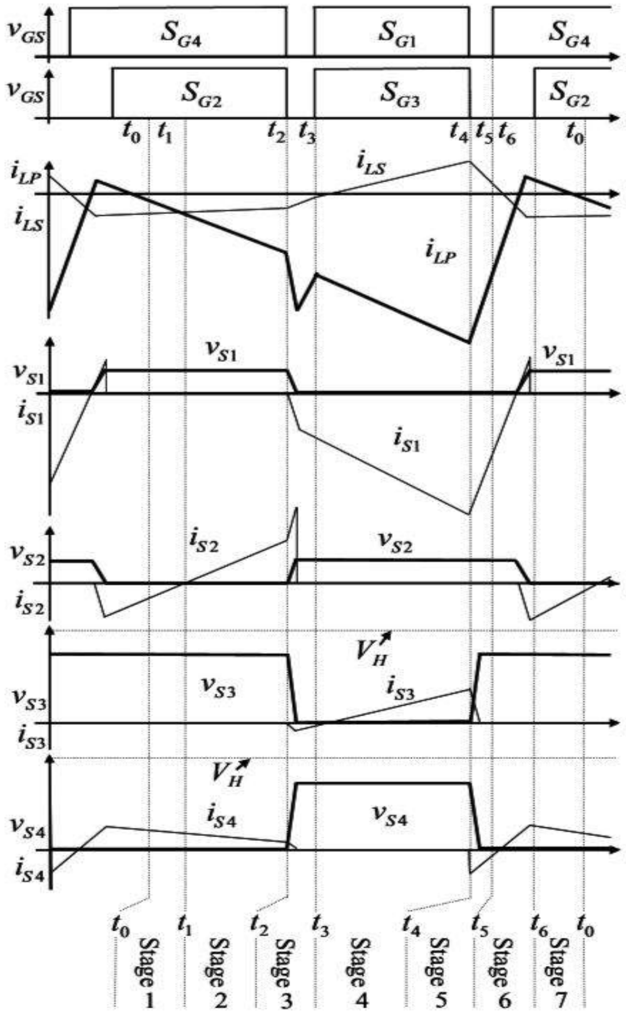

Fig. 2. Characteristic waveforms of bidirectional converter in buck mode.

B. *Boost Mode*

When the proposed converter operates in boost mode, power flow is from the battery to the HVS. Fig. 3 shows the characteristic waveforms in boost mode. Fig. 5 shows the topological stages in one switching cycle.

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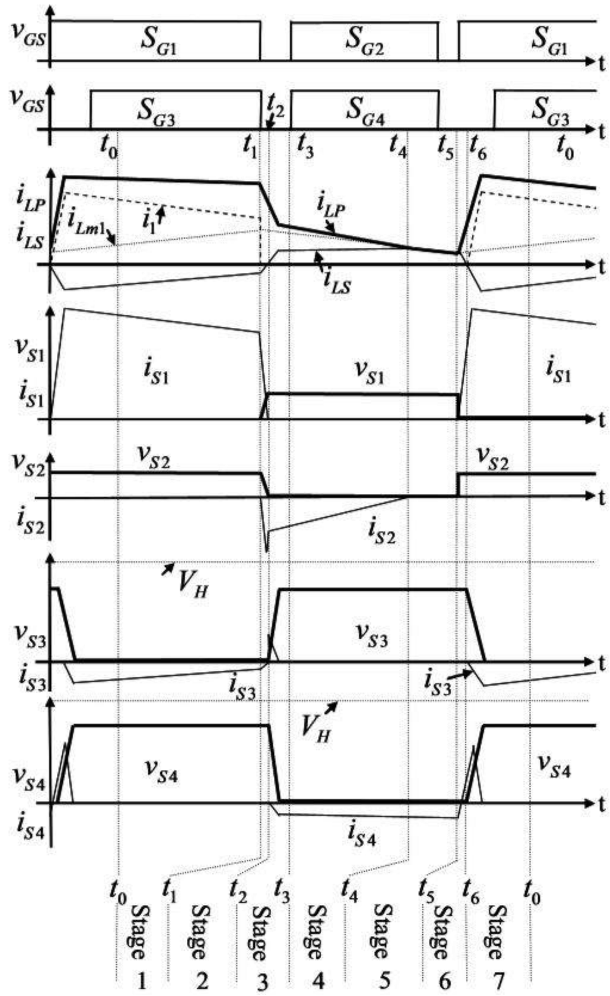

Fig. 3. Characteristic waveforms of bidirectional converter in boost mode.

III. THE TOPOLOGY AND OPERATING PRINCIPLE

Voltage-source PWM converter could achieve sinusoidal current in grid side, operate under the unit power factor, and transform power bilaterally. In the low-to-medium power occasion, a well-known single-phase full-bridge VSC is usually used, as shown in Fig. 1.

