Grid to Vehicle and To Grid Energy Transfer using Bidirectional AC – DC Converter

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***Abstract*—This paper proposes a bidirectional ac/dc converter for vehicle to grid power transfer. The proposed converter consist of single-phase current-source rectifier (SCSR) and an auxiliary switching network (ASN). This offers bidirectional power flow between battery and grid in buck or boost mode with wider voltage range, The topology structure and operating principles of the proposed converter are analyzed in detail. An indirect control algorithm is used to realize the charging and discharging of the battery. This paper main objective is to present the principles of charging and discharging with buck-boost modes and to verify the efficiency of the proposed converter the circuit will be simulated using MATLAB simulink.**

Keywords*— Bidirectional AC/DC converter,.Single-phase current-source rectifier (SCSR), Auxiliary switching network (ASN).

I. INTRODUCTION

Now a day with the increasing cost of petroleum and growing acceptance of global climate change due to co2 emission by vehicles as a critical environmental problem, policy makers, engineers and business leaders are searching for alternative energy solutions. Re-electrification of automobile transportation and enhancement of the existing power system grid is one such solution. The electric power system is a complex and critical infrastructural system, yet it lacks energy storage capacity, so electricity must be simultaneously produced and consumed[1]

For this energy storage capability the Developing plug-in hybrid electric vehicles (PHEV) or electric vehicles (EV) is an effective way to solve the increasingly serious energy crisis and global warming issues because of their reduced fuel usage and greenhouse emissions[2] [3]. In the longer term, there may be potential for smart-grid technology to enable EVs to be used as distributed storage devices, feeding electricity stored in their batteries back into the system when needed (vehicle-to-grid, or V2G, supply). This can help to reduce electricity system costs by providing a cost-effective means of providing regulation services, spinning reserves and peak-shaving capacity.

In a V2G system, the battery charger plays a critical role, because the charging time, the quality of the power and the battery life are linked to it [3], [4]. A battery charger with a high power density, low cost, high efficiency, and flexibility, has been the main focus of current research in both industrial and academic communities.

Nowadays, a two-stage topology that voltage-source rectifier (VSR) cascades a dc-dc converter is widely applied in EV/PHEV [5]-[6]. This type of charger offers a two-way electrical energy flow and communication. In addition, the quality of the input current is improved by the PWM technique.

According to the duality between the VSR and the current-source rectifier (CSR), the CSR is suitable for a battery charger. However, there are relatively few studies on their application to the battery area. Actually the conventional CSR used as a charger was reported early [7]-[8]. A charger based on the CSR and H-bridge inverter was reported, where the H-bridge inverter works as an inverting link [9]. It supports bidirectional energy flow and has fewer switches when compared with AC/DC matrix converters. However, undesired redundant switches still exits and that may restrict the scope of its application. Therefore, a simplified topology which can perform multiple functions was studied [10]. For reducing the switch power losses and EMI noise, a bidirectional swiss rectifier [11], [12] and a bidirectional 3rd harmonic injection active filter rectifier [13] were proposed. Their common advantage is that the rectifier works as the fundamental frequency. All the CSCs mentioned above are three phase chargers. When a low power charger is required, for example, when charging at home or in an office, a single phase charger is usually preferred [4]. Various topologies and schemes based on a diode rectifier or a voltage-source rectifier have been reported for single phase chargers [4], [14]-[15]. However, few studies have focused on single phase current-source chargers. In [16], a novel inductor voltage control method was proposed for a single phase CSC to achieve any input power factor. This paper's main objective is to present the principles of charging and discharging with buck-boost modes and to verify the feasibility of the proposed topology, modulation scheme and control algorithm.

This paper is organized as follows: Section I, II, III introduces the topology, the operation modes and the averaged switching modeling of the proposed converter. Section IV shows simulation and experimental results to validate the capabilities of the proposed converter. Finally, the main points of this paper are summarized in Section V.

II. PROPOSED DC – DC CONVERTER

A) Circuit Configuration and Detail

The topology of the proposed single-phase current-source bidirectional converter is shown in Fig. 1. It consists of an *LC* input filter, a conventional SCSR and an ASN. For the reverse voltage blocking capability, each IGBT in the SCSR is connected with a diode in series. Under normal operation switches *S*1 and *S*3 are complementary; the same restriction is applied to *S*2 and *S*4. The ASN includes two IGBTs, two diodes, an inductor *L*dc and a capacitor *C*o, which is the key part of the system. Its main function is to change the direction of the power flow and converter voltage.

