A Study of Charging Control of Lead-Acid Battery for Electric Vehicles

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Abstract—The object of this paper is to investigate the circuit topologies and control techniques for fast charging of battery for the Electric Vehicle (EV). Analysis and comparison of fast charging characteristics for different charging controls are presented. A charging and discharging monitoring system was implemented based on a DSP. To improve the utilization of EV, it is necessary to design a charger with the function of fast charging and the capability of charging control, thus to longer the battery life. The charging characteristics (charging time, charging current, temperature, switching frequency, and pulse period) of different charging methods (two-step, pulse, and Reflex™) are analyzed and presented. Experiments were carried out based on the battery set of four 26AH lead-acid batteries in series. A LabVIEW-based monitoring system was constructed to record the voltage, current and temperature for the batteries. The DSP-based charging control combining with the monitor system features fast charging, digital and adjustable control.

Keywords : Electric Vehicle, fast charging, monitoring system, charging control

I. Introduction

It is urgent that the acute problem of air pollution in recent years to follow society industrialization. Environmental protections place restrictions on motor vehicle and motorcycle emission waste gas, thus accelerate the development of EV. Electric Vehicles (EV) are driven by electricity. There are a lot of technique problems for EV batteries at present, such as life cycle of battery, promotion of energy density and performance, convenience of charging, need to be greatly improved. The charging method of conventional chargers and the indicator of state-of-charge (SOC) do not work well, result in reduction of battery life and lowering of system performance.

Most EV's are powered by 12 V lead-acid batteries, and the state-of-charge of the batteries is essential information in EV operations. Battery charging techniques[1]-[9] includes SOC estimate, optimization of charging control. reduction of charging time, and series-connected method. Series connected battery strings are prone to dramatic reduction in life and potential damage if high rate charging is continued after the onset of gassing. Differences in cell chemistry, and normal differences during repeated cycles of cell charge/discharge, lead to a large non-uniformity in cell charge levels and correspondingly different cell terminal voltages. Maintenance of cells at an equalized charge level is critical for enhancing battery life. Battery life is one of major factors presently limiting the realization of economically viable EV.

The mathematical model for lead-acid batteries was presented in [1]-[3]. Several battery equivalent models have been developed and adopted for the design of battery charger : 1) ideal model, 2) linear model, 3) thevenin model. A battery is assumed as a voltage source in the model because the battery internal parameters are ignored. But the practical circuits are nonlinear, the parameters have to be considered in the design. The life cycle of battery and estimation of SOC are discussed in [4],[5]. There are several practical techniques available to monitor the battery: 1) specific gravity, 2) open circuit voltage, 3) load voltage, 4) coulometric measurement, (1) and (2) are used to indicate the state of charge, and (3) is used to indicate the usable capacity. Technique (4) measures the amount of amp-hours taken out of (or put into) a battery, which can be thought of as an indirect indication of usable capacity.

Main factors affecting battery characteristics are : 1) battery internal electrochemical reaction, 2) design and implementation of battery, 3) environments and operating state. Besides, the extension of battery life is an important issue, thus a sealed lead-acid battery needs enough electrolyte, because electrolyte loss will result in reduction of electrolyte capacity. Large voltages can not be used for battery charging, because the aeration speed will exceed the absorbing speed of electrolyte under large voltage conditions. The charging voltage and time need to be considered to prevent battery overcharging. The basic considerations for battery charger circuit topologies : 1) select the type of battery, 2) design of charging method, 3) design of fast charging. Conventional charging methods include constant current method, constant voltage method, and constant current-constant voltage method (two-step). In this paper, the charging characteristics (charging time, charging current, temperature, switching frequency, and pulse period) of different charging methods (two-step, pulse, and Reflex™) are analyzed and presented.

II. Battery Charging Control Methods

The battery charging techniques include constant current, constant voltage, Two-step, Pulse charging, and Reflex™ charging.

A. Constant current charging

This is a simple charging method using constant currents for battery charging and the charging currents for the series connected batteries are equal. However, battery overcharging will result in the degradation of battery life. Small charging current will prolong the charging time. Fig. 1(a) gives the charging

curves for constant current charging.

