Bidirectional DC-DC Converter with Full-bridge / Push-pull circuit for Automobile Electric Power Systems

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Abstract— In recent years, energy storage systems assisted by super capacitor have been widely researched and developed to progress power systems for the electronic vehicles. In this paper, a full-bridge/push-pull circuit-based bidirectional DC-DC converter and its control methods are proposed. From the results of detailed experimental demonstration, the proposed system is able to perform adequate charge and discharge operation between low-voltage high-current super capacitor side and high-voltage low-current side with drive train and main battery. Furthermore, conduction losses and voltage/current surge are drastically reduced by ZVS operation with loss-less snubber capacitor in high voltage side as well as the synchronous rectification in low-voltage high-current super capacitor side.

Keywords— *Bidirectional DC-DC converter, super capacitor, synchronous rectifier, high frequency power conversion, automobile electric power system*

I. INTRODUCTION

With the increasing needs for electric power in future automobiles such as electric vehicles (EVs), hybrid EVs and Fuel-Cell EVs, supercapacitor (S.C.) based energy storage systems are required for charge/discharge assistance of the main battery array. For these applications, bi-directional DC-DC converters to transfer the electric energy between low voltage S.C. based energy storage system and the high voltage drive train including three phase inverter-motor system and the main batter, are required as shown in Fig.1. Generally, electric power conversion with a high step-up/down ratio can be efficiently performed only in topologies with a high frequency transformer. For the low voltage and high current side, the synchronous rectifier has been widely adopted to reduce the rectification conduction losses [1].

In this paper, a high frequency transformer linked full-bridge/push-pull circuit based bidirectional DC-DC converter is proposed for automobile electric power system. The presented concept with charge and discharge operation between low voltage high current S.C. side and high voltage low current main battery side, is simulated and demonstrated by the experimental proto-type system. Furthermore, synchronous rectification (S.R.) is considered to reduce conduction losses and voltage/current surge caused by diode recovery characteristics as well as soft switching operation accomplished with lossless snubber capacitor.

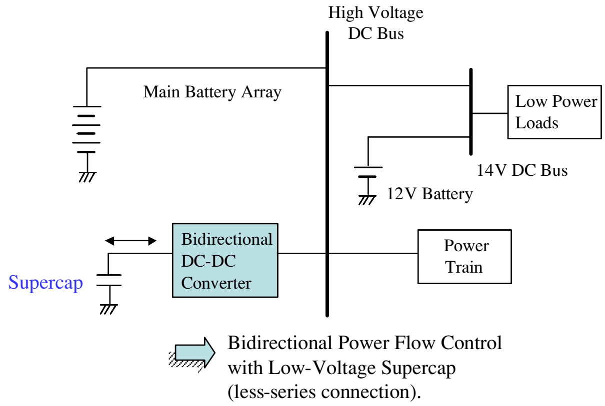

Fig. 1: Supercapacitor based energy storage system for automobiles.

II. PROPOSED CIRCUIT TOPOLOGY

A proposed circuit configuration of a bidirectional DC-DC converter is shown in Fig.2. In this figure, V_b and S.C. represent the main battery bank high voltage source and the supercapacitor. The high voltage power train system is replaced to resistance R1. The full-bridge circuit (S_1/D_1 to D_4/S_4) in high voltage side and the push-pull circuit (S_5/D_5 and S_6/D_6) in the low voltage side are connected with the high frequency transformer T. In case of the charge mode in S.C., full-bridge circuit operates as a high frequency inverter. On the contrary, push-pull circuit operates as a high frequency inverter in S.C. discharge mode. $Cr_1$and Cr_2 are additional loss less capacitor for zero voltage switching (ZVS) commutation.

