Analysis on the Output Ripple of the Non-isolated Boost Charger for the Li-ion Battery

Nguyen Van Sang and Woojin Choi

Department of Electrical Engineering, Soongsil University,

Abstract – In the design of the battery charger it is important to limit the ripple current and voltage according to the manufacturer’s recommendation for the reliable service and the extended life of the battery. However, it is often overlooked that these ripple components can cause internal heating of the battery, thereby reducing its service life. Thus the care must be taken in the design of the switching converter for the charger application through the accurate estimation of the output ripple values. In this research analysis on the output ripple of the dc-dc converter is detailed to provide a guideline for the design of the battery charger.

Index Terms – Li-Ion Battery, Battery Charger, Output Ripple Current, Output ripple voltage, Output Inductor

I. INTRODUCTION

An understanding of battery-charging fundamentals and system requirements enable designers to choose a suitable switch-mode charging topology and optimize battery performance in the application. Often, the battery-charging system is given low priority, especially in cost-sensitive applications. However, the quality of the charging system plays a key role in the life and reliability of the battery. To develop an optimized charging system for lithium-ion (Li-ion) batteries, designers must be familiar with the fundamental requirements for charging the batteries. Designers also should be aware of the tradeoffs of each dc-dc converter topology. To maximize performance, the voltage regulation tolerance on the output voltage applied to the cell should be better than ±1%. The minimum current approach monitors the charge current during the constant-voltage stage and terminates the charge when the charge current diminishes in the range of 0.02 C to 0.07 C [2]. Though the current approach monitors the charge current during the constant-voltage stage and terminates the charge when the charge current diminishes in the range of 0.02 C to 0.07 C [2]. Though the current approach monitors the charge current during the constant-voltage stage and terminates the charge when the charge current diminishes in the range of 0.02 C to 0.07 C [2]. Though the current approach monitors the charge current during the constant-voltage stage and terminates the charge when the charge current diminishes in the range of 0.02 C to 0.07 C [2]. Though the current approach monitors the charge current during the constant-voltage stage and terminates the charge when the charge current diminishes in the range of 0.02 C to 0.07 C [2].

II. THE OUTPUT ARCHITECTURE OF THE CONVERTER WITH A BATTERY MODEL

Fig. 1 shows the common output architecture of several kinds of conventional DC-DC converters such as the boost converter, flyback converter, buck-boost converter and SEPIC converter including an equivalent circuit model of the battery.

![Fig. 1. Common output architecture of the conventional DC-DC converters](image)

Since the above mentioned topologies have a front-end inductor and the output diode, the output current is not continuous. Thus the ripple current is bigger than that of the topology with an output inductor. This ripple can be filtered by the output capacitor when the load is the battery due to the huge capacitance value of its equivalent circuit as shown in Fig. 1.

This has to be considered to guarantee the reliable operation of the battery. The ripple current flowing into a battery during the charge can cause heating by the interaction with the internal resistance of the battery (I²R losses). This adds to the internal heat generated inside the battery. Thus the excessive ripple currents lead to diminishing the service life of the battery. In order to meet the ripple requirements of the battery care must be taken in designing the converter.

III. ANALYSIS ON THE OUTPUT RIPPLE OF THE PROPOSED NON-ISOLATED BOOST CONVERTER

In the proposed non-isolated boost converter, an inductor is added in between the output capacitor and the load to meet the ripple requirements of the Li-ion battery.

![Fig. 2. Equivalent circuit of the proposed converter when the switch is closed](image)

In order to analyze the output ripple current of the proposed boost converter, steady state analysis is performed when the switch is closed as in Fig. 2. The voltage loop equation in the rear-end subcircuit can be expressed as (1). All the parasitic components are included for the accurate analysis.

\[-V_{i1}+V_{m1}+V_{m2}=0, \quad L \frac{di_0}{dt} = V_f, \quad C_0 \frac{dv_{i1}}{dt} = -i_0\] (1)

From (1) we have,

\[-\frac{1}{C_0} \int_{\infty}^{t0} i_0 dt - R_{i1} i_0 + L_0 \frac{di_0}{dt} + R_{i2} i_0 + R_{i3} i_0 + \frac{1}{C_0} \int_{\infty}^{t0} i_0 dt = 0\] (2)

The equation (2) can be rewritten as (3) since the last term can be neglected considering the huge capacitance value of the battery.

\[-\frac{1}{C_0} \int_{\infty}^{t0} i_0 dt + \frac{R_0 + R_{i2} - R_{i3}}{L_0} \frac{di_0}{dt} = 0, \quad C_0 \gg C\] (3)

By differentiating both sides of equation (3) and dividing it by \(L_0\) the second order differential equation can be obtained as (4).

\[\frac{d^2i_0}{dt^2} + \frac{R_0 + R_{i2} - R_{i3}}{L_0} \frac{di_0}{dt} + \frac{1}{CL_0} i_0 = 0\] (4)

From the characteristic equation of (4) it can be easily noticed that the output current may have three different forms depending on the damping factor \(\zeta\) as (5).

\[\zeta = \frac{R_0 + R_{i2} - R_{i3}}{2L_0} \sqrt{C_0} \] (5)

When the damping factor is smaller than 1 (\(\zeta < 1\)) the relationship between the capacitance and inductance value can be derived as (6) and hence the output current can be expressed as (7).

