An Adaptive and Wide-Range Output DC-DC Converter for Loading Circuit of Li-Ion Battery Charger

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Abstract

In this paper, an adaptive and wide-range output DC-DC converter designed for lithium-ion (Li-Ion) battery charger circuit is proposed. The converter operates in continuous conduction mode (CCM) to provide an output voltage in response to battery voltage and a wide-range output current to ensure that circuit requirements are met. This circuit is designed on Cadence using 0.35-μm BCD technology. Simulation results show that the circuit fully operates in CCM mode with a load current from 50 mA to 1000 mA and output voltage ripple factor is less than 1%. Furthermore, the current supplied to the load circuit responses to three types of Li-Ion rechargeable currents. The output voltage of the converter varies from 2.8 to 4.5 V corresponding to the voltage range of the battery being charged from 2.5 to 4.2 V. The average power efficiency of the converter in large load current mode (1000 mA) reaches 94%.

Keywords: Li-Ion battery, charging mode, charger circuit, DC-DC converter, adaptive reference voltage.

1. Introduction

Today, Li-Ion batteries are widely used in consumer electronics for its significant advantages such as high energy density, high recharge cycle (> 1000 cycles), no memory effect, low self-discharged rate (2 - 8 % per month), wide range of operating condition (charge at -20 – 60 °C, discharge at -40 - 65 °C). In addition, a single cell of Li-Ion battery can operate in the range of 2.5 to 4.2 V [1]. The charging circuit is designed according to three modes following the charging standard [2, 3] as shown in figure 1. Trickle constant current mode (TC) occurs when the battery voltage is less than 2.9 V, large constant current mode (LC) when the battery voltage is in the range of 2.9 to 4.2 V, and constant voltage charging mode (CV) when the battery voltage reaches 4.2 V.

In [4-6], the charging circuit is designed based on the structure of a low dropout regulator which offers high integration, fast and accurate control. But this charging structure has low power efficiency due to large deviation between supply voltage and battery voltage. To overcome this drawback, some techniques were proposed and presented in [7, 8].

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Figure 1. Li-Ion battery charging modes.

The switching mode power supply converter is used to generate a variable supply voltage changing in response to the battery voltage during the charging process. However, the use of large off-chip elements for the boost converter structure in [7] and the flyback converter in [8] increase the size of printed circuit board (PCB). The rechargeable circuit in [9, 10] adopted the buck converter structure minimizing the size of PCB. However, the TC charging mode was not introduced and there was no isolation between DC-DC converter and battery so the self-discharge of battery may occur and battery performance cannot be guaranteed. In this article, we propose an adaptive buck DC-DC converter based on a buck converter structure that operates in continuous conduction mode (CCM) with a wide range of voltage and current variations in accordance with the Li-Ion charging circuit that was presented in our previous work [11].

The rest of the paper is structured as follows: Section 2 describes the structure of an adaptive and wide-range output DC-DC converter with a battery charger as load. Design parameters are considered and calculated in Sub-Section 2 to ensure that the converter operates stably in CCM mode and can supply a wide range of voltage and current to the load circuit. In Section 3, the simulation results are shown to evaluate the converter’s performance. Finally, the conclusion is given in Section 4.

2. Circuit descriptions

In general, the PWM DC-DC converter, as shown in figure 2, is implemented to provide a stable output voltage $V_O$ from the input voltage $V_I$ thanks to the closed loop control. The feedback voltage $V_{FB}$ is sampled from the output through a voltage divider of two resistors $R_{F1}$, $R_{F2}$. In the compensator, the $V_{FB}$ will be compared with the reference voltage $V_{ARV}$ to generate the deviation voltage $V_C$ which is used to determine the duty cycle of $V_{PWM}$ from the PWM generator circuit. The switching signals $V_N$, $V_P$ to the gate of two power MOSFET N and P are finally generated by the non-overlap gate driver. The output filter LC$_O$ is well chosen to stabilize the output voltage that can be determined as follows (1)

$$V_O = \left( \frac{R_{F1} + R_{F2}}{R_{F2}} \right) V_{ARV}$$

Besides, the load of this DC-DC converter is a Li-Ion battery charging circuit which has been implemented in [11]. In that previous work, the varying battery voltage $V_{Bat}$ during the charging process is fed into the voltage level-shift circuit to provide a variable reference voltage $V_{ARV}$, which is also called an adaptive reference voltage. The DC-DC converter’s output voltage $V_O$ should also be controlled to follow the battery voltage $V_{Bat}$ so that the power efficiency of the whole system is improved. In this design, the value of the input voltage $V_I$ is around 6 V, switching frequency $F_{SW}$ is selected at 500 KHz and the output voltage $V_O$ of the converter is expected to be always 0.3 V higher than the battery voltage $V_{Bat}$. 
2.1. Compensator