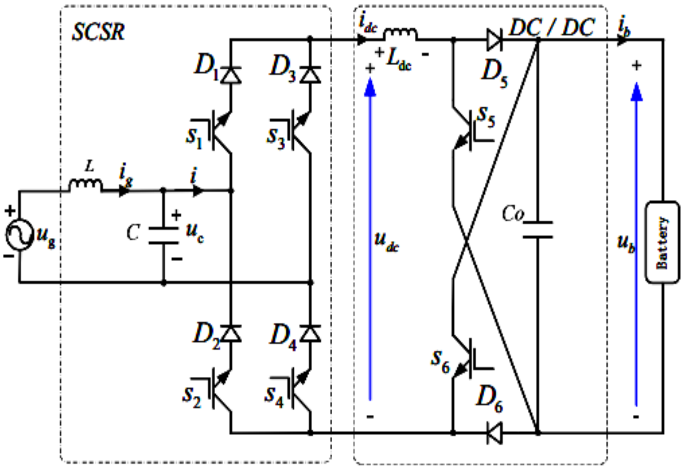


Fig. 1. Circuit diagram of Bidirectional AC-DC Converter.

Its front-end is a conventional CSR and its rear-end is an ASN composed of two IGBTs and two diodes. The role of the front-end SCSR is to convert the supply ac voltage into an intermediate dc link voltage and to realize PFC. The ASN is designed to control the direction of the power flow (charging or discharging). In addition, it works in a PWM manner to help in boosting the output voltage, which greatly expands its application range. Compared with the bidirectional buck-boost converter mentioned in [32], the proposed topology has fewer components, a wider output voltage range and better quality in the input current.

B) Modes of Operation

The proposed converter operation can be divided into four operating states. According to the characteristics of the CSR, the dc current *i*dc cannot be reversed. However, by controlling the ASN, the direction of the current flowing through the battery can be changed to achieve charging and discharging functionalities. Fig. 2 to 5 depicts the four operating modes of the ASN, where the CSR is represented by a controlled voltage source *druc*. *dr* is the difference between the steady state duty ratios of switches *S*1 and *S*2. The red lines illustrate the current paths. Under the charging operation, *ug* and *ub* are the input and output voltages, respectively, and the operating modes alternate between mode I and mode II.

Mode I: In this mode, switches *S*5 and *S*6 are in the off state, diodes *D5* and *D6* are forward-biased and the battery absorbs energy.

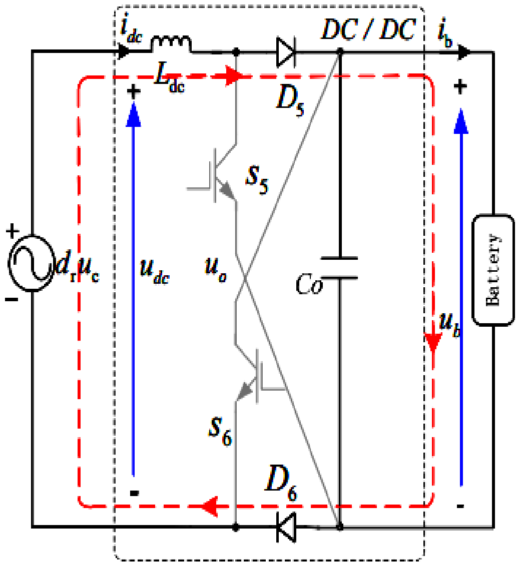


Fig. 2:Battery charging

Mode II: In this mode switch *S*5 is in the on state and a corresponding diode *D6* is forward-biased, which disconnects the battery from the circuit.

