영전압 방전 기능을 갖는 새로운 배터리 충방전시스템

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A Novel Battery Charge/Discharge System with Zero Voltage Discharge Function

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ABSTRACT

One important test for formation and grading of the lithium-ion battery is to confirm the performance of the battery while discharging battery down to zero volts. In this paper, a novel charge/discharge converter with zero-voltage discharge function is proposed. The proposed converter is able to discharge the battery until the voltage reaches to zero volts. The phase-shifted full bridge method is used to charge the battery and the current-fed push-pull method with bidirectional switches is used for the discharge. The ZVS turn-on is achieved in the charge operation and the ZVS turn-off in the discharge operation. The performance of the system is verified by the experiments using lithium-ion batteries.

1. Introduction

Battery manufactures perform various kinds of tests to investigate the long life and reliability of the battery. One important test is the battery cell formation and it is the process of transforming the active materials of a new cell into their usable form. This test needs to be performed to confirm the performance of the battery when the discharge voltage decreases to zero volts.

Recently, a battery discharge system with zero voltage discharge function has been introduced [1]-[2]. With the proposed topology [1], zero voltage discharge function can be achieved however the converter is not able to charge the battery. In order to overcome the disadvantage, an improved topology capable of charge was presented [2]. Since many switches are used to avoid the short circuit, the converter is high in cost, low in efficiency and complex in control.

This paper presents a novel battery charge/discharge converter with zero voltage discharge function. As compared to the previous topologies, the proposed converter can achieve higher power conversion efficiencies due to less number of switches and soft switching technique. It is also advantageous that the proposed converter allows the bidirectional power flow for the charge/discharge and the natural zero voltage switching (ZVS) can be achieved with no additional components.

2. Analysis of the proposed converter topology in the charge/discharge mode

Fig. 1 shows the proposed charge/discharge converter with zero voltage discharge function. The primary side consists of a traditional full-bridge circuits and the current-fed push-pull circuit with bidirectional switches are located in the secondary side. Primary and secondary sides are isolated by the single phase three windings transformer.

Generally, the zero voltage discharge function cannot be achieved due to the voltage drop of the circuit components. When the battery

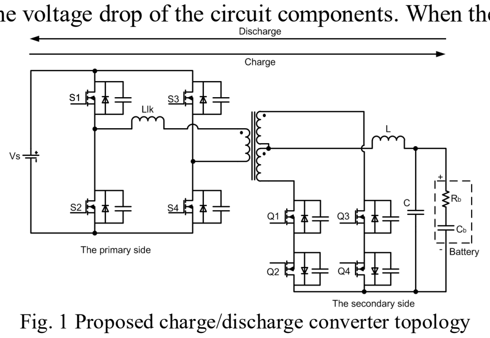
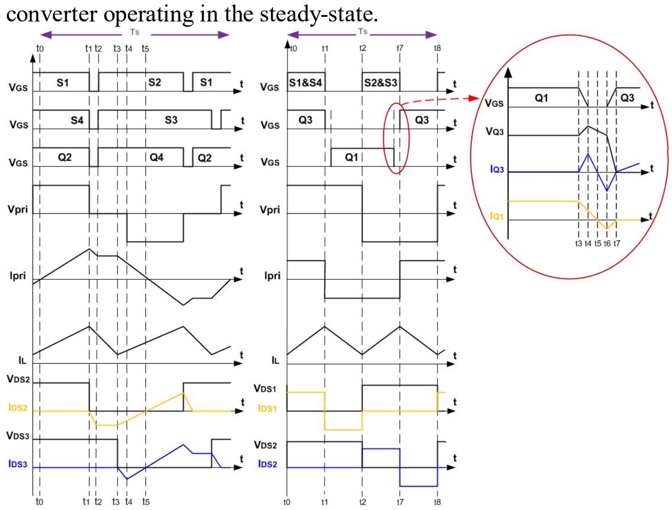


Fig. 1 Proposed charge/discharge converter topology

voltage equals to the total sum of the forward voltage drop of the circuit components, the battery cannot be discharged anymore. This problem can be solved by applying the voltage from the primary side to the secondary side. Hence the battery can be continuously discharged until the battery voltage reaches to zero volts.

Fig. 2 shows the voltage and current waveforms of the proposed converter operating in the steady-state.



