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Modeling, Control and Implementation of a Lithium-ion Battery Charger in Electric Vehicle Application

***Abstract**.The rapid development of Electric Vehicle powered by lithium-ion battery has resulted in significant interesting to charging device. However, the nonlinear characteristics of lithium-ion battery increase the complexity of charger designing. In this paper, to overcome the disadvantages, battery model is established and its parameters are evaluated adopted an exponential fitting method. Then an appropriate control strategy is proposed based on small signal model to realize the proposed charging strategy. Finally, experimental results from a laboratory prototype are shown to verify the feasibility of the proposed strategies.*

*S**treszczenie**. W pracy przedstawiono układ ładowania baterii litowych stosowanych w pojazdach elektrycznych. Problemem jest nieliniowa charakterystyka baterii dlatego układ musi mieć odpowiedni system sterowania zapewniający właściwą strategię ładowania. (**Modelowanie i zastosowanie układu ładowania baterii litowych stosowanych w pojazdach elektrycznych**)*

Keywords: Lithium-ion Battery, Parameters fitting, Charging strategy
Słowa kluczowe: baterie litowe, układ ładowania

Introduction

The development of Electric Vehicle (EV) has rapidly proliferated in recent years. And rechargeable batteries used as energy storage devices are playing an increasingly significant role in EV application. In this case, lithium-ion cells, due to their higher energy density, high energy efficiency, light weight, and good cycle life, may provide a good solution for powering the EV[1][2].

Usually, an EV powered by lithium-ion battery storage can only travel at full power over a limited range. The limited usable range makes it necessary to develop some kind of battery charger installed in electric service station [3]. And the charger should be designed properly for the best system efficiency and performance.

Traditional battery charger, which extracted power from an ac-line source, adopted a thyristor ac/dc converter rectifier to control the power flow to charge the battery system [4]. Such a charging circuit drew a high charging current ripple and low efficiency. Nowadays topologies with high switching frequencies are used to reduce the charging current ripple and extend the battery life [5]-[7]. In this paper a low ripple and high performance charger is developed, which adopted phased-shifted PWM (PS-PWM) ZVS converter topology.

On the other hand, the high availability characteristics of charger in EV application require the powering control system be robust, and operate without instability, under a variety of electrical and environmental conditions. However, the nonlinearity of lithium-ion batteries presents some difficulties for designing controller of this system [8]. In order to overcome the negative factor, an electrical model is set up and its parameters are evaluated through the method of pulse current discharge. Based on the accurate model, a proper control strategy is presented and analyzed in detail.

Furthermore, charging strategy should be considered in EV application. Because the life cycles of lithium-ion batteries are easily affected by undercharging and overcharging. Many battery charging strategies have been proposed, such as pulse current, constant trickle (CTC), constant current (CC), constant voltage (CV), and constant current-constant voltage (CC-CV) strategies [9]. CC-CV charging strategy is widely used these days among these strategies aforementioned. And the strategy can effectively avoid overcharging and achieve almost 100% full charge.

This paper presents a lithium-ion-powered battery charging converter and control strategies. The outline of this paper is listed as follows. The Lithium-ion battery model is established and a parameter fitting method is proposed in Section II. Section III describes the small-signal model and proposed control strategy of the charger. Finally, experiment results are present to validate the method above.

Lithium-ion battery modeling

Due to the low lithium-ion cell voltage (3.3V), to use this component as energy storage device in EV, it is necessary to connect several cells in series and/or in parallel to obtain a high energy storage level[10][11]. In this paper 25-cells with capacity of 40AH are connected in series to supply a voltage scope of 50-100V, which is suited for EV application.

A. Discharge with pulse current

The used method for battery modeling and parameters estimation is based on the experimental data obtained from lithium-ion discharge at a pulse current. Fig.1 shows voltage response curve at a pulse discharge current of 15A.

As shown in Fig.1, the voltage *Voc* of the battery pack is the open circuit voltage depending on the instantaneous battery state of charging (SOC). Afterwards an instantaneous voltage drop of the battery pack appears when the battery pack begins being discharged. The drop ΔV_1 is due to the ohmic resistance of the battery cells and the resistance of the connecting-cables. In the subsequent time of discharge, the voltage of the battery pack drops continuously. The dropping value ΔV_2 is caused by the factor of polarization effect, which is far greater than the drop caused by the decrease of battery SOC [11].