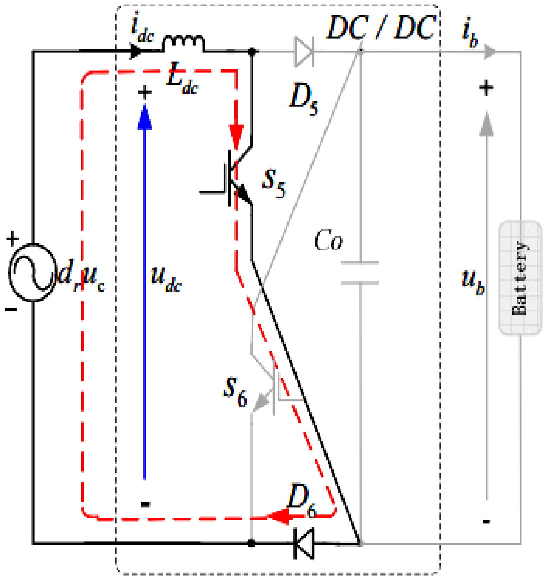


Fig. 3:Freewheeling action

Under the discharging operation, *ub* and *ug* are the input and output voltages, respectively, and the operating modes alternate between mode Ⅲ and mode Ⅳ .

Mode III: In this mode, switches *S*5 and *S*6 are in the on state, diodes *D5* and *D6* are reverse-biased and the battery supplies energy.

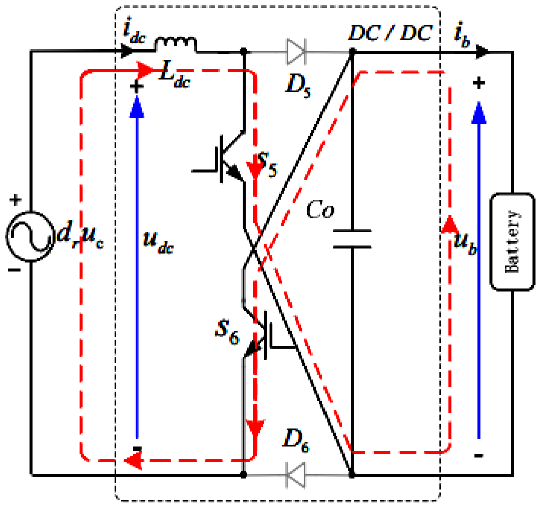


Fig. 4: Battery discharging

Mode IV: In this mode , plays the role of freewheeling. The ASN works as a buck circuit and the system is still a buck-boost converter.

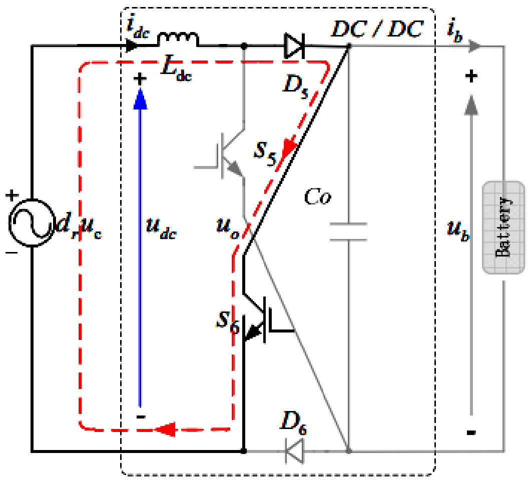


Fig. 5: Freewheeling action

III. MODELING OF THE PROPOSED CONVERTER

Assume that the system works in continuous mode. According to Fig 1 , the state space average switching model for the proposed converter is formulated as follows:

$$L\frac{di_g}{dt} = u_g - u_c \qquad (1)$$

$$c\frac{du_c}{dt} = i_g - d_r i_{dc} \qquad (2)$$

$$L\frac{di_{dc}}{dt} = d_r u_c - d_b u_b \qquad (3)$$

$$C_0\frac{du_b}{dt} = d_b i_{dc} - i_b \qquad (4)$$

where, *ig* is the gird current, *uc* is the terminal voltage of capacitor *C*, u_b is the battery voltage, *idc* is the dc current flowing through inductor L_{dc}, *d*r=*d*1-*d*2, *d*b=1-*d*5-*d*6. *d*i is the duty ratio of switch *S*i (*i*∈{1,2…6}).