(a) (b)

Fig. 2 Voltage and current waveforms of the proposed converter in the steady-state (a) charge mode (b) discharge mode

2.1 Operation of the proposed converter in the charge mode

During the time t_0~t_1, the switches (S1, S4) are turned on while the switch Q2 is conducting. In this mode, the power is delivered from the primary side to the secondary side and input voltage V_s is applied to the primary winding of the transformer. The current and voltage of the inductor can be expressed as (1) and (2).

$$v_L = \frac{N_s}{N_p}\left(V_s - 2V_Q\right) - V_{bat} - \left(V_D + V_Q\right) \tag{1}$$

$$i_L(t) = i_L(t_0) + \frac{\frac{N_s}{N_p}\left(V_s - 2V_Q\right) - V_{bat} - \left(V_D + V_Q\right)}{L}\left(t - t_0\right) \tag{2}$$

Where, V_Q is forward voltage drop of the switch, V_D is the forward voltage drop of the body diode of the switch, V_{bat} is the battery voltage and the N_s/N_p is the turn ratio of the transformer.

During the time t_1~t_2, the switches S1 and Q2 are turned off. When S1 is turned off at t_1, the energy stored in the leakage inductance L_{lk} starts to charge and discharge the parasitic capacitor of switch S1 and S2, respectively. The ZVS can be achieved when the condition in (3) is satisfied. Here, the C_{oss} is the parasitic capacitance of the switch.

$$E = \frac{1}{2}L_{lk}\left(I_{pri}\left(t_1\right)\right)^2 \geq \frac{4}{3}C_{oss}V_s^2 \tag{3}$$

Thus, the ZVS turn-on of the switch S2 can be achieved at t_2. Similarly ZVS turn-on of the switch S3 can be achieved, too.

2.2 Operation of the proposed converter in the discharge mode

During the time t_0~t_1, the switches S1 and S4 are turned on while the switch Q3 is conducting. The body diode of Q4 is forward-biased. The voltage, $N_s/N_p \cdot V_s \cdot D$, is applied to the secondary side of the transformer to overcome the voltage drop of the circuit components (D: duty cycle). The current and voltage equations for the inductor can be obtained as (4) and (5), respectively.

$$v_L = \frac{N_s}{N_p}\left(V_s - 2V_Q\right) + V_{bat} - \left(V_D + V_Q\right) \tag{4}$$

$$i_L(t) = i_L(t_0) + \frac{\frac{N_s}{N_p}\left(V_s - 2V_Q\right) + V_{bat} - \left(V_D + V_Q\right)}{L}\left(t - t_0\right) \tag{5}$$

During the time t_1~t_2, the switches S1 and S4 are turned off, then the switch Q1 is turned on. The energy of battery continues to discharge to the primary side, thus the body diodes of the switches S1 and S4 are forward-biased and begin to conduct. In this mode, the current I_{DS1} changes its direction and flows through the anti-parallel diodes of the switch S1. The voltage and current of the inductor L at this time can be expressed as followings.

$$v_L = -\frac{N_s}{N_p}\left(V_s + 2V_D\right) + V_{bat} - \left(V_D + V_Q\right) \tag{6}$$

$$i_L(t) = i_L(t_1) - \frac{\frac{N_s}{N_p}\left(V_s + 2V_D\right) - V_{bat} + \left(V_D + V_Q\right)}{L}\left(t - t_1\right) \tag{7}$$

On the other hand, switches S1 and S4 are off when the drain-source voltage of it equals to 0[V], thus the ZVS turn-off of the switches S1 and S4 are completed. The ZVS turn-off can also be achieved at switches S2 and S3 in the following mode.

3. Design of the charge/discharge controller

Fig. 3 is the block diagram of battery charge control algorithm using double control loop. It consists of an outer control loop regulating the converter output voltage (CV Mode) and an inner control loop serving for output current control (CC Mode).

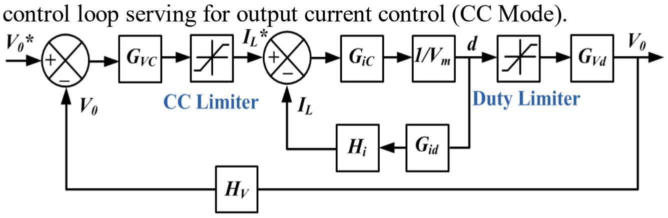


Fig. 3 Block diagram of the battery charge control algorithm

In the discharge mode, the battery is discharged by the constant current control until the battery voltage is reduced to the zero volts. The controller is designed to maintain the constant discharge current by adjusting the duty cycle of PWM signals.

4. Experimental results

The system parameters for the experiments can be found in the Table 1.

Table 1 System parameters for the experiments

Input voltage/ Output voltage	V_s/V_o	42 V/4.2 V
Maximum output power/ Frequency	P_o/f_{sw}	210 W/50kHz
Output inductor	L	80 μH
Samsung battery	ICR18650	1 cell
Battery initial voltage	V	2.75 V
Equivalent capacitance of the battery	C_b	2663 F
Equivalent series resistance of the battery	R_b	0.1 Ω

As shown in the Fig. 4, the ZVS turn-on is achieved at the switches S2 and S3 during the charge mode. Fig. 5 shows the voltage and current waveforms of the switches S1 and S2. As seen in the figure, ZVS turn-off can be achieved at each switch S1 and S2 in the discharge mode.