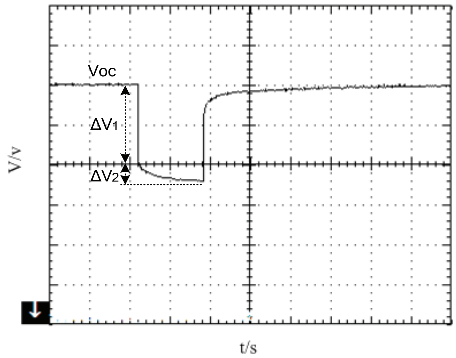


Fig.1. Voltage response curve with pulse discharge current

B. Model and parameters fitting of lithium-ion

It can be drawn from the frame in Fig.1 that the absolute value of the polarization voltage varies in accordance with the exponential function no matter whether it is increasing or decreasing. Based on the measured waveform characteristics, two-dimension exponential fitting is used to model the lithium-ion battery pack.

(1) $$f(x) = ae^{bx} + cx^{dx}$$

The fitting curve is shown in Fig.2, and its corresponding parameters can achieve as *a*= 2.584, *b* = -0.04655, *c* = 217.6, *d* = -3.221e-003.

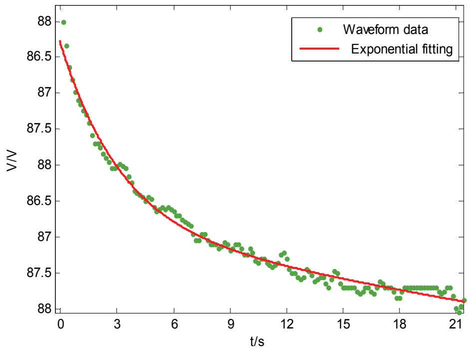


Fig.2. Curve of two-dimension exponential fitting

The electric equivalent circuit of the lithium-ion battery pack is depicted in Fig. 3. This circuit consists of an ohmic resistance, two nonlinear *RC* circuits. *RC* circuit is used to simulate polarization effect.

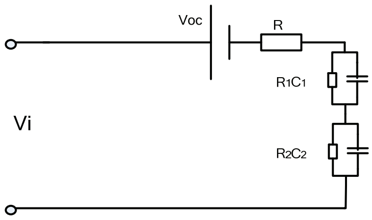
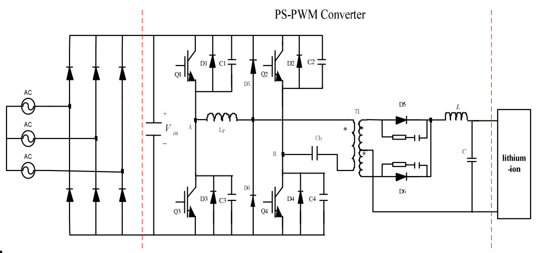


Fig.3. Model of lithium-ion battery

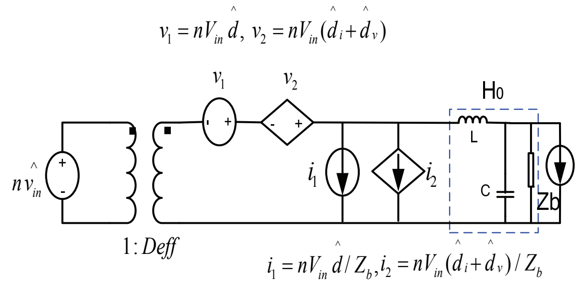
The parameters of lithium-ion battery pack are shown in Table 1 which concluded from fitting parameters of two-dimension exponential fitting method.