Assume that $u_g=U\sin(\omega t)$, and that *U* and *ω* represent the grid voltage magnitude and the angle frequency, respectively. In order to obtain a sine grid current with a unity power factor, according to (2), the following equation should be satisfied in the steady state:

$$i_g \approx d_r i_{dc} = I\sin(\omega t) \qquad (5)$$

where, *I* is the amplitude of the input current. If *I* is greater than zero, the system works in the charging status; else the system works in the discharging status. For satisfying the volt-second balance of the inductor L_{dc}, according to equation (3), equation (6) can be obtained (ignoring the effect of the input filter) as follows:

$$d_r u_g \approx d_r u_c = d_b u_b \qquad (6)$$

where, $-1 \le d_r$, $d_b \le 1$. It is clear that the value of the battery voltage can be larger or smaller than that of the grid voltage. As a result, the charging/discharging operation under buck/boost mode can be realized. According to (5) and (6), there is one degree of freedom available. Therefore there are lots of methods to accomplish the control task mentioned above in theory. In this context, i_{dc} is controlled to be a constant and d_r is controlled to vary with a sine shape, as shown in (7).

$$d_r = c.\mathrm{sgn}(I).\sin(\omega t).\left(i_{dc}^* / i_{dc} \right) \qquad (7)$$

where *c* is the modulation index, and sgn() is the sign function. i_{dc}^* is the reference dc current. (i_{dc}^*/i_{dc}) i_{dc} i_{dc} is an extra compensation term to improve the dynamic responses of the duty cycle to prevent distortion of the grid current. In particular, when the grid voltage u_g is near the zero-crossings under the charging operation, the power losses of the circuit and switches are more than the grid can supply.

From (5) and (7), *I*, *c* and i_{dc} satisfy the restriction $|I|=c\cdot i_{dc}$. Taking the power losses into account, a minimal i_{dc} is expected. Therefore, according to (6) and (7), *c* can be given by:

$$c = \min\left(\frac{u_b}{u}, 1\right) \qquad (8)$$

where, min() is the minimum function.
According to (6), d_b can be obtained as follows:

$$d_b = c.U.\sin^2(\omega t) i_{dc}^* / (i_{dc} u_b) \qquad (9)$$

A) Control Algorithm

A control diagram for realizing the charging/discharging is shown in Fig. 4. To improve the reliability and reduce the cost, only the grid voltage, the battery terminal voltage and the current through the inductance L_{dc} are sampled. To regulate the current through the inductor, a control scheme including feed-forward control and PI feedback control is presented. The feed-forward control compensates the effects of the grid voltage directly, which increases the dynamic response of the current control. The PI control will help to stabilizing the system and handle some unknown disturbance. A simple open-loop control is used for modifying *dr* to obtain a sine grid current and to realize PFC.

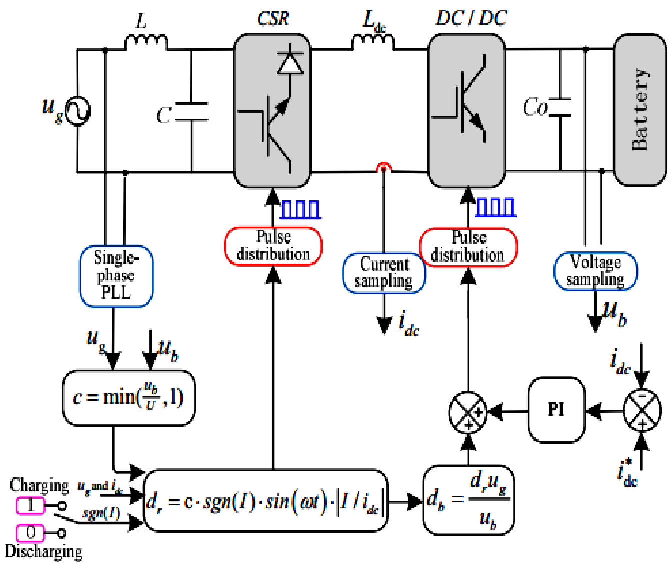


Fig.6 Control diagram of charging, and discharging.

B) Switching Pattern Arrangements

The performance of the converter depends on both the modulation strategy and the switching pattern arrangement. In this paper, reducing the switching power losses and output current ripple are the main consideration when arranging the switching pattern. Therefore, a symmetrical switching pattern is usually applied [20]. Both the front-end switching pattern and the rear-end switching pattern need to be arranged. In addition, coordination control between the front-end switching pattern and the rear-end switching pattern is required.