A. S.C. charge mode (PWM and phase shift PWM)

In this paper, two types of PWM scheme for S.C. charge

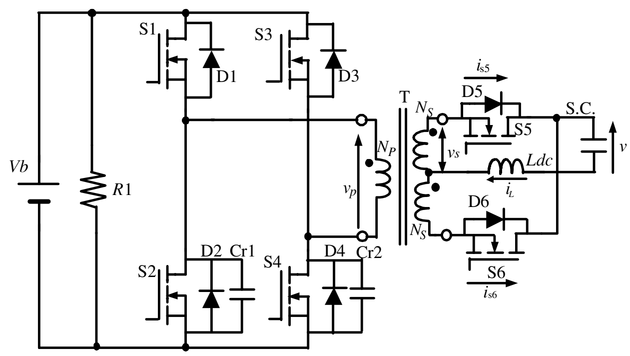

Fig. 2: Full-bridge/push-pull based bidirectonal DC-DC converter

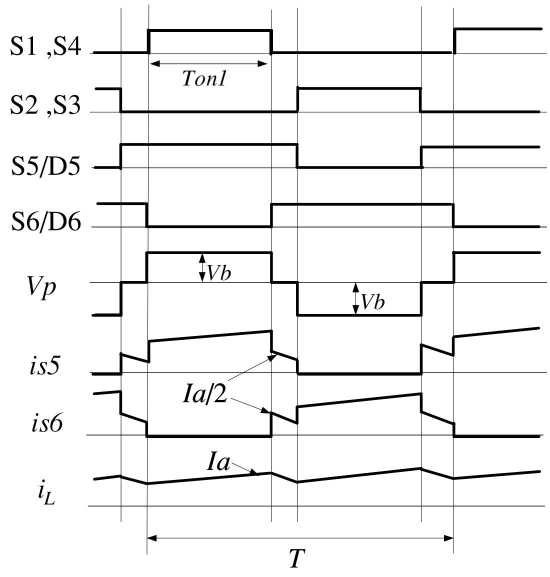

Fig. 3: S.C. charge mode operation waveforms (basically PWM control)

mode are considered. The basically PWM controlled operation waveforms of the proposed converter are shown in Fig.3. S.C. charging current I_{sc} (= I_L) is regulated by the charging duty ratio D_{charge}. Here, D_{charge} can be described with turn on time T_1 of the main switch S_1/S_4 and S_2/S_3 as follows,

$$D_{charge} = \frac{T_{on1}}{T} \quad (1).$$

As shown in Fig. 3, gate signals of push-pull side (S5 and S6) for SR can be generated by detecting the secondary-side voltage of high frequency transformer T. Gate signal of S_5 is turned on at the turn off timing of S_2 (S_3), and turns off at the timing when the secondary-side transformer voltage V_s reaches to E_s. Here, E_s is described as

$$E_s = \frac{N_s}{N_p} V_b \quad (2).$$

The operating waveforms of phase shift PWM control scheme are shown in Fig.4. As shown in this figure, The switches S_1 and S_2, or S_3 and S_4 are driven complementary

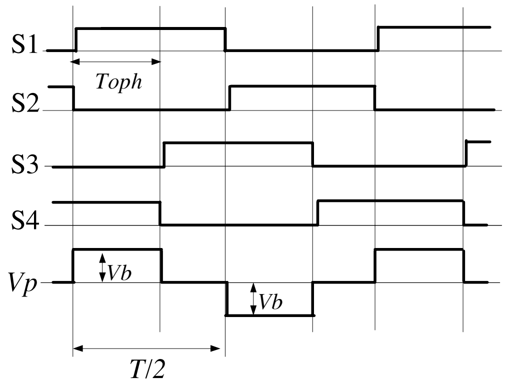

Fig. 4: S.C. charge mode operation waveforms (phase shift PWM control)

with the blanking dead time interval t_d. This interval t_d is needed to obtain the ZVS commutation of the switches S_1 and S_2 at the turn-on instant. The output current I_{sc} of the proposed DC-DC converter is regulated by lagging the gate pulse of the switch S_4 (S_3) with respect to the gate pulse of the switch S_1 (S_2) and varying by this way an interval t_{on} (t_{on}=DT/2) as PS-PWM control with the constant switching frequency f=1/(T/2).

$$D_c = \frac{T_{oph}}{T/2} \quad (3).$$

Fig.5 represent the synchronous rectification control circuit. Reference voltage E_s is considerably adjusted because of the practical conditions such as the device operation delay from the gate signal.

B. S.C. discharge mode

The operation waveforms in S.C. discharge mode are shown in Fig.6. The push-pull switches (S_5 and S_6) are operated with overlapping interval. S.C. discharge current I_{sc} is controlled by overlapping interval. At this interval, I_{sc} is stored to L_{DC}, after that, stored current flows to the battery side. This means that discharging duty ratio $D_{discharge}$ should be larger than 0.5.

$$D_{discharge} = \frac{T_2}{T} \quad (4).$$

In discharge mode, full-bridge circuit acts as a full-bridge diode rectifier.

