A High-Efficiency Li-ion Battery Switching Charger with Dual-Path Three-Level Buck Converter

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Abstract - **This paper proposes a Li-ion battery switching charger with a three-level DC-DC buck converter adopting a loop-free auto-calibration technique for self-balancing of two flying capacitors. The proposed Li-ion battery switching charger provides four operation modes including trickle, pre-charge, constant current (CC) and constant voltage (CV) mode as the Li-ion battery voltage level. It is designed by 0.13-µm CMOS BCD process and used 0805 size two flying capacitors of 4.7 μF each and an inductor of 10 μH with a DC resistance (DCR) of 100 mΩ as output components. The core chip size without pads is 3.7 × 3.7 mm². The measurement verified the proposed loop-free auto-calibration scheme and the simulation result shows charging process. The supply voltage is 9 V and the load voltage condition varies 2.7-4.2 V and the maximum load current is 1.5 A. The simulation peak efficiency of constant current mode is 93.2% at 1 MHz switching.**

***Keywords*—Dual-Path, Flying capacitor, Li-ion battery charger, Loop-free calibration, Self-balancing, Three-level buck converter**

I. INTRODUCTION

Recently, many products are powered by various kinds of batteries such as electronic vehicles, tablets and mobile phone etc. The needs of battery charger are growing and the required specifications are also getting higher. Thus, the battery charger should be designed with high efficiency and short charging time.

For Li-ion battery, the chargers need to have a charging process depending on the battery voltage level to protect the battery lifetime. The charging process consists of trickle, pre-charge, constant current (CC), constant voltage (CV) and end of charge mode [1]-[5]. The trickle and pre-charge mode are for a voltage state of Li-ion battery under 3 V and provide low constant current if not, the Li-ion battery can be damaged and shorten lifetime. When the battery reaches enough to be charged by high current, the operation mode is changed to CC mode which is for fast charging. The CV mode is for almost fully charged battery so the output voltage of the charger is regulated to the fixed voltage and charging current is gradually decreased.

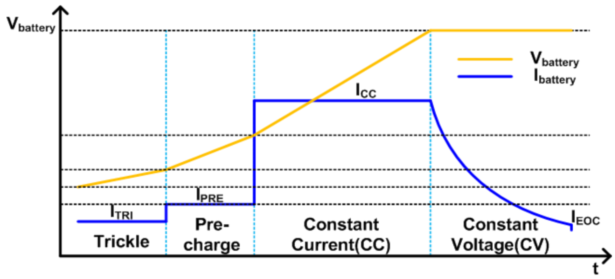

Fig. 1. Charging process of the Li-ion battery

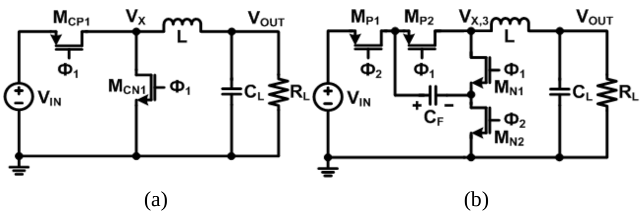

Fig. 2. Conventional (a) two-level and (b) three-level buck converters

Several kinds of DC-DC step-down converter exist such as linear regulators and switching converters. Linear regulator is inefficient when the difference between input and output is large or a heavy load condition. Therefore, the switching converter with inductor is suitable for high efficiency under the condition. However, a conventional two-level buck converter shown in Fig. 2(a) has two primary disadvantages to convert 9V supply to 2.7 to 4.2V output voltage. First, the buck converter needs high-voltage transistors (e.g. > 9 V) to endure a high supply voltage without breakdown. Such transistors have large size and parasitic capacitance leading to high switching losses. Second, the converter suffers from high power dissipation at DCR because large inductor current ripples. To overcome these issues, a three-level buck converter shown in Fig. 2(b) can be used [6]-[7]. The three-level buck converter has half the V_{IN} and makes the swing range of the switching node, $V_{X,3}$ becomes half. Additionally, high-voltage transistors can

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be replaced with low-voltage transistors (e.g. 5 V Tr.). However, the practical operation of the three-level converter suffers from parameter mismatches in power transistors, leakages, gate signal timing, and parasitic capacitors, which lead to voltage variations in C_F during phase transition [8]. The switching node voltage, $V_{X,3}$ can then be different at each operation phase, increasing inductor current ripples and conduction losses. In addition, the power transistors can breakdown if voltage differences across transistors exceed the tolerable range due to unbalancing of the flying capacitor voltage. To prevent this issue and minimize the inductor current ripple, state-of-the-art papers have suggested calibration techniques to balance the flying capacitor voltages in three-level buck converters [9]-[11].