To ensure the current and voltage requirements to the load circuit, the analysis of a conventional buck converter presented in [12] is employed to determine the value of inductor \( L \) and the ceramic capacitor \( C_0 \). The theoretical calculation pointed out that the corresponding values of inductor and capacitor should be 22 \( \mu \)H (\( R_L \approx 46 \) m\( \Omega \)) and 22 \( \mu \)F (\( R_C \approx 5 \) m\( \Omega \)) respectively. The transfer function of power converter stage is thus defined as a function of double-pole \( \omega_{LC} \) (7.23 KHz) generated by the \( LC_0 \) filter and one zero \( \omega_{ESR} \) (1.45 MHz) created by the equivalent series resistance \( R_C \) and \( C_0 \). To stabilize the circuit and compensate the phase degradation caused by the double-pole, the type-III compensation is adopted as shown in figure 3. Error amplifier EA is designed using a class AB two-stage op-amps with high and symmetrical slew rate [13]. Transfer function of the compensation circuit given in (2) consists of three poles (\( \omega_{P0}, \omega_{P1}, \omega_{P2} \)) and two zeros (\( \omega_{Z1}, \omega_{Z2} \)). The zero frequency \( \omega_{ESR} \) is much larger than the switching frequency \( \omega_{SW} \) so that it does not affect the frequency range of the converter. In this approach, zero frequencies \( \omega_{Z1} \) and \( \omega_{Z2} \) are designed in adjacent to the double-pole at frequencies 0.6\( \omega_{LC} \) and 1.5\( \omega_{LC} \) respectively. Pole frequency \( \omega_{P1} \) is set at 0.5\( \omega_{SW} \) and \( \omega_{P2} \) is calibrated in frequency range of (0.8 – 0.9)\( \omega_{SW} \).

\[
K_C(s) = \frac{1}{R_{F1}(C_2 + C_3)s} \left( \frac{1}{1 + \frac{s}{\omega_{Z1}}} \right) \left( \frac{1}{1 + \frac{s}{\omega_{P2}}} \right) \left( \frac{1}{1 + \frac{s}{\omega_{P1}}} \right)
\]

(2)

With,

\[
\omega_{P0} = 0, \quad \omega_{P1} = \frac{1}{R_1C_1}, \quad \omega_{P2} = \frac{1}{R_2}\left(\frac{C_2}{C_2 + C_3}\right)
\]

\[
\omega_{Z1} = \frac{1}{R_2C_2}, \quad \omega_{Z2} = \frac{1}{C_1(R_1 + R_{F1})}
\]

Figure 2. Structure of adaptive DC-DC converter with Li-Ion battery charger as load.

Figure 3. Type-III compensation circuit.
From (2), the design values of the compensation network components are calculated and summarized in table 1. The phase margin and gain margin in figure 4 demonstrated a loop gain of converter ~ 59.4 deg at cross frequency 54 KHz and 27 dB at frequency 445 KHz.

2.2. PWM generator

In figure 5(a), the high-speed comparator is used [14] to provide pulse width modulator (PWM) signals. As mentioned above, the signal $V_C$ is compared to ramp signal $V_R$ at fixed amplitude and frequency to produce the pulse signal $V_{PWM}$ where its duty cycle $D$ is defined as in (3). The waveforms of $V_C$, $V_R$ and $V_{PWM}$ are illustrated in figure 5(b). The PWM circuit functions correctly as expected through the loop control and it is able to regulate the output voltage of DC-DC converter.

$$\frac{V_O}{V_I} = D = \frac{V_C}{V_R} \quad (3)$$

Figure 4. Bode plot of the converter’s loop gain for $V_0 = 4$ V and $I_O = 1$ A.

2.3. Ramp generator

The schematic of a ramp generator is shown in figure 6(a). The reference current $I_B$ is created and controlled by reference voltage $V_{Ref}$ as a current source. The topology of low-voltage cascode current mirror is used to create the currents $I_R$ and $I_{Ch}$. The reference voltages $V_H$ and $V_L$ are then created by the flow of current $I_R$ through two resistors $R_H$ and $R_L$ in series. The ramp signal is produced by the charging and discharging of the capacitor $C_R$. In steady state, when $V_L < V_R < V_H$, the transistors $M_{10} - M_{12}$ are OFF, the reference voltage $V_H$ is connected to the negative input of the

<table>
<thead>
<tr>
<th>Resistors Parameters</th>
<th>Capacitors Parameters</th>
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<tbody>
<tr>
<td>$R_{F1}, R_{F2}$ 13 KΩ</td>
<td>$C_1$ 1100 pF</td>
</tr>
<tr>
<td>$R_1$ 566 Ω</td>
<td>$C_2$ 510 pF</td>
</tr>
<tr>
<td>$R_2$ 71.5 KΩ</td>
<td>$C_3$ 5.1 pF</td>
</tr>
</tbody>
</table>
The capacitor $C_R$ is then charged during this period until the voltage $V_R$ is higher than $V_H$. That will turn the transistors $M_{10} - M_{12}$ ON so the reference voltage is switched to $V_L$. The capacitor $C_R$ is discharged rapidly, the voltage $V_R$ is reduced to a value smaller than $V_L$ that turn the transistors $M_{10} - M_{12}$ to OFF state. The process is then repeated. The period of ramp signal is calculated as a function of the charging time ($T_{\text{rise}}$) as expressed in equation (4) and the discharging time ($T_{\text{fall}}$) of the capacitor $C_R$. The ratio of $T_{\text{fall}}/T_{\text{rise}}$ is approximately of 5% that lead to a discharging time $T_{\text{fall}}$ of about 100 ns.