B. Constant voltage charging

This constant voltage charging for battery can be easily implemented with simple and controls. During the initial stage of charging, the possible large charging currents need to be limited to protect devices. When the battery voltage reaches the default value, charging voltage is hold and charging current decreases with time. The charging will cause temperature rise and degradation of the battery life. Fig. 1(b) shows the battery charging characteristics for constant voltage charging.

C. Two-step charging

Two-step charging method combines the constant current and constant voltage charging. In the first stage of charging, the batteries are charged by a constant current until the battery voltage reaches a preset voltage. In the second stage, a constant voltage is applied for battery charging. Fig. 1(c) shows the charging curves for the two-step charging.

D. Pulse charging

A pulse current is applied to the battery periodically, this provides the battery a relax time in charging process. The electrochemical reaction and neutralization of battery internal electrolyte are helpful to enhance the life cycle of battery. Using a large pulse current will shorten the battery charging time. Fig. 2 shows the current waveform of pulse charging method.

E. Reflex^{TM} charging

The Reflex^{TM} charging method is an improvement on the pulse charging. A charging period consists of a positive pulse, a negative pulse, and a relax interval. Fig. 3 shows the current waveform of Reflex^{TM} charging.
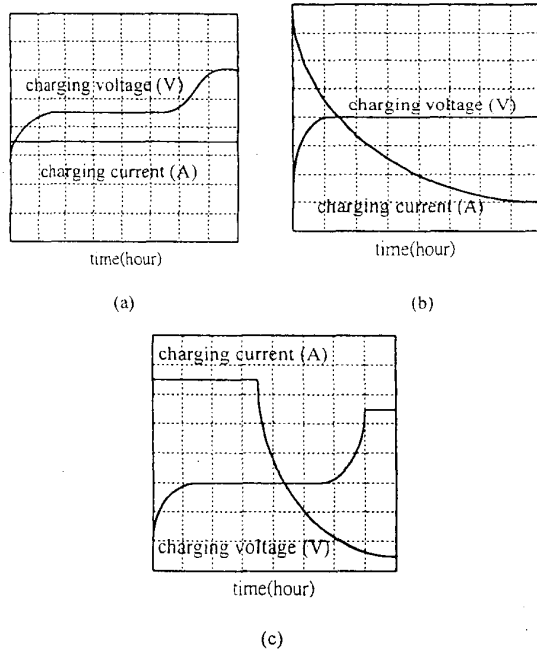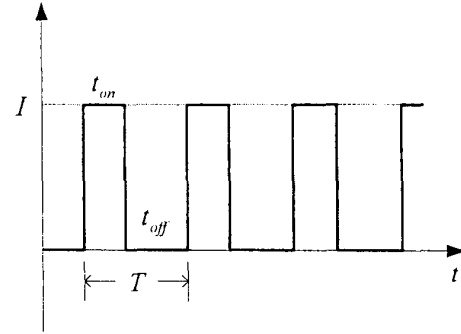

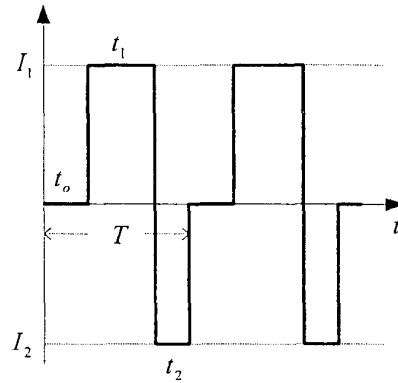Fig. 2 Current waveform of pulse charging

Fig. 3 Current waveform of Reflex^{TM} charging

III. Battery Charging System Control

A. Charging system feedback control

1. Voltage-Mode Control

Fig. 4 shows the voltage-mode control circuit. The DC output voltage (battery voltage V_b) is compared with the reference voltage V_{ref} and the error signal V_{error1} is processed by the triangular wave of several hundred hertz modulation frequency in order to obtain the PWM signal.

2. Current-Mode Control

Fig. 5 shows the current-mode control circuit. The DC output voltage V_b is compared with the reference voltage V_{ref} and the error signal V_{error1} is further compared with the battery current, thereby obtaining error signal V_{error2}. Error signal V_{error2} is then processed with the triangular wave at the modulation frequency to obtain the PWM signal.

B. Charging current control scheme

Three battery charging controls are considered for the experimental investigations.