In the following section, we propose the dual-path three-level buck converter with loop-free auto-calibration. The current control method of the CC mode for Li-ion battery charger is also explained in detail. The implementation of current control circuit is given in section III. The simulation result and conclusion is shown in section IV.

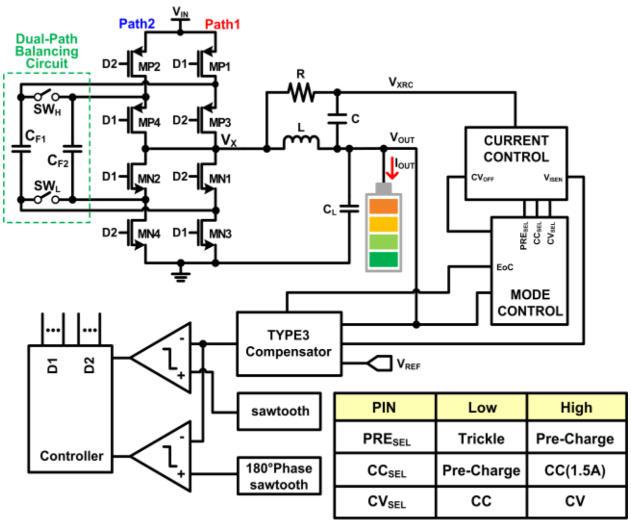
II. SYSTEM DESIGN

The proposed system consists of three-level buck converter, current control, mode control, two different phases of saw-tooth waveforms and other logic blocks.

A. Operation of the switching charger

Fig. 3 shows the block diagram of the proposed switching charger. The dual-path three-level buck converter is adopted to step down the 9 V input voltage [12]. The three-level buck converter has two paths, M_{P1}-M_{P3}-M_{N1}-M_{N3} with C_{F1} and M_{P2}-M_{P4}-M_{N2}-M_{N4} with C_{F2}, and two balancing switches, SW_H and SW_L, are added between C_{F1} and C_{F2}. The power switches in path1 and 2 operate complementary. The operation sequence is following. In phase1, $M_{N3,\ P3}$ on path 1 and $M_{N2,\ P2}$ on path2 turn on. Half of I_L flows from V_{IN} to the load via the flying capacitor, C_{F2}, on path 2. The rest of I_L flows from GND to the load via the flying capacitor, C_{F1}, on path 1. For phase2, all NMOS transistors on both paths turn on and all PMOS transistors turn off for de-energizing. For phase3, $M_{N3,\ P3}$ on path1 and $M_{N2,\ P2}$ on path2 turn off and all other power transistors turn on. After that, the phase2 is again. In short, the three-level buck convert operation is phase1 to 2, phase2 to 3 and phase3 to 2 repeatedly.

For constant current generation of the CC mode, we use the voltage difference of DRC at the inductor. The R and C components beside the inductor make the average of VX which is VXRC1. The VXRC1 is compared to VOUT and kept a bit higher than VOUT by control blocks. As the result, the voltage difference and DCR make constant current values.



PIN	Low	High
PRE_{SEL}	Trickle	Pre-Charge
CC_{SEL}	Pre-Charge	CC(1.5A)
CV_{SEL}	CC	CV

Fig. 3. Proposed switching charger for Li-ion battery

III. IMPLEMENTATION

A. Mode control and charging system

The mode control circuit is composed of hysteresis comparator and logic circuits as shown in Fig. 4. The PRE_{SEL}, CC_{SEL}, CV_{SEL}, and EoC (End of charge) signals are determined as V_{OUT} state, and the operation mode of the circuit for each signal is as shown in Fig. 5. When the battery voltage is 2.7 V~2.8 V, the trickle mode operates and a current of 100 mA charges the battery. When the V_{OUT} voltage reaches 2.8 V, the signal of the pre-charge logic becomes high, and it operates in pre-charge mode and supplies about 300 mA of current. When the V_{OUT} voltage becomes 3 V, the CC_{SEL} logic becomes high, it operates in CC mode, and provides 1.5 A of current for fast charging. Finally, when V_{OUT} reaches 4.2 V, the CV_{SEL} logic becomes high and in CV mode and the charging current gradually decreases. In this operation phase, if the charging current decreases to about 5% of 1.5 A, the CV_{OFF} logic, received from the current control circuit, becomes high, making the EoC logic high and the charging process is terminated with EoC.

