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Short communication

A simple and low-cost charger for lithium-ion batteries

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ABSTRACT

A simple low-cost battery charger based on a saturated controller is proposed for charging of lithium-ion (Li-ion) batteries. When the reference voltage of the closed-loop process is set to 4.2 V, the charging process resembles a constant-current and constant-voltage (CC–CV) charging strategy. The charging process can easily be shortened by raising the limit on the saturated controller. Experimental results are included to demonstrate the effectiveness of the charger. It is anticipated that the charger can be a low-cost high-performance replacement of existing Li-ion battery chargers.

1. Introduction

Because of the rapid growth in the usage of portable electrical devices in recent years, a simple and effective battery charger for these devices has become essential. The lithium-ion (Li-ion) battery has become the most common power source for many portable devices because of its high specific energy and high operation voltage. The most widely used charging strategy is the constant-current and constant-voltage (CC–CV) charging strategy [1]. There are special integrated circuits [2,3] to handle the charging mechanism. On the other hand, a much simpler implementation where the charging process resembles the CC–CV charge strategy can easily be realised using a saturated proportional-plus-integral (PI) controller. Moreover, by adjusting the saturation level of the PI controller, the peak charging current can easily be modified to reduce the charging time. A prototype has been implemented to show the effectiveness of the proposed charger. The charger is able to out-perform many existing chargers and some novel chargers, such as the phase-locked battery charger [4], in terms of charging time.

2. System description

Based on the dynamic Li-ion battery model introduced in [5], a Li-ion battery can be approximated by a RC circuit, as shown in Fig. 1. The transfer function of the circuit is given by

$$G_B(s) = \frac{V(s)}{I(s)} = \frac{R_1R_2C_1C_2s^2 + (R_1C_1 + R_2C_1 + R_2C_2)s + 1}{C_1(1 + R_2C_2s)s} \tag{1}$$

where $V(s)$ and $I(s)$ are the Laplace transforms of the battery voltage and the charging current, respectively; R_1 and R_2 are the equivalent resistances and C_1 and C_2 the equivalent capacitances for the battery. The transfer function of a PI controller is given by:

$$G_{\mathrm{PI}}(s) = K_P + \frac{K_I}{s} \tag{2}$$

where K_P and K_I are constants. If it is included to form the closed-loop system shown in Fig. 2a, the closed-loop transfer function of the process becomes:

$$H(s) = \frac{V(s)}{V_r(s)} = \frac{K_PAs^3 + (K_PB + K_IA)s^2 + (K_P + K_IB)s + K_I}{(K_PA + R_2C_1C_2)s^3 + (K_PB + K_IA + C_1)s^2 + (K_P + K_IB)s + K_I} \tag{3}$$

where $A = R_1R_2C_1C_2$, $B = R_1C_1 + R_2C_1 + R_2C_2$ and $V_r(s)$ is the Laplace transform of the reference voltage to the battery. The output of the PI controller will send a reference charging current to a current pump which, in turn, will produce the required current to charge the Li-ion battery. Applying the Routh–Hurwitz analysis to the denominator of (3), the characteristic polynomial is found to be stable for all positive values of K_P and K_I. Hence there is considerable design freedom for the selection of K_P and K_I. In order to avoid over-charging, the output of the PI controller is limited by a saturation element with the lower limit set to zero and the upper limit set to the maximum allowable charging current. Such an arrangement is also able to solve the problem of integral wind-up in the PI controller. A block diagram of the proposed charging scheme is given in Fig. 2a.

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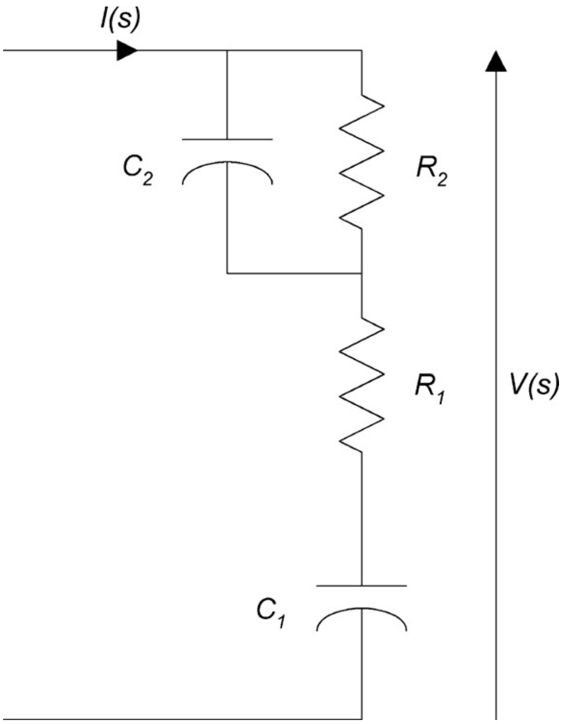

Fig. 1. Li-ion battery model.