1. Two-step charging

A two-step charging circuit is shown in Fig. 6. First, the charging control circuit is set on constant current mode (C.C. mode). The charging current i_s is kept constant in the first stage,

time(hour)

(a)

time(hour)

(b)

time(hour)

(c)

Fig. 1 Charging curves for batteries. (a) Constant current charging. (b) Constant voltage charging. (c) Two-step charging.

and battery voltage slowly rises. When battery voltage approaches to dc bus voltage, the charging current i_s goes down. The voltage and charging current of End-of-Charging (EOC) for the battery is 58V and 3.9A, respectively.
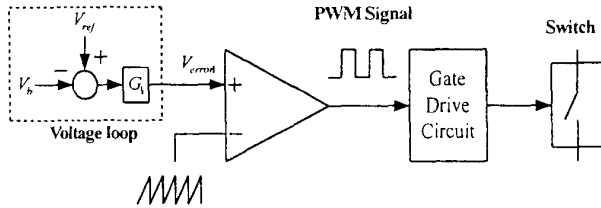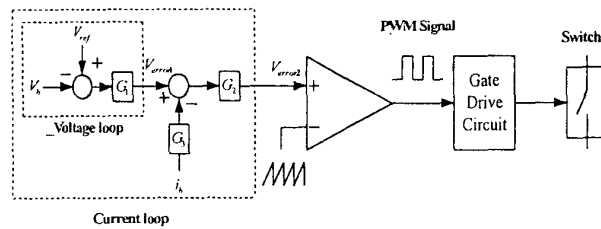

Fig. 4 Voltage-mode control
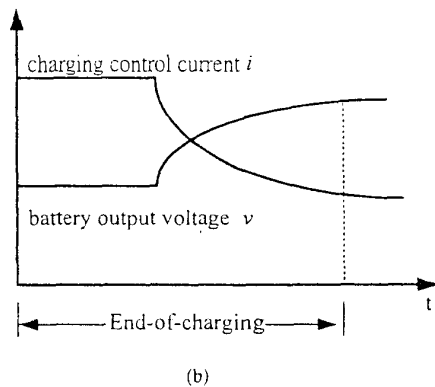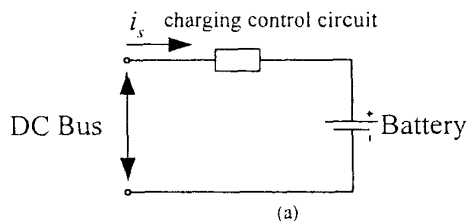

Fig. 5 Current-mode control

(a)

(b)

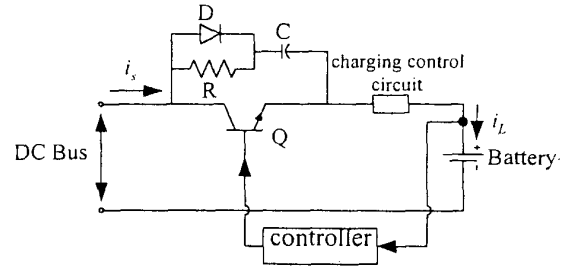Fig. 6 (a) Two-step charging circuit. (b) End-of-Charging graph.

Fig. 7 Pulse charging circuit
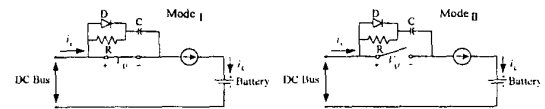
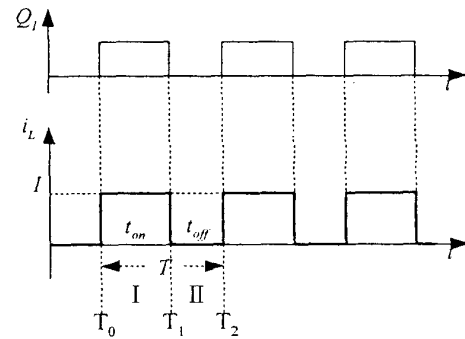Fig. 8(a) Switch mode of pulse charging

Fig. 8(b) Switch and pulse current waveform

2. Pulse charging

The pulse charging circuit is shown in Fig. 7. The control is discussed in two parts: 1). Switching frequency of PWM signal is fixed, pulse current is varied. 2). Pulse current is fixed, switching frequency is varied. The circuit switching modes (Mode I : T_0~T_1, Mode II : T_1~T_2) are shown in Fig. 8(a). Switching and current waveforms are shown in Fig. 8(b). The measured waveform of pulse charging current is shown Fig. 9.