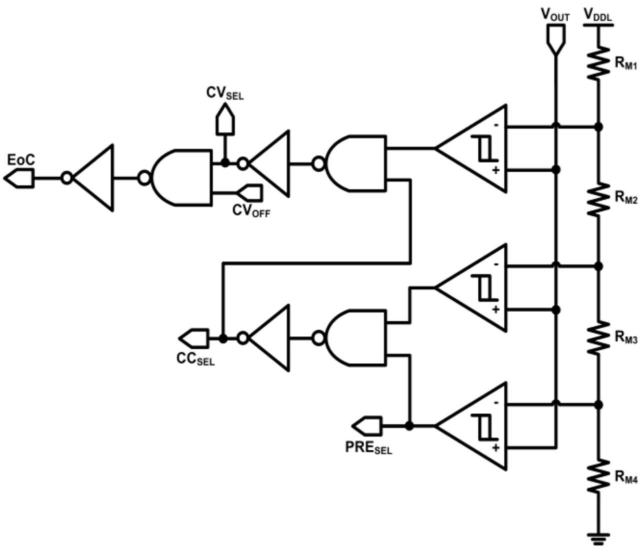


Fig. 4. Schematic of the mode control block

V_{OUT} (V)	I_L (mA)	PRE_{SEL}	CC_{SEL}	CV_{SEL}	EoC	Mode
2.7~2.8	100	Low	Low	Low	Low	Trickle
2.8~3	200 ~ 300	High	Low	Low	Low	Pre-charge
3~4.2	1500	High	High	Low	Low	CC
4.2	1500 ~ 70	High	High	High	Low	CV
4.2	≈ 70	High	High	High	High	OFF

Fig. 5. Operation modes of the switching charger

B. Current control

The current control circuit is composed as shown in Fig. 6. The CV_{OFF} logic is to end charging in CV mode and created by comparing V_{XRC2} with the V_{OUT} value that passed the source follower. The V_{XRC2} is a voltage that is about 10mV higher than the value of V_{XRC1} passing through the source follower. If the charging current decreases, the average value of V_X and the voltage of V_{OUT} become closer, and eventually the CV_{OFF} logic changes. The CV_{OFF} logic uses logic in the mode control circuit to make the EoC logic, which is a signal that actually ends charging. Therefore, even in trickle mode, when the voltage difference between the average value of V_X and the voltage of V_{OUT} is small, the CV_{OFF} may come out high because of the CV_{SEL} logic and AND logic gate. However, at this time, since the CV_{SEL} logic of the mode control circuit is kept low, the EoC logic is kept low regardless of the CV_{OFF}.

In CC mode, the charging current value is controlled by using the voltage difference between both ends of DCR at the inductor. The voltage difference across the DCR according to the charging mode is determined by the logic signals of the PRE_{SEL} and CC_{SEL}. According to these logics, the output of V_{ISEN} is set as V_{XRC3} to V_{XRC5}, which is a voltage lower than the average value of V_X. This V_{ISEN} value is compared with V_{OUT} through the compensation stage to make the average value of V_X higher than V_{OUT} by a certain voltage.

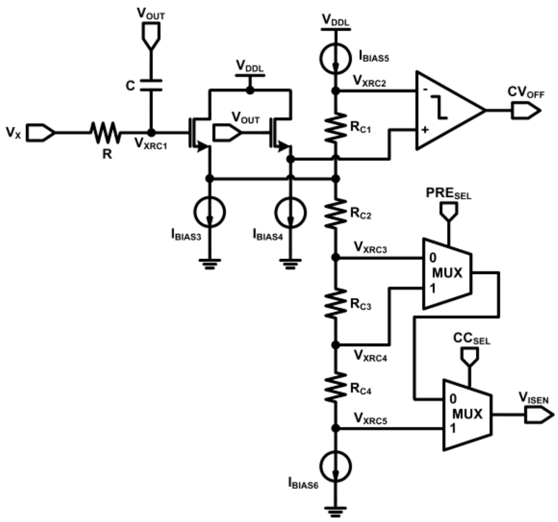


Fig. 6. Schematic of the current control block

C. Type-3 compensator

The Type-3 compensator circuit is designed as Fig. 7. The reference voltage of the compensator is selected and supplied depending on the charging mode whether it is the trickle, pre-charge, CC mode that supplies current to the battery or the CV mode that maintains the battery voltage at 4.2 V. The connection state of the input is changed by CV_{SEL}. In CC mode, the V_{ISEN} signal of the current control circuit is connected to the negative input and V_{OUT}, the reference signal, is connected to the positive input, so that the average value of V_X is maintained a certain voltage higher than V_{OUT}. In CV mode, the V_{OUT} value is connected to the negative input and V_{REF}, the external input of the chip, is designed to be connected to the positive input.