C. Circuit design

First of all, rate of the handling storage energy in S.C. is defined as 75% of the maximum capacity. This rate corresponds the minimum voltage of the S.C. is a half of the maximum voltage V_{C_max}. And then, the turn ratio of high frequency transformer N_T can be determined based upon eq.(5).

$$N_T = \frac{N_P}{N_S} = \frac{V_b}{V_{C\_max}} \quad (5).$$

The supercapacitor cell used in this system is PSLF-1350, Power System Co., and the specification in four series of cells is described in TABLE I. The total design specifications and circuit parameters of the proposed bidirectional DC-DC converter are shown in TABLE II.

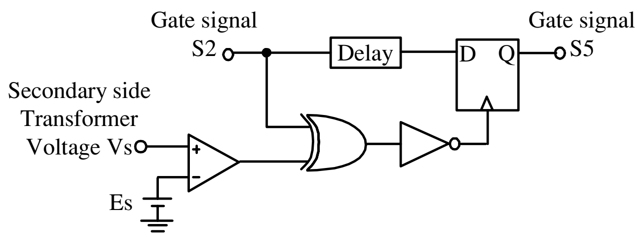

Fig. 5: Push-pull side synchronous rectification controller.

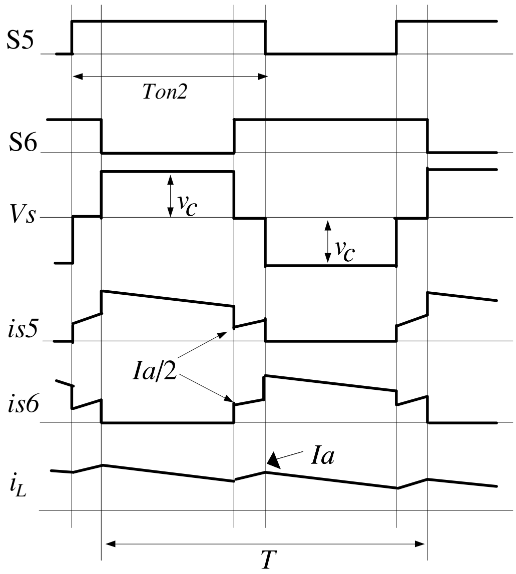

Fig. 6: S.C. discharge mode operation waveforms

TABLE I.
CHARACTERISTICS OF THE SPERCAPACITOR

Capacitance	340 F
Maximum Voltage	10.8 V
Continuous Charge-Discharge Current	60 A
Maximum ESR	1.5 mΩ
Energy Density	6.5 Wh/kg
Power Density (cell)	5.5 kW/kg

(four series of 1350 F cells)

TABLE II.
CIRCUIT CONFIGULATIONS

Item	Symbol	Value
DC Source Voltage	*Vb*	50 V
Inductor	*Ldc*	60 μH
Switching Frequency	*Fs*	60 kHz
Trans. Winding Turn Ratio	*Np:Ns:Ns*	5:1:1
Additional lossless snubber capacitor	*Crx*	4.7 nF
On-resistance of MOSFET (Infeneon, BUZ 341)		35 mΩ

III. PERFORMANCE ANALYSIS

A. *Steady state experimental results with PWM control*

To verify the steady state performances of the proposed bidirectional DC-DC converter, a small scale lab. model is built and tested. In the experimental set-up, trench-gated IGBT 2 in 1 modules (CM100DUS-12F: Mitsubishi electric Co. Ltd.) are used for full-bridge stage. At the same time, two paralleled MOS-FETs (BUZ341: Infeneon Co. Ltd.) in each arm are applied for the push-pull stage.

Figure 7 shows the operating waveforms in S.C. charge mode without S.R. and without lossless snubber capacitor for ZVS at full-bridge stage. The S.C. charge current I_{sc} (= I_L) is well regulated by full-bridge side operation. As shown in these waveforms, recovery current surge at the rectifier diodes D_5 and D_6 cause measurable voltage spikes at S.C. voltage (V_C), however, these diode recovery characteristics oriented spikes can be easily reduced by synchronous rectification, as follows in the next chapter.