3. Reflex™ charging

The Reflex™ charging circuit is shown Fig. 10. There are three operation modes for the charging circuit (Mode I : 0~T_0, Mode II : T_0~T_1, Mode III : T_1~T_2) shown in Fig. 11(a). Fig. 11(b) shows the switch and current waveforms for Reflex™ charging, and the measured waveform is shown in Fig. 12.
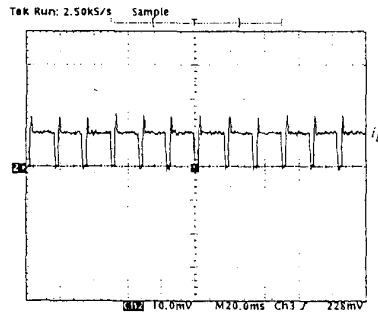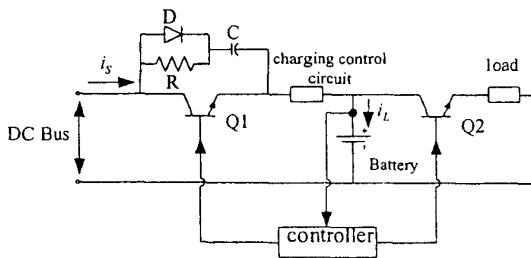
Fig. 9 Charging current waveform (10A/div, 20ms/div)
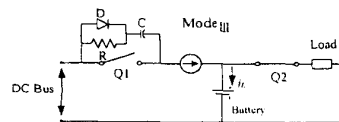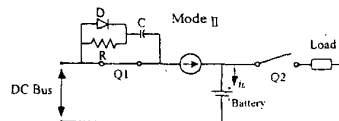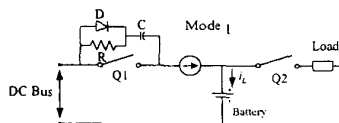

Fig. 10 Reflex™ charging circuit

Fig. 11(a) Switching mode of Reflex™ charging

Fig. 11(b) Switch and current waveform for Reflex™
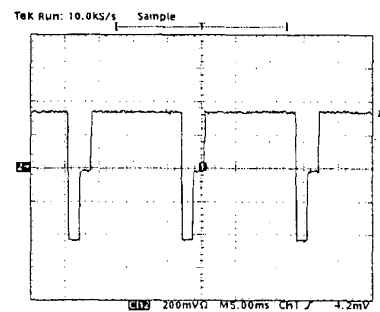
Fig. 12 Charging current waveform (10A/div, 5ms/div)

IV. Experimental Result

A battery set of four 26AH lead-acid batteries was used in the experiments. Three charging methods, two-step, pulse, and Reflex™, were investigated and the load conditions were recorded. The battery charging time for two-step charging is longer with a small charging current. The control for pulse charging was more complicated than the two-step charging, but it
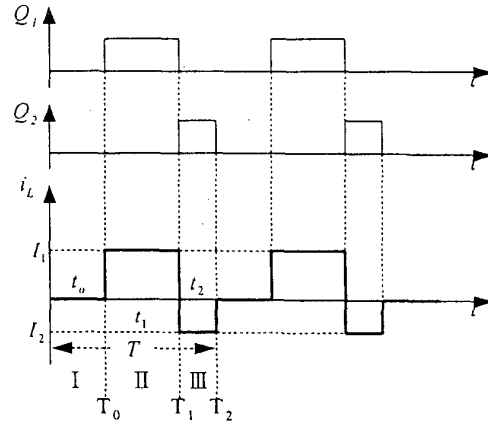
can enhance the life cycle of battery. The control for Reflex™ charging is most complicated because pulses of positive and negative current are required.

The experiments were carried out as the following :

A. *Two-step charging*
  Charging current : 0.4C(10.53A)~1C(26A), Table 1.
B. *Pulse charging*
  1. Switch frequency =60Hz, pulse current : 15.3A~30.6A, Table 2.
  2. Pulse current =30.6A, switch frequency : 1.2Hz~900Hz, Table 3.
C. *Reflex™ charging*
  1. Positive pulse period (t_1=0.5), negative pulse period (t_2=0.1~0.4);
  2. Negative pulse period (t_2=0.1), positive pulse period (t_1=0.5~0.8) , Table 4.