Asymmetrical half-bridge (AHB) resonant DC/DC converter as shown in Fig. 2 is a basic form of LLC resonant converter [14], which has good characteristics, such as zero-switching (ZVS) for primary-side switches, zero-current switching (ZCS) for secondary-side rectifiers, low switch voltage stress, and small circulating current. Hence, the AHB resonant DC/DC converter [15]-[17]can operate at a high switching frequency with lesser switch loss. The resonant inductor L_r, the magnetizing inductor L_m of the high-frequency transformer, and the resonant capacitor C_r constitute the resonant tank. Because there are three dynamic components in circuit, the converter can output different dc voltage under different working frequency. By changing the working frequency of the converter, it can be obtained what output voltage you need within a certain range. It is very suitable for the on-board charger of EVs, whose nominal dc voltages are different. However, for the V2G system, the most basic requirement of the converter is transforming power bilaterally, which is impossible for traditional AHB resonant DC/DC converter because of the diodes in the secondary-side rectifier. So, if one would have a LLC resonant converter used in V2G system, some necessary improvement is must to be done.

Fig. 3 shows the proposed topology of bidirectional power converter for V2G system. The topology has two-stage: AC/DC converter (front-stage) and DC/DC Converter (post-stage). The front-stage is a single-phase full-bridge of voltage source PWM converter, which makes the voltage of DC bus steadily at a constant value. The post-stage is a novel half-bridge LLC resonant (HB LLC) converter which is called symmetrical half-bridge LLC (SHB LLC) resonant converter.

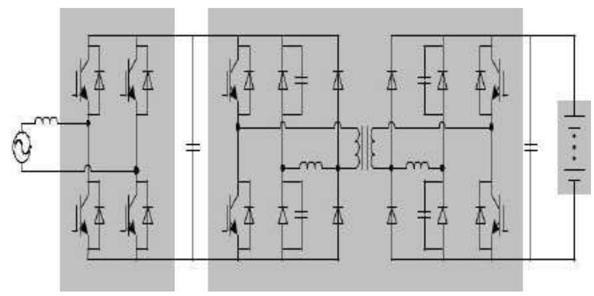

Fig. 4. The proposed topology of bidirectional power converter for V2G

The SHB LLC converter means (post-stage) that the circuit topologies on both sides of the high-frequency transformer are exactly the same. Each side of the SHB LLC converters could work as a typical HB

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LLC resonant converter. When the converter on one side of the high-frequency transformer works in the high-frequency inverter mode, the one on the other side will work in the high-frequency rectifier mode. The SHB LLC resonant converter is composed of a switching network, a resonant network and a rectifier network in series. V_{11}, V_{12} and V_{21}, V_{22} constitute the two side switching network, respectively. It is used to get symmetrical square wave signal with complementary with primary switch pulse (on 50% and off 50%) which is given to the resonant tank as an input. One resonant tank is consisted by the resonant inductor L_{r1}, the magnetizing inductor L_m of the high-frequency transformer, the resonant capacitor C_{11} and C_{12}. The other is consisted by the resonant inductor L_{r2}, the magnetizing inductor L'm of the high-frequency transformer, the resonant capacitor C_{21} and C_{22}, similarly. The uncontrolled full-bridge rectifiers in the two side are composed of the diodes (VD_{11}, VD_{12}, VD_{15}, VD_{16}) and (VD_{17}, VD_{18}, VD_{21}, VD_{22}). Depending on the direction of power transmission, the proposed converter has two modes: the forward mode and the reverse mode, as shown in Fig. 4

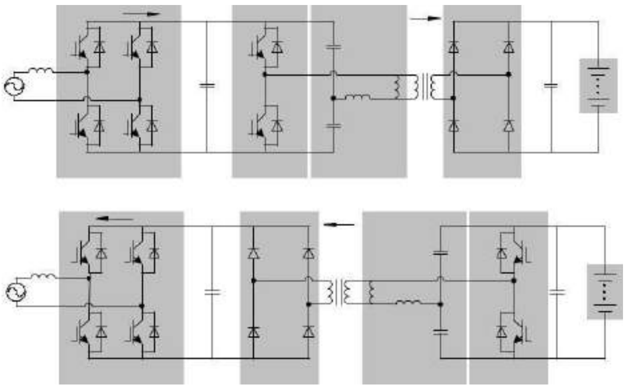

Fig. 5. Two modes of the SHB LLC resonant converter

The SHB LLC resonant converter could realize ZVS/ZCS operational mode in the whole load range. It reduces the switching loss effectively and slows down the transient over-voltage and over-current of the switches. This topology can solve the problem which is accepted that it is difficult for the lagging arm to achieve soft switching using the traditional ZVS bridge phase-shift PWM converter or the bridge ZVS PWM converter. Compared with the single resonant capacitor topology, using split resonant capacitor, the ripple and root mean square (RMS) of the input current through resonant capacitors are both smaller. The split resonant capacitor receives only half RMS current of the single resonant capacitor and the capacitance of the split resonant capacitor is also only half of the single resonant capacitor.

