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 charge 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 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 magnitude of the ripple component in the output voltage and current is important for the reliable performance and the extended life of the battery, it has been often neglected in the design of the charger. In this research analysis on the ripple voltage and current is detailed for the suitable design of the dc-dc converter for the charge application.

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, fly-back converter, buck-boost converter and SEPIC converter including an equivalent circuit model of the battery.

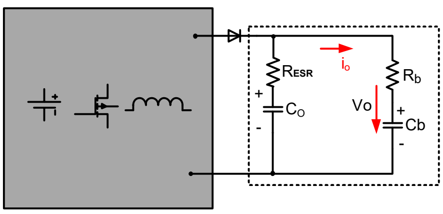


Fig. 1. Common output architecture of the conventional DC-DC converters

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 pure resistive. However, most of the ripple current cannot 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 (I^2R 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.

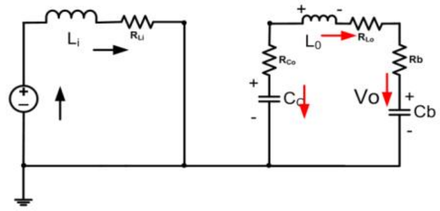


Fig. 2. Equivalent circuit of the proposed converter when the switch is closed

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.

$$-v_{C_0}+v_{L_0}+v_{bat}=0,\ L\frac{di_L}{dt}=V_f,\ C_0\frac{dv_{C_0}}{dt}=-i_0 \qquad (1)$$

From (1) we have,

$$-\frac{1}{C_0}\int_{\infty}^{\tau=t} i_0 dt-R_{C_0}i_0+L_0\frac{di_0}{dt}+R_{L_0}i_0+R_b i_0+\frac{1}{C_b}\int_{\infty}^{\tau=t} i_0 dt=0 \qquad (2)$$

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

$$-\frac{1}{C}\int_{\infty}^{\tau=t} i_0 dt+L_0\frac{di_0}{dt}+\left(R_b+R_{L_0}-R_{C_0}\right)i_0=0,\ \because C_b\gg C \qquad (3)$$

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

$$\frac{d^2 i_0}{dt^2}+\frac{R_b+R_{L_0}-R_{C_0}}{L_0}\frac{di_0}{dt}-\frac{1}{CL_0}i_0=0 \qquad (4)$$

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 (ζ) as (5).

$$\zeta=\frac{R_b+R_{L_0}-R_{C_0}}{2}\sqrt{\frac{C_0}{L_0}} \qquad (5)$$

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).

$$\frac{R_b+R_{L_0}-R_{C_0}}{2}\sqrt{\frac{C_0}{L_0}}<1\rightarrow C_0<\frac{4L_{0-\min}}{\left(R_b+R_{L_0}-R^*_{C_0}\right)^2} \qquad (6)$$

$$i_0(t) = Ae^{-\alpha t}\sin(\omega_d t + \varphi) \qquad (7)$$

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

$$\Delta I_{\max} = \frac{I_o D}{\left(2\sqrt{2}\pi f_s L_0 - R_{ESR}\right) C f_s} \qquad (8)$$

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

$$\frac{4L_{0-\min}}{\left(R_b + R_{L_0} - R_{C_0}^{max}\right)^2} < C_0 < \frac{4L_{0-\max}}{\left(R_b + R_{L_0} - R_{C_0}^{\min}\right)^2} \qquad (9)$$

$$i_0(t) = B_1 t e^{-\alpha t} + B_2 t e^{-\alpha t} \qquad (10)$$

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

$$\Delta I_{\max} = \frac{1}{\sqrt{2}\omega L_0 + R_b + R_{Lo} - R_{ESR}} \frac{I_o DT}{C} \qquad (11)$$

When the damping factor ζ is bigger than 1 (ζ > 1), the relationship between the capacitance and inductance value can be derived as (9) and the output current can be expressed as (12).

$$\frac{R_b + R_{L_0} - R_{C_0}}{2}\sqrt{\frac{C_0}{L_0}} > 1 \rightarrow C_0 > \frac{4L_{0-\max}}{\left(R_b + R_{L_0} - R_{C_0}\right)^2} \qquad (12)$$