Fig. 13 shows the experimental results for pulse charging with pulse current of 30.6A. Fig. 14 shows the comparison of charging times for three battery charging methods (two-step, pulse, - Reflex™). Fig. 15 shows the charging time for different control and parameters.
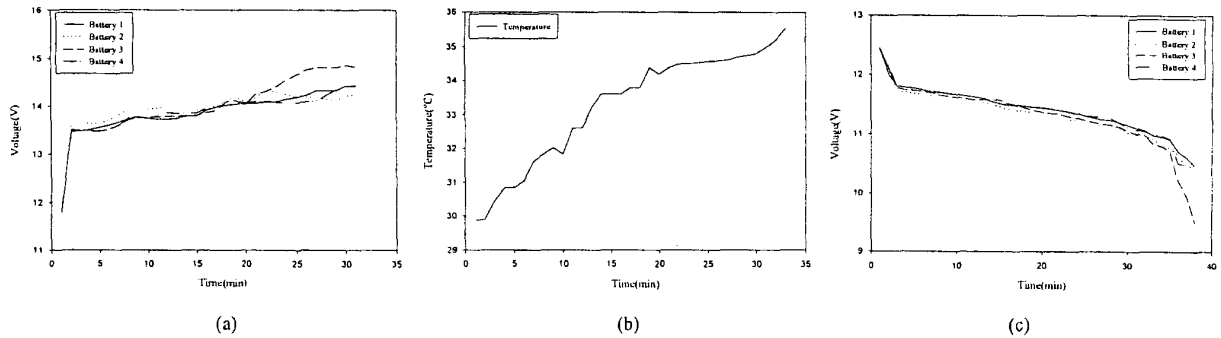
Fig. 13 Experimental results for pulse charging. (a) Voltage curves. (b) Temperature curves. (c) Discharging voltage curves.

Table 1 Charging time for Two-step charging

Charging Current (A)	0.4C	0.5C	0.6C	0.7C	0.8C	0.9C	1C
Charging Time (min)	113	87	69	62	48	41	37

Table 2 Charging time for Pulse charging (15.3A~30.6A)

Pulse Current (A)	15.3	18.4	21.41	24.5	27.5	30.6
Equivalent Average Current (A)	10.12	12.61	14.26	14.76	17.57	18.3
Charging Time (min)	63	45	37	33	27	31

Table 3 Charging time for Pulse charging (1.2Hz~900Hz)

Switch Frequency (Hz)	1.2	10	20	30	40	50	60	300	600	900
Charging Time (min)	27	25	26	31	29	30	31	24	21	25

Table 4 Charging time for Reflex™ charging

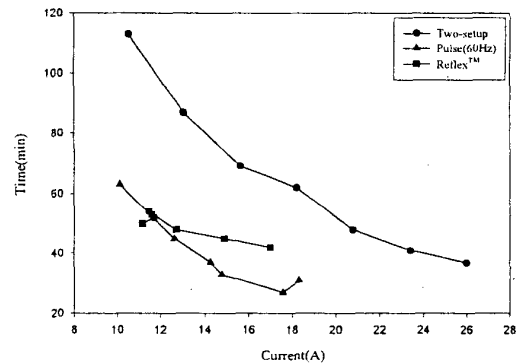| Period	$t_1=0.5$				$t_2=0.1$			
	$t_2=0.1$	$t_2=0.2$	$t_2=0.3$	$t_2=0.4$	$t_1=0.5$	$t_1=0.6$	$t_1=0.7$	$t_1=0.8$
Equivalent Average Current (A)	11.15	11.67	11.58	11.45	11.15	12.7	14.89	16.89
Charging Time (min)	50	52	53	54	50	48	45	42

Fig. 14 Comparison of charging time.