3. Design example

A Li-ion battery manufactured by Xianyang Voltix Energy with a capacity of 1100 mAh (model number VLP063455AR) was used to test the performance of the proposed charger. The equivalent resistances and capacitances for the given Li-ion battery were estimated based on the charging profile as $R_1 = 0.15\,\Omega$, $R_2 = 0.44\,\Omega$, $C_1 = 7200$ F and $C_2 = 170$ F. The reference voltage was set to 4.2 V and the maximum charging current $I_{\max}$ was set to 1100 mA. K_P was set to 0.5 such that the proportional control would generate a reference charging current of 5 mA when the battery was 0.01 V away from the reference voltage. K_I was set to 5.5 such that the integral part of the controller would generate $I_{\max}$ after 2 s when the battery was 0.1 V away from the reference voltage. With the given R_1, R_2, C_1, C_2, K_P and K_I, the system described by (3) is a stable system because the characteristic polynomial of (3) is:

$$\Delta(s) = 578952s^3 + 453673.4s^2 + 23775.94s + 5.5 \tag{4}$$

with all characteristic roots on the left-half of the s-plane.

4. Circuit implementation

The circuit diagram of the saturated PI battery charger is shown in Fig. 2b. The charger needs only two integrated circuit chips. L165V is a low-cost power operational amplifier with a 3 A output capability for charging the battery. It may be replaced by a power transistor with an ordinary operational amplifier. LM358 is a

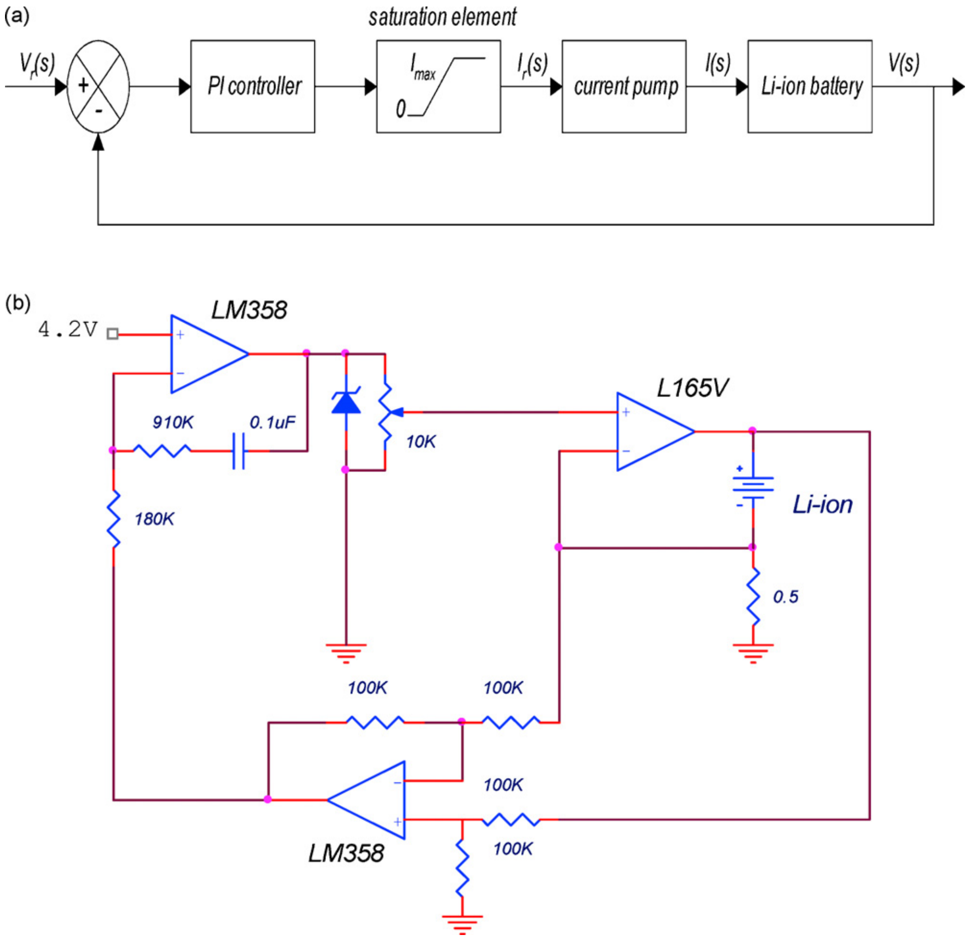

Fig. 2. (a) Block diagram of saturated PI battery charger. (b) Circuit diagram of saturated PI battery charger.