Figure 8 illustrates the operating waveforms in S.C. discharge mode. Significant current surges are observed in the push-pull current waveforms. These surges are coursed by hard switching operation of MOS-FETs (S_5 and S_6). From the other experimental results in our research, these current surges are able to damp by adding the RCDi snubber to the MOS-FET in push-pull circuit.

B. *Current surge suppression with Synchronous rectification*

Figure 9 depicts the magnified current surge waveform of rectifying diode D_5 without S.R., observed in Fig.7. This current surge is caused by the recovery characteristics of rectifying diodes in opposite side (D_6). These recovery-oriented surges can be effectively suppressed by S.R. shown in Fig.4. Figure 8 represents the effectively suppressed current waveform with S.R..

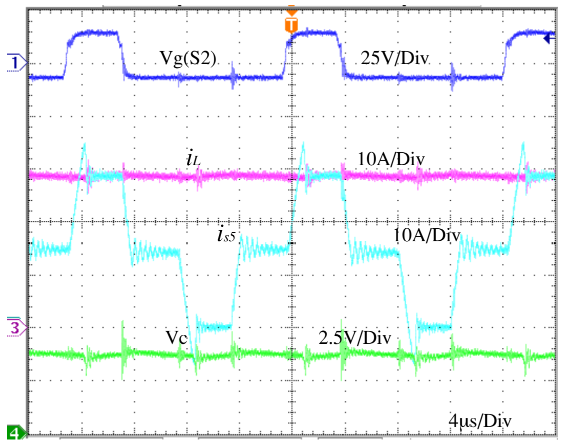

Fig. 7: Operating waveforms in S.C. charge mode without Synchronous rectification.(PWM control without lossless snubber capacitor)

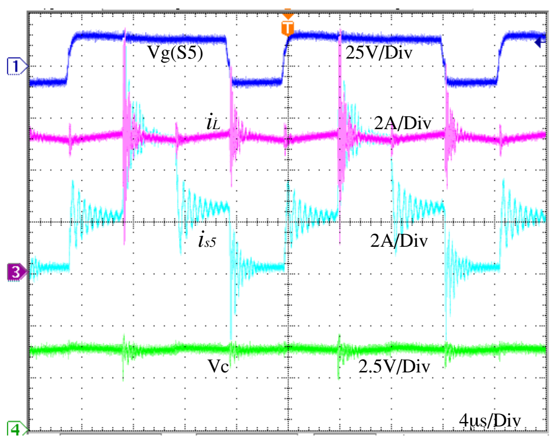

Fig. 8: Operating waveforms in S.C. discharge mode

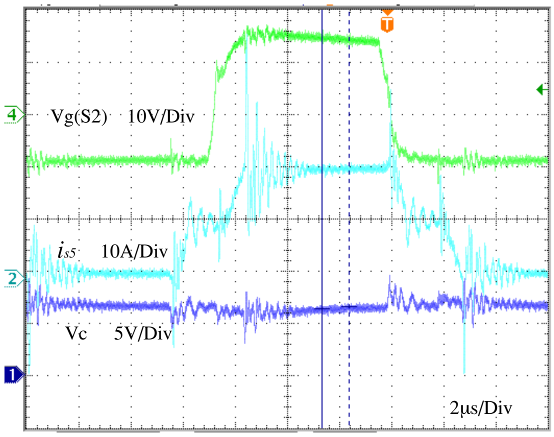

Fig. 9: Observed rectifying current in push-pull stage without Synchronous rectification (PWM control).

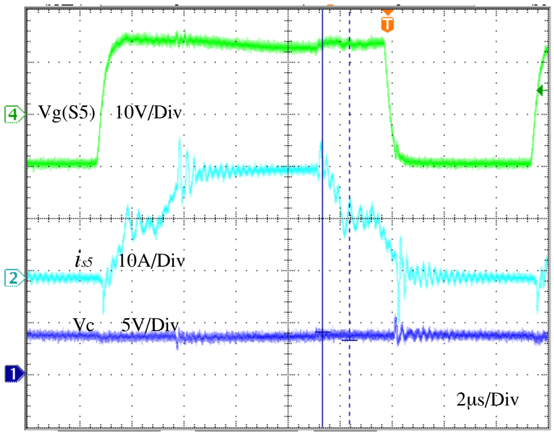

Fig. 10: Observed rectifying current in push-pull stage with Synchronous rectification (PWM control).