Table 1 Parameters of lithium-ion battery pack

Parameter	Value
Ohmic resistance(*R*)	300 $m\Omega$
Polarization resistance1(*R1*)	0.265 $m\Omega$
Equivalent capacity1(*C1*)	50.5 F
Polarization resistance2(*R2*)	0.2 $m\Omega$
Equivalent capacity2(*C2*)	5 μF



(a) Charger with PS-PWM converter topology



(b) Small-signal model of PS-PWM converter

Fig. 4 Circuit diagram of a charger

Modeling and control of Charger

Fig.4 (a) shows the circuit diagram of the proposed charger based on PS-PWM DC-DC converter topology. The front is adopted three-phase non-controlled rectifier to supply dc voltage. And the PS-PWM DC-DC converter transforms the energy from grid to the charging batteries. The design parameters are shown in Table 2 (Section IV)

A. DC-DC Converter modeling

The PS-PWM converter is a buck-derived topology [12]. Different from Buck circuit, the duty cycle of the secondary voltage depends not only on the duty cycle of the primary voltage, but also on the load current *Io*, leakage inductance L_r, input voltage *Vin*, and switching frequency *fs*.

As a prerequisite to the design of feedback compensation circuit, the small-signal model of the converter should be analyzed first. As seen from Fig.4 (b), the small-signal transfer function of this converter will depend on L_r, *fs,* and the perturbations of the filter inductor current $\hat{i}_L$, input voltage $\hat{v}_{in}$ and duty cycle of the primary voltage $\hat{d}$. It is shown [13] that the total change of duty cycle of the secondary voltage is:

(2) $$\hat{d}_{eff} = \hat{d} + \hat{d}_i + \hat{d}_v$$

(3) $$\hat{d}_{eff} = \hat{d} - \frac{R_d}{nV_{in}}\hat{i}_L + \frac{R_d^2}{nV_{in}^2}\hat{v}_{in}$$

$R_d = 4n^2 L_r f_s$, and $\hat{d}_i$, $\hat{d}_v$ are the duty cycle perturbations of $\hat{i}_L$, $\hat{v}_{in}$ respectively. Based on the above analysis, the control-to-output transfer function can be conclude as

(4) $$\begin{cases} G_{vd} = \dfrac{v_o}{d} = H_0 nV_{in}\dfrac{Z_f}{Z_f + R_d} \\ G_{id} = \dfrac{i_L}{d} = \dfrac{nV_{in}}{Z_f + R_d} \end{cases}$$

Output impedance of the output filter is

(5) $$Z_f = \frac{Z_b}{(1 + sCZ_b)H_0(s)}$$

It can be conclude form Fig.3, the transfer function of a Lithium-ion battery during charging can be depicted as

(6) $$Z_b = R + \frac{R_1}{1 + sC_1R_1} + \frac{R_2}{1 + sC_2R_2}$$

Due to smaller effect of R_2C_2 to small-signal model, this element can be omitted. According to formula (4)-(6), control-to-output voltage transfer function of the converter with battery load can be approximated to

(7) $$G_{vd}(s)=\frac{\hat{v}_o(s)}{\hat{d}}=(nV_{in}(RR_1C_1s+(R+R_1)))/(LCC_1RR_1s^3+(LR_1C_1+LC(R+R_1)+R_dRR_1CC_1)s^2+(L+RR_1C_1+R_d((R+R_1)C+R_1C_1))s+(R+R_1+R_d))$$

And control-to-output current transfer function of the converter also can be concluded as

(8) $$G_{id}(s)=\frac{i_L(s)}{d}=(nV_{in}(RR_1C_1Cs^2+s((R+R_1)C+R_1C_1)+1))/LCC_1RR_1s^3+(LR_1C_1+LC(R+R_1)+R_dRR_1CC_1)s^2+(L+RR_1C_1+R_d((R+R_1)C+R_1C_1))s+(R+R_1+R_d)$$

The condition of system stability is

(9) $$(LR_1C_1+LC(R+R_1)+R_dRR_1CC_1)(L+RR_1C_1+R_d((R+R_1)C+R_1C_1))-LCC_1RR_1(R+R_1+R_d)>0$$

B. Charging strategy

The proposed CC-CV charging strategy is shown in Fig.5. The CC stage can be divided into two parts: CTC and CC stage. The charging current *I* decline as the voltage *V* of the battery increases. As shown in Fig. 5, battery is first charged at a constant current until the battery voltage reaches the predefined upper voltage V_H, then charged by a constant voltage until the current reaches a predetermined minimum current (0.1C). With the CC-CV charging method, the battery is charged by a degrading current after switching from CC stage to CV stage, preventing the battery from overcharging.