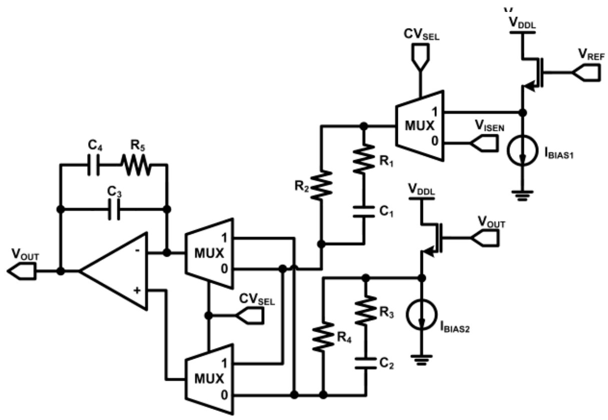


Fig. 7. Schematic of the type-3 compensator

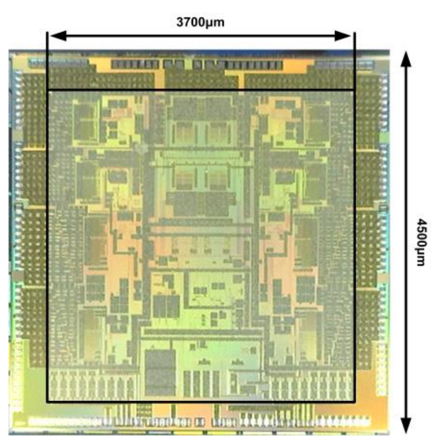
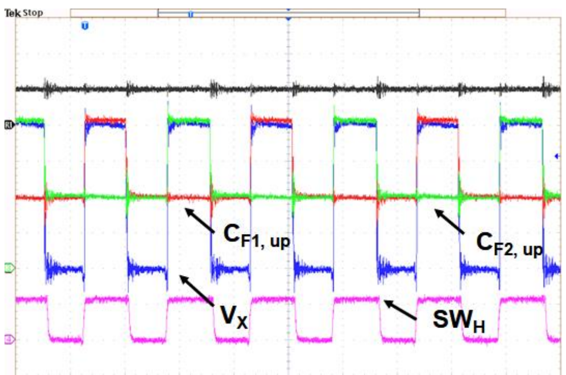


Fig. 8. Die micrograph of the proposed switching charger

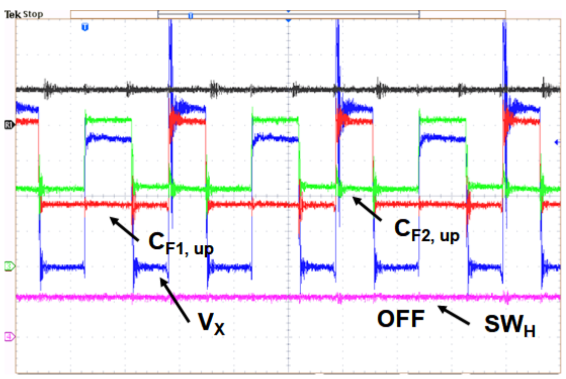
IV. SIMULATION AND MEASUREMENT RESULT

Fig.8 is the die micrograph of the proposed switching charger fabricated by 0.13-μm CMOS BCD process. The whole chip size including pads is 4.5 × 4.5 mm^2 and core chip size without pads is 3.7 × 3.7 mm^2. It uses two flying capacitors 4.7 μF each and one 10 μH inductor with 100mΩ DCR. Fig. 9 depicts the effects of balancing switches for auto-calibration of voltages in $C_{F1,\ 2}$. When the balancing switches operate, as shown in Fig. 9(a), the $C_{F1,up}$ and $C_{F2,up}$ nodes swing the same voltage levels from $V_{IN/2}$ to V_{IN} but are phase shifted each other. V_X also swings from GND to $V_{IN/2}$, showing that V_{CF1} and V_{CF2} are self-balanced. However, if the balancing switches are deactivated in the dual-path structure by intentionally turning off S_{WH} and S_{WL}, as shown in Fig. 9(b), V_X varies irregularly, implying that the balance of flying capacitors is broken. This unbalancing leads to not only efficiency degradation but also risk of damages in power transistors [12].