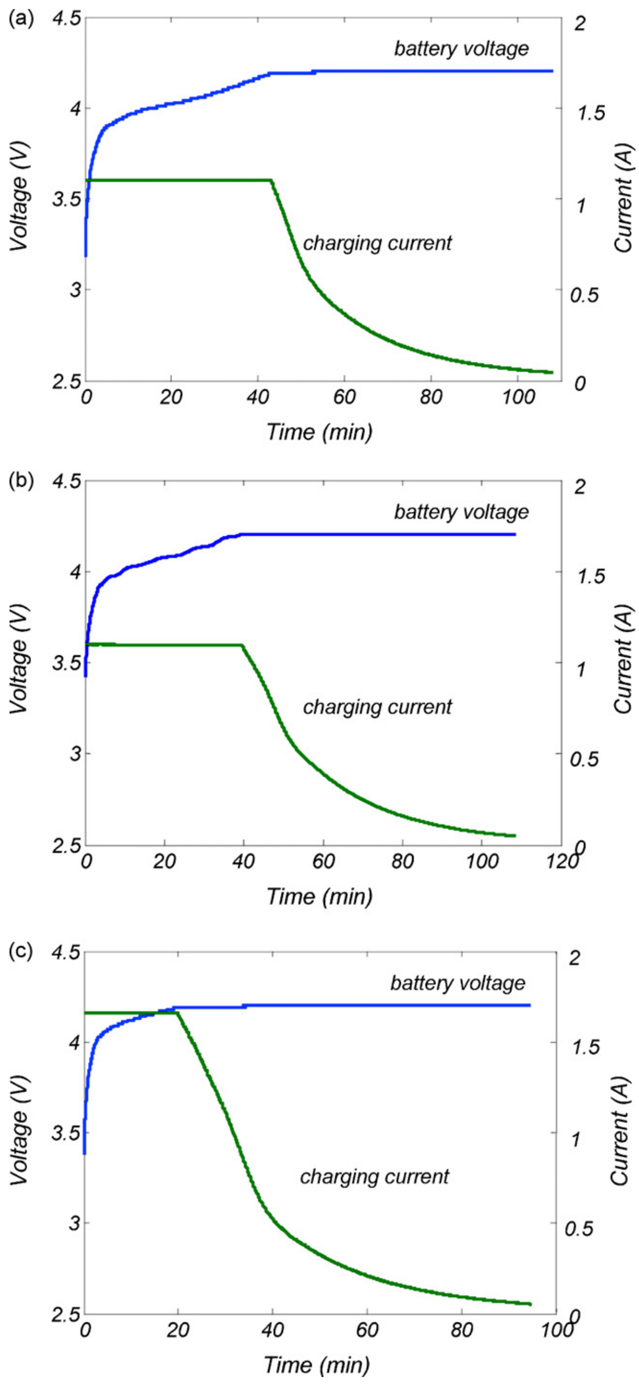

Fig. 3. (a) Charging profile using saturated PI battery charger with I_{max} = 1100 mA. (b) Charging profile using CC–CV charge strategy. (c) Charging profile using saturated PI battery charger with I_{max} = 1650 mA.

low-cost, dual-operational amplifier for implementing the PI controller. The saturation element is implemented by a Zener diode and the maximum charging current I_{max} is controlled by the 10 kΩ potentiometer. Although it is possible to add a temperature control loop, as suggested in [6], the cost of the proposed charger will be increased.

5. Experimental results

The charger was put to test and Fig. 3a shows the charging profile of the saturated PI battery charger with the maximum charging current I_{max} set to 1100 mA. It takes around 105 min to charge the battery. The total charging capacity is 1090 mAh. The charging profile using the standard CC–CV charge strategy is shown in Fig. 3b where the constant-current part is set to 1100 mA. Around 108 min are required to charge the battery. The total charging capacity is 1092 mAh. Clearly, the charging profile of the saturated PI battery charger resembles the CC–CV charge strategy. When the limit of the saturated PI controller is pushed to 1650 mA, the charging time is shortened. Fig. 3c shows the charging profile when I_{max} is set to 1650 mA. It takes around 88 min to charge the battery and the total charging capacity is 1090 mAh.

6. Conclusions

A saturated PI battery charger has been successfully implemented for the charging of Li-ion batteries, and uses the CC–CV charging strategy. The charging time can easily be improved by raising the limit on the saturated PI controller. The charging current and the battery voltage are protected by the reference battery voltage and the saturated PI controller. This charger could be a low-cost high-performance replacement for existing Li-ion battery chargers.

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