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

$$i_0(t) = C_1 e^{-\omega(\zeta + \sqrt{\zeta^2 - 1})t} + C_2 e^{-\omega(\zeta - \sqrt{\zeta^2 - 1})t} \qquad (13)$$

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

$$\Delta I_{\max} = \frac{I_o D}{Cf\left(R_b + R_{Lo} - R_{ESR}\right)}\left(1 - \frac{\sqrt{R_{ESR}{}^2 + \frac{1}{4\pi^2 f^2 C^2}}}{2\pi f L_0}\right) \qquad (14)$$

From the above anaylsis it can be noticed that the output ripple current has three different forms and values accroding 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 5uH, 10uH and 20uH inductance and three different capacitors were selected to satisfy the three cases according to the value of the damping factor (50uF, 150uF and 2000uF). Also PSIM simulation was performed to compare the results with experimental results as shown in Fig. 3.

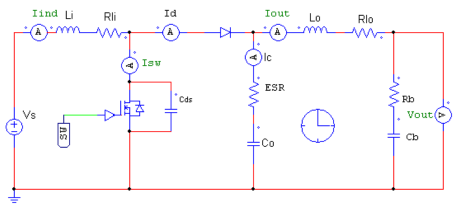


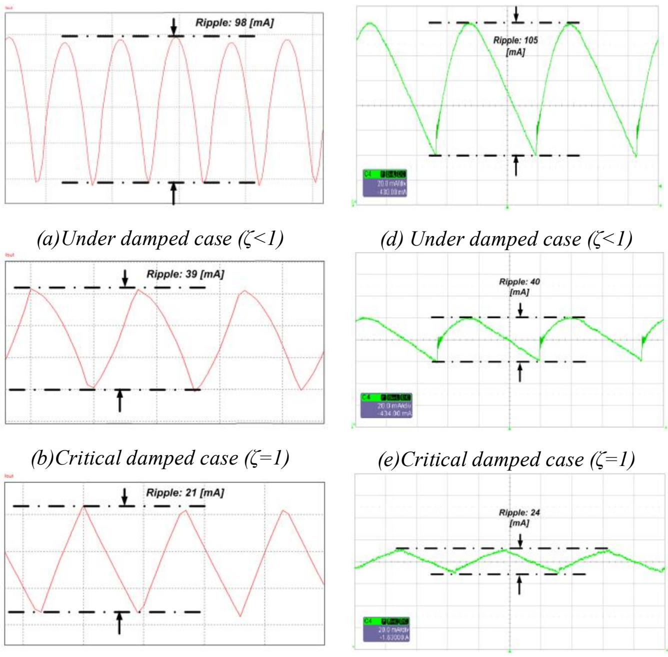
Fig. 3. Circuit simulation of the proposed converter with PSIM

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.

TABLE I. SYSTEM PARAMETERS

Specification of the converter	Non-Isolated Boost Converter	
Input voltage/ Output voltage	V_i / V_0	6 ~ 9/ 12.6 V
Output power/ Frequency	P_O/f	50 W/ 60kHz
Input inductor	Li	32 μH
Capacitors	C_0	50~2000 μF
Output inductors	L_0	5/10/20 μH
Specification of the battery	Li-Ion Battery Pack(3S2P)	
Nominal Current	$I_{nominal}$	5.2 A
Charging Current	I_0	4 A
Charging Voltage	V_O	12.6 V
Battery Initial Volatge	V_b	10.8 V
Output Ripple Voltage	ΔV_{output_ripple}	0.126 V (1%)
Output Ripple Current	ΔI_{output_ripple}	0.26 A (0.05C)
Equivalent capacitance of the battery	C_b	9660 F
Equivalent series resistance of the battery	R_b	0.3 Ω



(a)Under damped case (ζ<1) *(d) Under damped case (ζ<1)*

(b)Critical damped case (ζ=1) *(e)Critical damped case (ζ=1)*

(c) Over damped case (ζ>1) *(f) Over damped case (ζ>1)*

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

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.

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

[1] Vorperian, V. "A ripple theorem for PWM DC-to-DC converters operating in continuous conduction mode" Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual

[2] Scott Dearborn "Charging Li-ion Batteries for Maximum Run Times" Power Electronics Technology Magazine, April 2005