On the resonance side, the clamp diodes circuit can be used as the over-voltage protection of the resonant inductor in the resonant network, while the symmetrical clamp diodes automatically convert to a rectifier arm of the single-phase full-bridge rectifier and separate the unused resonant inductor on the output side from the main circuit. It avoids large internal impedance voltage drop in the output loop. Similarly, the clamp diodes can also be used as over-voltage protection of the resonant capacitors in the resonant network, while the symmetrical clamp diodes on the output side. It can effectively suppress the LC resonance phenomena that may occur in the output-rectifier circuit. Therefore the diode clamp circuit of the resonant capacitors has a complex function of resonant voltage clamping protection and inhibiting resonance in the rectifier circuit.

IV. CONTROL THEORY AND DESIGN

The Fig. 5 shows the control diagram of bidirectional power converter proposed above. The control method of front-stage (VSC converter) adopts double-closed-loop control based on dq transformation with outer voltage loop and inner current loop. It could realize the unit power factor and low harmonic in grid side, whether VSC work in the rectifier mode or inverter mode. The control method of post-stage (SHB LLC resonant converter) has two parts: and reverse control module. The two modules share a VCO (voltage-controlled oscillator) circuit and a driving signal producer circuit. When the bidirectional power converter works in the forward control mode, the switch S connects to the forward control module circuit. Hence the Voltage and current of the EV battery are under control in order to adapt different voltage level and capacity of the EV batteries. And when the bidirectional power converter works in the reverse control mode, the switch S connects to the reverse control module circuit. It can control the current of the DC bus for the VSC at a constant value. Then the VSC inverter the power flow to the grid side. ZVS can be ensured in the primary side switches by keeping the current through these switches negative on the instant they are turned ON. The primary current should be able to charge and discharge the output capacitors of the primary side switches during the dead-time. The magnitude of this current depends on the magnetizing inductance and the duration of the dead-time. So, the ZVS in the primary side depends on the magnetizing inductance, the switch output capacitance and the dead-time duration. The operation of this converter during dead-time is similar to the operation of LLC resonant converter during dead-time. So, the magnetizing inductance can be designed using the same expression as the full-bridge LLC resonant converter [26]. Magnetizing inductance cannot be too low. As, it would make the magnetizing current very high, resulting in huge conduction losses, increased apparent power requirements for switches and increased peak voltage requirement for the primary side capacitor. Large magnetizing inductance will result in a small magnetizing current, but it limits the voltage gain of the converter. So, magnetizing inductance cannot be too large. For longer dead-time, the magnetizing inductance can be made large to reduce the magnetizing current, but it will result in large primary RMS current as no energy is transferred during dead-time. All these factors should be kept in mind while designing magnetizing inductance.

V. SIMULATION RESULTS

Performance of the dc motor drive with the above battery model and bidirectional converter is simulated under different speed command. The simulations are carried out using MATLAB/SIMULINK. The inductor parasitic resistance and MOSFET turn-on resistance are not considered in this case. For the test condition of the proposed drive topology the following values of the different components of the converter are considered. A separately excited DC motor model is used as load to the bidirectional dc-dc converter. The motor rated at 5 hp, 240 V, and 1750 rpm. Principal parameters of the bidirectional converter are: *L = 1600 µH, CH=470 µF, CL = 470 µF, fSW =20 kHz Battery voltage=48 V. Battery capacity=16 Ah, SOC=88%.*

Fig. 6(a). Output Voltage of the Boost Mode

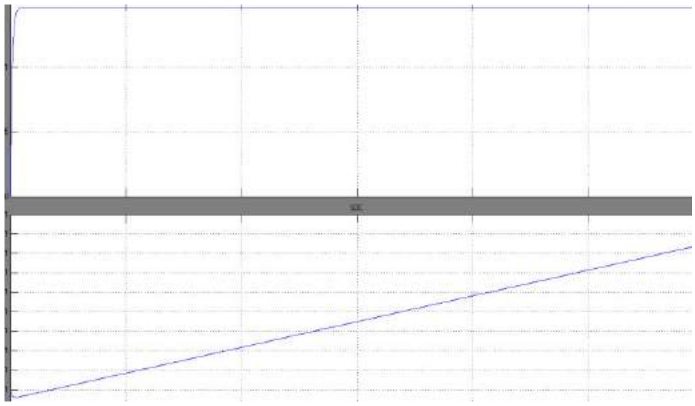

Fig. 6(b). Output Voltage of the Buck Mode

6. CONCLUSION

In this work we demonstrate the performance of a battery operated electric vehicle system and it shows satisfactory performance at different driving condition. The proposed control technique with PI controller find suitable for this electric drive. The overall cost and volume of the battery operated electric vehicle is less with the least number of components used in the system.

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