Fig. 10 shows the measurement results of the trickle mode and mode transition from trickle to pre-charge modes. The trickle and pre-charge currents were set as 100mA and 200-300 mA as shown in Fig. 5. Measured current levels were a bit deviated from the target values due to variations of inductor DC resistance and reference voltages, which may be further adjusted with external tuning functions. Fig. 11 depicts the simulation result of the proposed switching charger. Under V_{OUT} = 2.8 V, it provides 100 mA. In pre-charge mode between 2.8 and 3 V, 300 mA is transferred to the battery. At V_{OUT} = 3 V, fast charging mode begins so, 1.5 A is supplied and the battery is charged quickly. When V_{OUT} is between 4 and 4.1 V, it shows the peak efficiency which is 93.2%. The Li-ion battery is almost fully charged, V_{OUT} is reached to 4.2 V, the operation becomes CV mode and the current is slowly decreased. If the load current is about 70 mA at CV mode, the charger finishes the charging operation. Fig. 12 shows the simulated efficiencies (P_{OUT}/P_{IN}) of the Li-ion battery switching charger. The efficiencies were obtained at V_{IN} = 9V through trickle (2.7-2.8V), pre-charge (2.8-3V), CC (3-4.2V) modes with charging current of 100 mA, 300mA, 1.5A, respectively. It shows 93.2% peak efficiency when V_{OUT} is 4.2 V and the charging current is 1.5 A. However, when V_{OUT} is 2.7 V, the efficiency is relatively lower because it is out of optimum point.



(a)



(b)

Fig.9. Measurement waveforms of (a) with and (b) without self-balancing functions

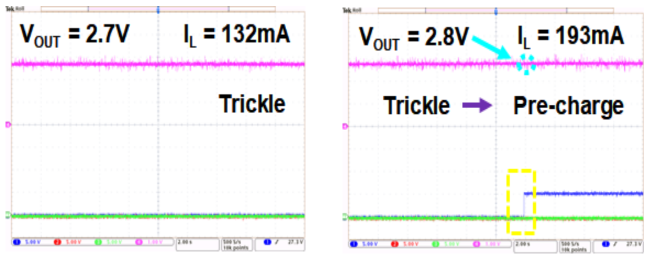


Fig. 10. Measurement graphs of the mode transition

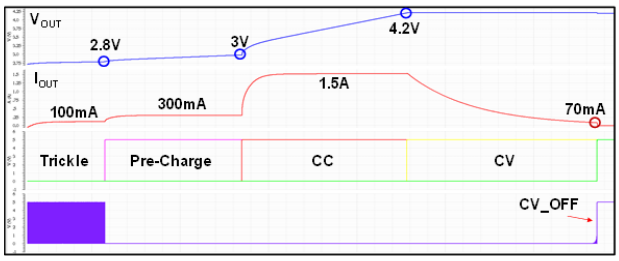


Fig. 11. Simulation graph of the charging process

TABLE I. Specification Table

	2016 [1]	2018 [10]	This work
Process	0.13μm	0.65μm	0.13μm (BCD)
Topology	two-level	three-level	three-level & charger
Inductor	-	100 nH	10 μH
Flying cap.	X	5 nF	4.7 μFx2
Frequency	1.5 MHz	50 MHz	1 MHz
V_{IN}	6 - 16 V	5 V	9 V
V_{OUT}	2.5 - 4.2 V	0.6 - 4.2 V	2.7 – 4.2 V
Peak I_L	1.5A	0.7A	1.5A
Peak efficiency	87%	90%	93.2%
Flying cap. Balancing	X	Feedback loop control	Dual path + Loop-free cal.

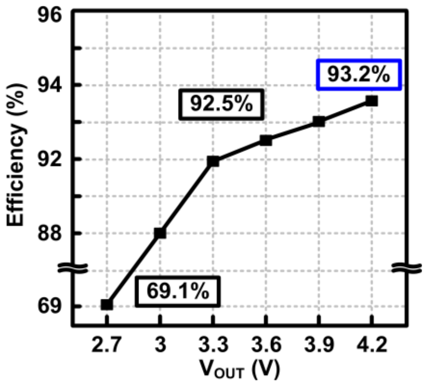


Fig. 12. Simulated efficiencies of the switching charger

IV. CONCLUSION

The proposed switching charger adopted three-level buck topology with loop-free auto-calibration method and utilizes inductor DCR for charging current regulation. Consequently, it implements four operation modes, trickle, pre-charge, constant current and constant voltage mode, as the charged battery voltage. Finally, it improved the charging efficiency by saving switching loss and power dissipation at DCR. Consequently, the three-level buck converter with loop-free auto-calibration shows simple and robust flying capacitor balancing operation and improves power efficiencies, especially for applications where the input voltage is much higher than the output voltage.

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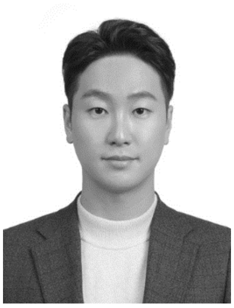

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