In addition, S.R. is an effective approach to reduce the device conduction losses generated in rectifying devices at large current push-pull stage. The measured conduction losses in the MOS-FET rectifier are shown in Fig. 9. From the measured results, it can be seen that the suppressed conduction loss in each rectifying arm at the push-pull stage reached to 9.8W at I_{SC} =30A.

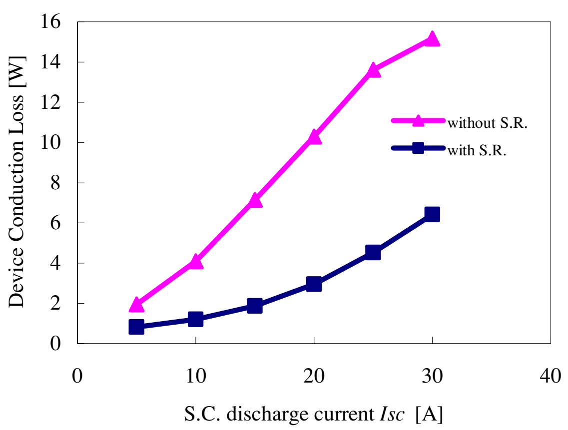

Fig. 11: Conduction losses reduction in the rectifier device.

C. Parasitic oscillation caused by lossless snubber capacitor and suppression technique

In case of S.C. charge mode, proposed DC-DC converter can achieve ZVS/ZCS turn on and ZVS turn off commutation by adding the loss less snubber capacitor Crx (x=1 or 2) in parallel with S_2 and S_4 as shown in Fig.2. Crx are set to 4.7nF, the leakage inductance of the high frequency transformer T is 10uH.

However, parasitic oscillation in dead time periods appears to voltage waveforms in both S.C. charge/discharge mode as shown in Fig. 12 and Fig.13. These oscillations are caused by Crx and the leakage inductance, because no current flows to S_2 and S_4 in these periods. They are able to be suppressed by introducing synchronous rectification in S.C. discharge mode and phase shift PWM in S.C. charge mode, as follows.

Figure14 shows the operating waveforms in S.C. charge mode (without S.R. in push-pull side) by introducing phase shift PWM control represented in Fig. 4. As shown in these waveforms, oscillation appeared in case of PWM control can be perfectly suppressed by phase shift PWM control. As shown in these waveforms, recovery currents in the rectifier

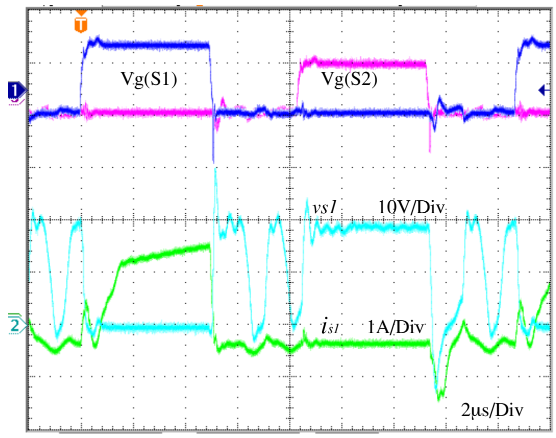

Fig. 12: Observed voltage oscillation in full-bridge stage in S.C. charge mode (PWM control).

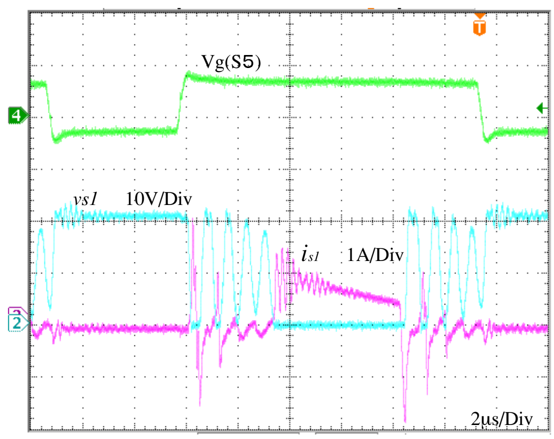

Fig. 13: Observed voltage oscillation in full-bridge stage in S.C. discharge mode (without S.R. in full-bridge side).

diode D_6 in push-pull stage caused measurable current spikes observed in S1 current (*is*1) waveform via high frequency transformer T. However, introducing S.R. in push-pull stage can easily reduce these rectifier-oriented current spikes as mentioned above.