\[\frac{R_0 + R_{i2} - R_{i3}}{2L_0} \sqrt{C_0} < C_0 < \frac{4L_{0\text{min}}}{(R_0 + R_{i2} - R_{i3})} \] (6)
\[ i_{ol}(t) = Ae^{-at} \sin(\omega_{ct}t + \varphi) \] (7)

By using the circuit analysis, the output ripple current can be expressed as (8)

\[ \Delta I_{\text{max}} = \frac{I_D}{(2\sqrt{2\pi f_1 L_0 - L_{\text{ESR}}}) C f_s} \] (8)

When the damping factor \( \zeta \) is equal to 1 (\( \zeta = 1 \)), the relationship between the capacitance and inductance value can be derived as (9) and the output current can be expressed as (10).

\[ \frac{4I_{L_{\text{min}}}}{\left( R_b + R_{\text{lo}} - R_{\text{c}} \right)^2} < C_b < \frac{4I_{L_{\text{max}}}}{\left( R_b + R_{\text{lo}} - R_{\text{c}} \right)^2} \] (9)

\[ i_{ol}(t) = B_1 e^{-at} + B_2 e^{-at} \] (10)

Also the output ripple current can be expressed as (11).

\[ \Delta I_{\text{max}} = \frac{1}{\sqrt{2\omega L_0}} \frac{I_D}{C} DT \] (11)

When the damping factor \( \zeta \) is bigger than 1 (\( \zeta > 1 \)), the relationship between the capacitance and inductance value can be derived as (12).

\[ \frac{R_b + R_{\text{lo}} - R_{\text{c}}}{2} \sqrt{\frac{C_b}{L_0}} > 1 \rightarrow C_b > \frac{4I_{L_{\text{max}}}}{\left( R_b + R_{\text{lo}} - R_{\text{c}} \right)^2} \] (12)

In this case the output ripple current can be expressed as (13).

\[ i_{ol}(t) = C_1 e^{-at} + \sqrt{\zeta - 1} e^{at} \] (13)

Also the output ripple current can be expressed as (14).

\[ \Delta I_{\text{max}} = \frac{I_D}{C f_s} \left( R_b + R_{\text{lo}} - R_{\text{c}} \right) \left( 1 - \frac{R_{\text{ESR}}^2 + \frac{1}{4\pi^2 f^2 C^2}}{2\pi f L_0} \right) \] (14)

From the above analysis it can be noticed that the output ripple current has three different forms and values according to the value of the damping factor which depends on the circuit parameters. In the actual circuit design the reactant component value was calculated to meet the ripple limit and three different sets of the parameters were selected to prove the above analysis. For the experiments, three different output inductors were made to have 5\( \mu \)H, 10\( \mu \)H and 20\( \mu \)H inductance and three different capacitors were selected to satisfy the ripple current limit value (126mA) in all three cases. The waveforms are also identical except the critical damped case. Fig. 4 shows the results with three different sets of the reactive components as mentioned in the above section. As can be seen in the figure the magnitudes of the ripple currents are well matched each other and satisfies the ripple current limit value (126mA) in all three cases. The waveforms are also identical except the critical damped case. This discrepancy is likely to be caused by the non-linearity of the circuit.

**IV. SIMULATION & EXPERIMENTAL RESULTS**

In order to prove the analysis of the ripple components PSIM simulation was performed and the results were compared to the experimental results. In the simulation and experiments a Li-Ion battery pack for the laptop computer (ICR18650) was used for both the simulation and experiments. All the system parameters are listed in the Table I.

![Fig. 3. Circuit simulation of the proposed converter with PSIM](image)

**TABLE I. SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>Specification of the converter</th>
<th>Non-Isolated Boost Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage/Output voltage V/VI</td>
<td>6~18/12.6 V</td>
</tr>
<tr>
<td>Output power/Frequency P/f</td>
<td>50 W/60kHz</td>
</tr>
<tr>
<td>Input inductor L</td>
<td>32 ( \mu )H</td>
</tr>
<tr>
<td>Capacitors C</td>
<td>50~2000 ( \mu )F</td>
</tr>
<tr>
<td>Output inductors L_0</td>
<td>5/10/20 ( \mu )H</td>
</tr>
<tr>
<td>Specification of the battery Li-Ion Battery Pack(3S2P)</td>
<td></td>
</tr>
<tr>
<td>Nominal Current I_{\text{nominal}}</td>
<td>3.2 A</td>
</tr>
<tr>
<td>Charging Current I</td>
<td>4 A</td>
</tr>
<tr>
<td>Charging Voltage V</td>
<td>12.6 V</td>
</tr>
<tr>
<td>Battery Initial Voltage V_0</td>
<td>10.8 V</td>
</tr>
<tr>
<td>Output Ripple Voltage ( \Delta V_{\text{ripple}} )</td>
<td>0.126 V (1%)</td>
</tr>
<tr>
<td>Output Ripple Current ( \Delta I_{\text{ripple}} )</td>
<td>0.26 A (0.05%)</td>
</tr>
<tr>
<td>Equivalent capacitance of the battery C_0</td>
<td>9660 ( \mu )F</td>
</tr>
<tr>
<td>Equivalent series resistance of the battery R_0</td>
<td>0.3 ( \Omega )</td>
</tr>
</tbody>
</table>

Fig. 4. Simulation and experimental results of the ripple current of the proposed converter in three different cases

**V. CONCLUSION**

In this paper a simple method to reduce the output ripple current of the converter for the charge application is proposed and the equations for estimating the output ripple have been derived. The proposed method and analysis can be used for the suitable design of the converter for battery charge applications.

**REFERENCES**