The actual charge/discharge profile for both CC and CV mode obtained with the Li-Ion battery from the experiments is shown in Fig. 6. In the charge mode, the charge current is regulated at the reference value of 1C (2.6[A]) and the voltage of the battery increase gradually until it reaches to the nominal battery voltage 4.2[V], then the charger changes its mode to CV mode charge.

In the CV mode, the battery voltage is maintained at 4.2[V] and the current decrease gradually by the time until the battery is fully charged. In the discharge mode, the discharge current is maintained

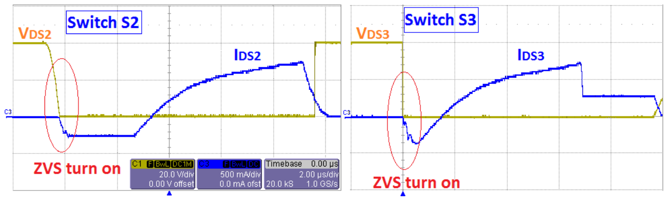


Fig. 4 ZVS turn-on at the switches S2 and S3 in the charge mode

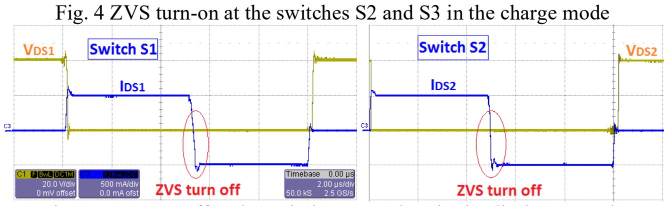
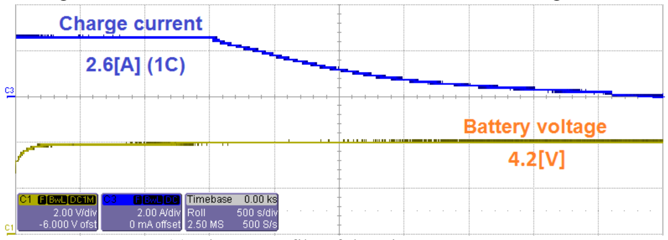
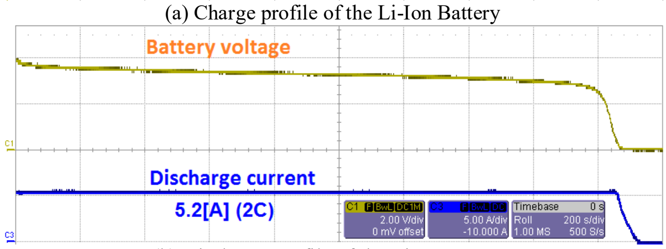


Fig. 5 ZVS turn-off at the switches S1 and S2 in the discharge mode

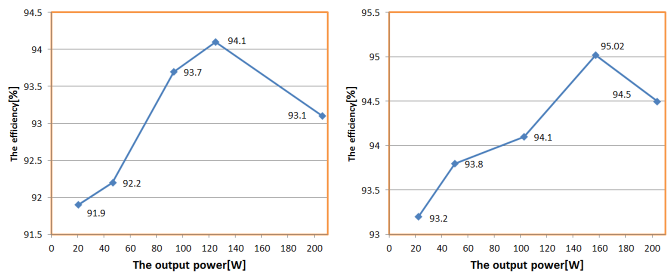


(a) Charge profile of the Li-Ion Battery



(b) Discharge profile of the Li-Ion Battery

Fig. 6 Charge/Discharge profile of the proposed converter



(a) Charge mode (b) Discharge mode

Fig. 7 Efficiency plots of the proposed converter

at the value of 5.2[A] and gradually decreases until the battery voltage reaches to 0[V]. Fig. 7 shows the efficiency plots of the proposed converter in the charge and discharge mode at different output power.

5. Conclusion

This paper proposed a novel charge/discharge converter with zero voltage discharge function. The operation of proposed converter with zero voltage discharge function was analyzed and the performance of the converter was confirmed through the experiments. The proposed converter exhibits the higher efficiency by the ZVS of the switches and lower cost by the reduced number of the switches compared to the previous topology.

References

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[2] Dae-Taek Chung, Soo-Yong Chae and Soon-Chan Hong, "New Secondary Battery Charger/Discharger Available for Zero Voltage Discharge," Journal of KIIEE, Vol.26, No. 11, pp. 62-74, 2012, November.