Furthermore, significant oscillations in S.C. discharge mode are observed in the full-bridge side S_1 voltage waveform as shown in Fig.13. These oscillations can be suppressed by introducing S.R. in full-bridge side as well as push-pull side. Figure 15 shows suppressed experimental waveforms by introducing S.R. in full-bridge side.

In this case, circulating current is generated at marked area in Fig.15. This circulating current flows S_1 to S_3 or S_2 to S_4, and this means newly conduction loss is generated. Figure16 shows the measured conduction losses generated by circulating current in full-bridge side. As shown in this chart, percentage of conduction losses is 0.3% at the maximum. It is not too much to say that newly generated conduction losses are negligible small compared to the improved efficiency by introducing soft switching operation.

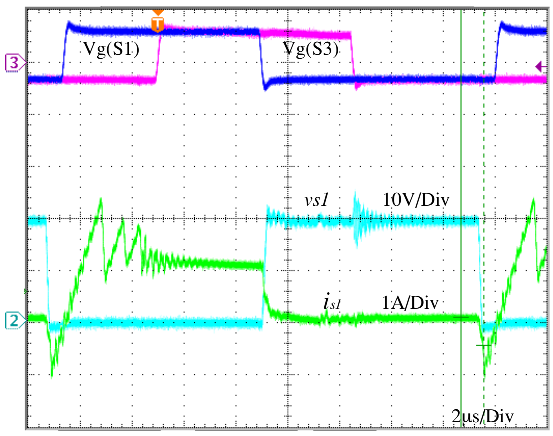

Fig. 14: Suppressed voltage oscillation in full-bridge stage in S.C. charge mode (phase shift PWM control).

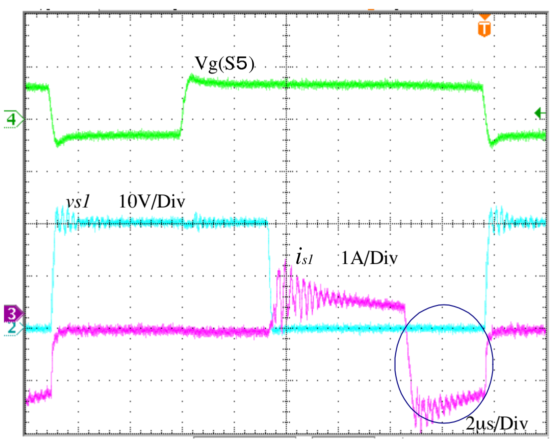

Fig. 15: Suppressed voltage oscillation in full-bridge stage in S.C. discharge mode (withS.R. in full-bridge side).

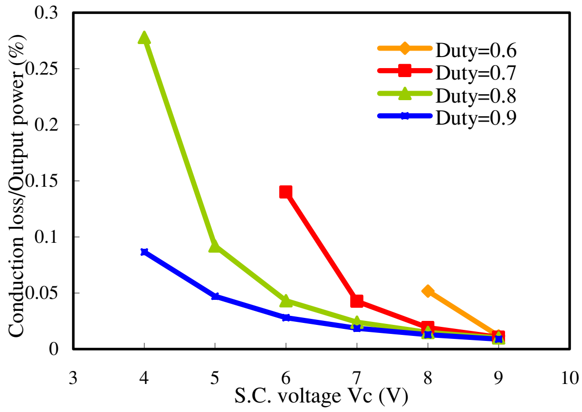

Fig. 16: Conduction losses in the rectifier device.

IV. CONCLUSION

In this paper, a full-bridge/push-pull stage-based bidirectional DC-DC converter for automobile electric power systems and its control schemes are proposed. From the experimental point of view, the proposed system is able to perform adequate charge and discharge operation between low-voltage high-current push-pull stage and high-voltage low-current full-bridge stage. Furthermore, conduction losses and voltage/current surges at S.C. charge mode are drastically reduced by synchronous rectification in push-pull stage. The parasitic oscillation caused by loss less snubber capacitor introduced for soft switching commutation is drastically suppressed by phase shift PWM control and synchronous rectification in full-bridge stage.

In future, further investigations in both S.C. charge /discharge operations, such as total performance evaluation and power conversion efficiency analysis are required.

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