$$T_{\text{rise}} = \frac{(V_H - V_L)C_R}{I_{\text{Ch}}} = \frac{I_R R_H C_R}{I_{\text{Ch}}} = R_H C_R \quad (4)$$

As can be seen in equation (4), the value of ramp frequency is a function of $R_H$ and $C_R$. To ensure the performance of ramp generator, a high gain OA [15] with loop gain stability is adopted. The high speed comparator C is designed with a propagation delay of about 10 ns that is suitable for our adaptive-output converter. Simulations of ramp generator is presented in figure 6(b). It can be seen that ramp signal $V_R$ meets the maximum value at 3.51 V and minimum value at 0.45 V where the operating signal reaches 500.5 KHz as expected.

### 2.4. Non-overlap and Gate Driver

The non-overlap and gate driver circuit are illustrated in figure 7(a). The gate driver is a buffer circuit consisting of four inverter layers designed according to the tapering factor in the range of 3 to 4 [14]. The gate driver is used to switch the power transistors $M_P$ and $M_N$ of DC-DC converter to obtain a certain output voltage level defined by the duty cycle of switching control signal $V_{PWM}$. In addition, to avoid power loss induced at each switching transition when both $M_P$ and $M_N$ are open resulting in shoot-through current loss, the non-overlap circuit is also implemented. A sufficient small delay between the rise time and fall time of two opposite $V_P$ and $V_N$ signals is added. Their waveforms are presented in figure 7(b).
3. Simulation results

The inductor current and output voltage of the proposed DC-DC converter are shown in figure 8. It is obvious that the continuous conduction mode is guaranteed for three different operation modes of battery charging circuit playing the role as load of the converter. The average inductor current, also called as the load current, reaches the value of 200 mA at output voltage of 3 V, 1000 mA with output voltage of 4 V and 50 mA with output voltage of 4.5 V, respectively. These results confirm that the circuit meets the requirement of power supply for battery charging circuit while it works at trickle charging mode (TC), large current charging mode (LC) and constant voltage charging mode (CV) respectively. Besides, the output voltage ripple is relatively small and almost lower than 1 %.

In figure 9(a), it can be observed that the results show smooth and stable transitions of load current from trickle mode (200 mA) to large current mode (1000 mA) and then to constant voltage mode (50 mA). This current profile meets completely the charging profile of a Li-Ion battery charger. It means that the proposed compensation circuit and the control loop including PWM and gate driver work effectively and guarantee the stability of the
whole system. At light load, when the load current is less than 50 mA, the converter gradually switches to DCM mode, that results in power loss. But this problem can be improved by a detecting-negative-current circuit from the inductor current of the power stage. In addition, a slight undershoot voltage at the transition from trickle to large current mode is also observed in figure 9(b). However, an undershoot voltage of 60 mV which is about 1.8 % of output voltage can be neglected. Interestingly, a constant 0.3 V difference between the output voltage $V_O$ of the proposed DC-DC converter and the battery is recorded for three different charging modes. The converter’s output voltage is always 0.3 V higher than the battery voltage. It is seen that $V_O$ is adjusted dynamically according to the battery voltage with the accuracy of over 99 %. As per its name, this DC-DC converter provides an adaptive power supply, not a constant output voltage like any other conventional DC-DC converter, to the battery charger circuit.

As can be observed in figure 10, the power efficiency of our proposed adaptive-output converter is higher than 94 % for an output voltage varying widely from 2.8V to 4.5 V. The highest efficiency can be reached at 97 % where output voltage varies from 2.8 to 3.2 V and load current is 200 mA. Efficiency is 94 % with an output voltage varying from 3.2 V to 4.5 V where load current is 1000 mA.

![Figure 8. Steady-state waveforms of inductor current and output voltage with.](image)

(a) Corresponding to TC mode of the battery charger
(b) Corresponding to LC mode of the battery charger
(c) Corresponding to CV mode of the battery charger

![Figure 9. Simulation results of adaptive DC-DC converter with Li-Ion battery charger load.](image)

(a) Output current.
(b) Output voltage and battery voltage.
4. Conclusion

An adaptive and wide-range output DC-DC converter for the Li-Ion battery charger circuit is proposed and designed on the 0.35 µm BCD technology. The converter operating in CCM mode offers a wide range of load current from 50 mA to 1000 mA as well as a broad range of voltage output (from 2.8 to 4.5 V) to the load circuit. The output current and voltage profile of the proposed converter meets perfectly the requirements for Li-Ion battery charger circuit. An average power efficiency of 94% obtained for the crucial stage of large-current charging mode (1000 mA). As a continuation to our previous work, this circuit helps to complete a charging system from power line DC to a Li-Ion battery by combining with the battery charger in [11].

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References