In this paper, the in-phase carrier PWM modulator is adapted under the charging operation, and the interleaved carrier PWM modulator is adapted under the discharging operation. which illustrates the specific operation of each switch in each switching period. An example is given in Fig.7 to show the changes of the voltage across inductor *L* and the dc current i_{dc}. Here the voltage drops across the IGBTs and the diodes are neglected. From Fig.6 the switching patterns are bilaterally symmetrical, and twice commutations occur in each switching period.

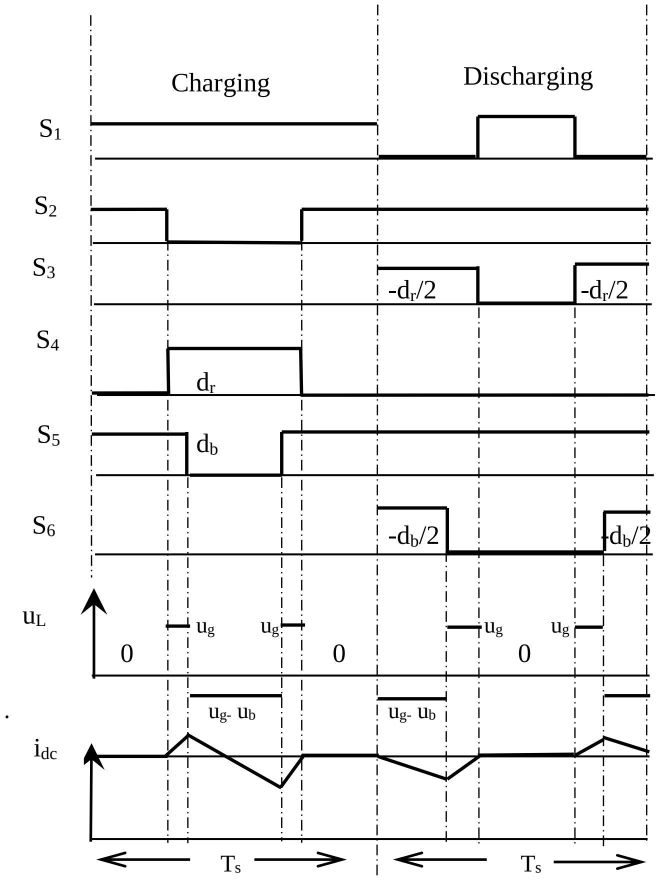


Fig.7 Switching pattern arrangements under different modes（$ug>0, ug<ub$）

TABLE I
PARAMETERS USED FOR SIMULATON

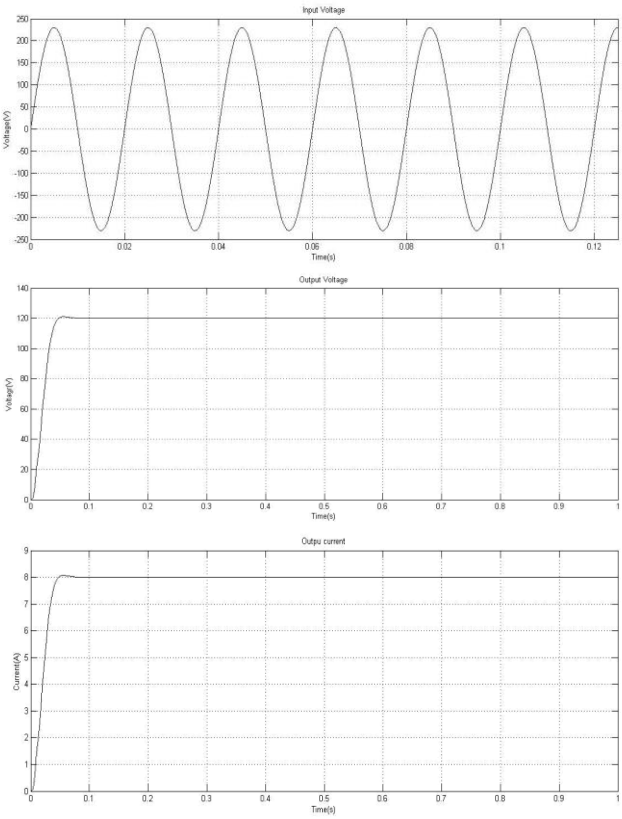
parameters	value
Amplitude of input voltage U	230V
Input filter inductor L	0.1H
Input filter capacitor C	10uF
Output filter inductor L_{dc}	400μH
Output filter capacitor C_0	470μF
Switching frequency f_s	20Hz
The reference current i_{dc}^*	8A
Value of the battery voltage u_b	120V