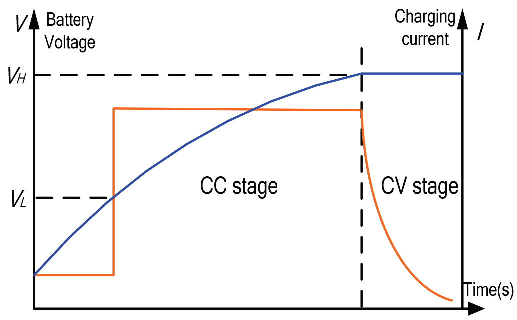


Fig.5. Charging strategy of lithium-ion battery

C. Control strategy

The control strategy has been presented as shown in Fig.6. Digital technology is applied in the control of power converter of charger.

The mode selection module realizes the CC-CV charging strategy shown in Fig.5 and outputs the charging mode selected signal. The charging mode is determined according to the present operating conditions (the measured currents $i_f(k)$, the measured voltage $u_f(k)$ and the previous charging mode).

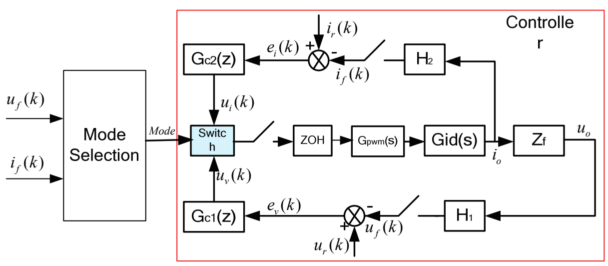


Fig.6.Propose control strategy

The controller consists of voltage loop and current loop. And different loop has different control objective. H_1 is the current feedback sensor gain and H_2 is the voltage feedback sensor gain. *Gpwm(s)* is the converter modulation index. *Vp* is the amplitude of PWM carrier signal.

(10) $$G_{pwm}(s)=\frac{1}{V_p}$$

In this study, a proportional-integral compensator (*Gc1(z)*、*Gc2(z)*) is used to regulate the output current and voltage.

(11) $$G_{c1,2}(z)=k_{p1,2}+\frac{k_{i1,2}z}{z-1}$$

When the system works in CC stage, the charger supplies a constant current to charge the battery. So the control objective is to regulate the feedback current following the reference current ($i_r(k)$). Associated to a first-order filter used to reduce measured current harmonics, the open loop transfer function of current loop can be written as

(12) $$G_v(s)=\overbrace{(k_{p1}+\frac{k_{i1}z}{z-1})}^{PIcontroller}H_2ZOH\overbrace{\frac{1}{V_P}}^{PWM}G_{id}(z)Z\overbrace{(\frac{1}{1+T_1s})}^{filer}$$

When the battery voltage reaches the predefined upper voltage, the controller switches from CC stage to CV stage. In CV stage, the objective of the controller is to supply constant voltage following the reference voltage ($u_r(k)$) until the output current decrease to zero. The open loop transfer function of voltage loop is

(13) $$G_v(s)=\overbrace{(k_{p0}+\frac{k_{i0}z}{z-1})}^{PIcontroller}\cdot H_1\cdot ZOH\cdot\overbrace{\frac{1}{V_P}}^{PWM}\cdot G_{vd}(z)\cdot Z\overbrace{(\frac{1}{1+T_os})}^{filer}$$

Once again, a first-order filter is used to reduce measured voltage harmonics.

An important question is found that the output current transients may occur when the charging mode is changed. This is caused by the transient of duty cycle during switching from CC stage to CV stage which has different control loop compensator. In order to reduce the transients, a smooth switch mechanism is adopted. The mechanism can be described as follows.

$$\begin{cases} u_v(k)=u_v(k-1)+k_{p0}(e_v(k)-e_v(k-1))+k_{i0}e_v(k) \\ u_i(k)=u_i(k-1)+k_{p1}(e_i(k)-e_i(k-1))+k_{i1}e_v(k) \end{cases}$$

$$u_i(k)\geq u_v(k)\longrightarrow \quad Mode=1$$

When the system operates in the current loop, the output of current loop compensator ($u_v(k)$) is calculated and stored in memory, while calculating and storing the output of voltage loop compensator ($u_i(k)$). When the charging mode needs to change, a comparison should be done about these two variables. If switching condition ($u_i(k)\geq u_v(k)$) is satisfied, the switch flag (*Mode)* can be set to 1 and then switch operation is carried out. By doing this, the duty cycle will not change a lot at the time of mode change.