V. Conclusion

In this paper, different charging methods (two-step, pulse, Reflex™) were investigated and compared. The performance of the battery charger for four 26AH lead-acid batteries in series was investigated. A larger charging current for battery charger is required to shorten the battery charging time. In the two-step charger, with charging current from 0.4C to 1C, charging time ranges from 113 minutes to 37 minutes. In the pulse charger, with pulse current of 30.6A equivalent to the average current of 18.3A(0.7C), the charging time is shorter compared to that with two-step charger (0.7C). With pulse charging current of 30.6A, the charging time was found approximately 30 minutes. For the Reflex™ charger, the charging time was found approximately 42~54 minutes, with average current of 11.15~16.89A.

A LabVIEW-based monitoring system was constructed to record the voltage, current and temperature for the batteries. The DSP-based charging control combining with the monitor system features fast charging, digital and adjustable control.
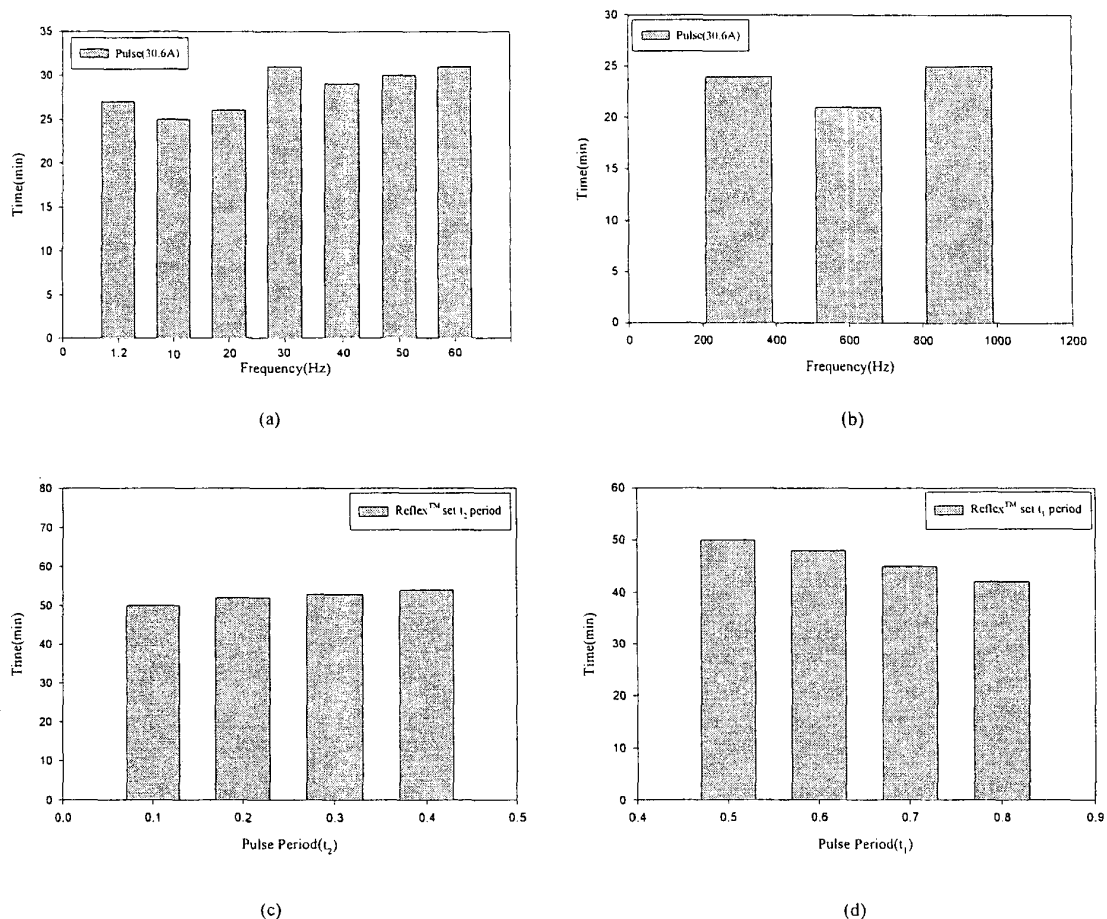
VI. Acknowledgment

Fig. 15 Comparison of charging time for different control and parameters.. (a) Pulse charging- time v.s. frequency. (b) Pulse charging-time v.s. frequency. (c) Reflex charging- time v.s. t_2. (d) Reflex charging- time v.s. t_1.

VII. Reference

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