IV. SIMULATION RESULT

To validate the proposed topology and method, simulations based on the Matlab/Simulink environment are implemented in this section. The models of the semiconductor devices and battery are from the SimPowerSystems/Power Electronics library.

A schematic diagram of the single-phase current source bidirectional converter in the simulation is shown in Fig. 1. The parameters used in the simulation are listed in Table I. The loads are 40Ah capacity lead-acid battery with nominal voltage of 120V. The simulation results in Fig. 8 show the performance of the proposed converter. From the top, the grid voltage u_g, the grid current *ig*, the output voltage u_{dc}, the dc current i_{dc} , the battery voltage u_b and the battery current i_b are sequentially displayed.

Grid voltage

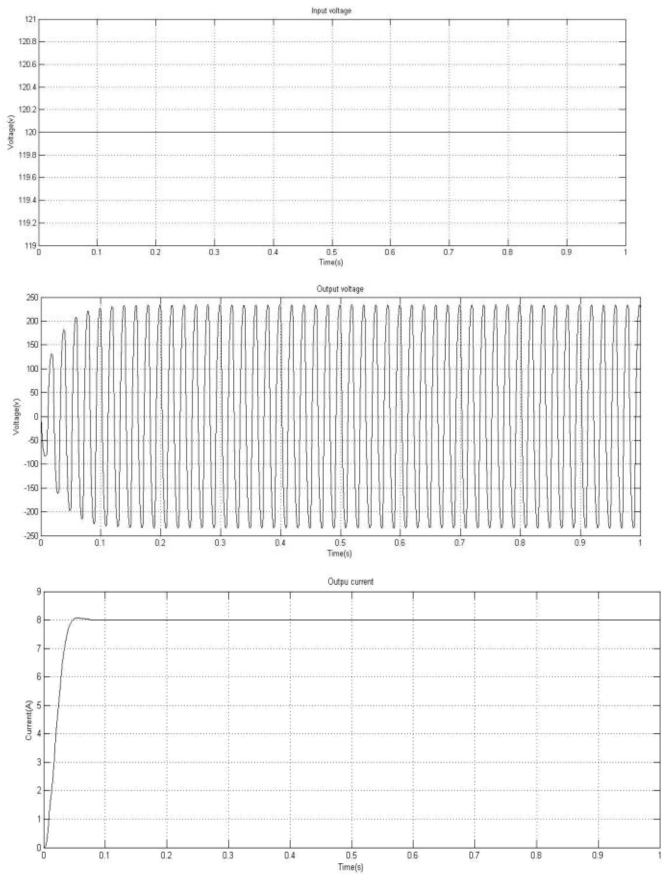


(A)

It can be clearly seen that in the charging mode, the grid currents are in phase with the grid voltages, while in the discharging mode, the input currents and the grid voltages are out of phase by 180^0. An interesting phenomenon can be found in the fact that the inductor current is distorted near the grid voltage zero-crossing region in all of the charging modes, even though it is designed to be controlled as a constant value.

In addition, in the discharging mode, as the battery is a constant voltage source, it can overcome the forward voltage and keep the inductor current constant. As a result, the inductor current is controlled well without distortion. In conclusion, the input current is in phase with the input voltage, and it is close to a unity power factor, and the input current is sinusoidal in all modes.

Battery voltage



(B)

Fig.8.Simulation results: (A) Buck charging.
(B) Boost discharging.

V.CONCLUSION

A bidirectional AC/DC converter for V2G application has been designed simulated mathematical models for the Buck and Boost modes of AC/DC converter are derived. An average model of AC-DC converter is obtained using MATLAB simulink. It is observed that current change its direction quickly as the mode of operation changes with out any overshoot of the peak values hence the converter voltage and current are stable in its operation on both direction.

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