Table 2 Design parameters of charger

Parameter	Value
Switching frequency,*fs* (Hz)	50k
Transformer turns ratio,*n*	18: 5
Resonance inductor *Lr* (μH)	20
Output filter inductor,*L* (μH)	70
Output flter capacitor,*C* (μF)	6
Input voltage,*Vin* (V)	380V(AC)
Output voltage,*Vo*(V)	50-100V
Output current,*Io*(V)	0-40A

Experimental results

A 3kW charger prototype with PS-PWM topology converter has been developed in a laboratory to confirm the functional operations. Table 2 lists the circuit parameters of the experiment results in the developed charger. The battery adopted has been introduced in Section II.

The charger prototype and battery system are shown in Fig.7.

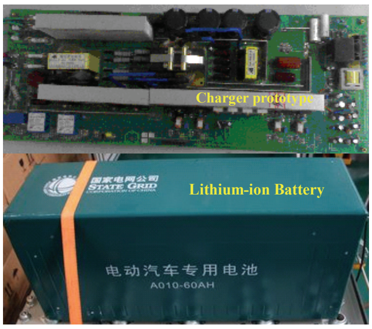


Fig.7 The charging system included charger prototype and lithium-ion battery pack for EV

Fig.8 shows experimental result of current step response and the overshoot is small. Fig.9 plots the terminal voltage of the battery and charging current, indicating that charging the battery to 80 V using a constant current of 20A.

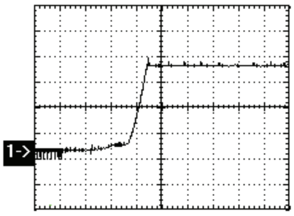


Fig.8. Experimental result of step response

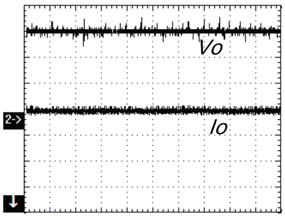
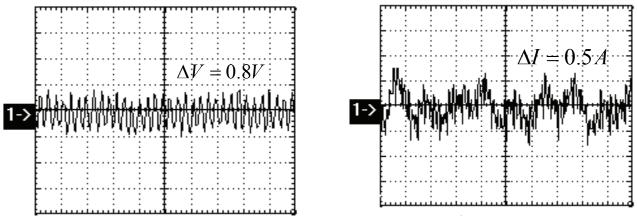


Fig.9 Experimental waveform of output current (20A) and voltage(80V)

Fig.10 shows AC coupling waveforms of charging voltage and current ripple. Seen from these two figures, the output voltage ripple is 0.8V and output current ripple is 0.5A, which can meet the requirement to charge Lithium-ion battery.



(a) Ripple of output voltage (b) Ripple of output current

Fig.10. Ripple of output voltage and current

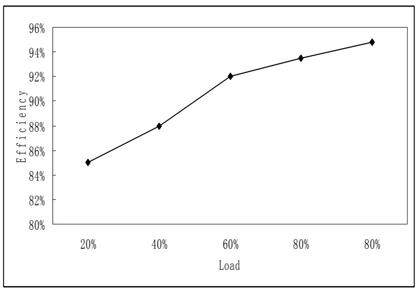


Fig.11 Measured efficiency of the battery charger

Finally, the measured efficiency is reported in Fig. 11. The minimal and maximal efficiencies of the battery charging circuit are about 83% and 95%, respectively, and the mean charging efficiency of the charger is 91.5%. Since most of the losses are independent of the converted power, the efficiency of the battery charger is higher at high loads.

Conclusion

A high performance charger and low ripple charger has bee presented in this paper. In order to overcome the nonlinearity of lithium-ion battery, the battery model was established and its parameters were achieved through two-dimension exponential fitting. Also the control strategy has been presented to realize the proposed CC-CV charging method in this study. The experimental results validate the feasibility and the charger is suitable for lithium-ion charging in EV application.

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