Journal of Power Sources 195 (2010) 3338–3343

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Online management of lithium-ion battery based on time-triggered controller area network for fuel-cell hybrid vehicle applications

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ARTICLE INFO

Article history:
Received 27 July 2009
Received in revised form
12 November 2009
Accepted 25 November 2009
Available online 29 November 2009

Keywords:
Fuel-cell hybrid vehicle
Lithium-ion battery
State of charge
Online control
Battery management
Ah current integration method

ABSTRACT

This paper introduces a state of charge (SOC) estimation algorithm that was implemented for an automotive lithium-ion battery system used in fuel-cell hybrid vehicles (FCHVs). The proposed online control strategy for the lithium-ion battery, based on the Ah current integration method and time-triggered controller area network (TTCAN), incorporates a signal filter and adaptive modifying concepts to estimate the Li_2MnO_4 battery SOC in a timely manner. To verify the effectiveness of the proposed control algorithm, road test experimentation was conducted with an FCHV using the proposed SOC estimation algorithm. It was confirmed that the control technique can be used to effectively manage the lithium-ion battery and conveniently estimate the SOC.

1. Introduction

Environmental issues, energy crises, and concerns regarding possible peak oil production have spurred research into development of various types of hybrid electric vehicles (HEVs). Meanwhile, various batteries have been applied to HEV including fuel-cell hybrid vehicles (FCHVs). For instance, lead-acid, Zero Emission Battery Research Activity (ZEBRA), NaS (sodium sulfur), nickel metal hydride (NiMH), and lithium-ion battery applications have been documented. In recent years, automotive lithium-ion batteries in HEV or electric vehicles (EVs) have been attracting special attention. However, the estimations of state of charge (SOC) and of state of health (SOH), with regard to efficient battery management, are problematic. The existing SOC estimation methods, including open circuit voltage (OCV) estimation [1,2], the Peukert model [3], the equivalent-circuit model [4], the Kalman filter [5–7], impedance measurements [8,9], and others [10–14], are based on varied equivalent battery models and focus on the requirements of the precise battery model and SOC estimation errors. They are required to effectively identify unknown parameters during off-line or real-time but require much time to adapt parameters and find even small estimation errors. In the present study, we focused on the observed battery behaviors in real-time operation with a simple equivalent battery circuit model, not trying to accurately estimate the SOC error every time, but rather permitting it within the permissible area. However, once the battery behaviors overran the pre-defined overcharge or over-discharge limit, we utilized the characteristics of the battery hybrid powertrain system to adaptively modify the estimated SOC online. That is, the main idea behind our proposed SOC estimation strategy is to manage the battery energy system (BES) according to the concept of permissible battery SOC estimation error and then to apply an adaptive modification method that leads to the reduction of SOC estimation errors and the prevention of battery overcharge or over-discharge in online SOC estimation.

A distributed control system (DCS) with two main communication networks was designed and installed in our FCHV. The DCS consists of the following subsystems: a vehicle control unit (VCU), DC/DC convertor control unit (CCU), motor control unit (MCU), gear control unit (GCU), fuel-cell control unit (FCU), hydrogen supply control unit (HCU), data acquisition unit (DAU), battery management unit (BMU), and others. In the DCS, the communication network plays an important role. Therefore, a time-triggered controller area network (TTCAN) and a traditional SAE J1939 control area network (CAN) were implemented into the DCS specifically to deal with the rigorous requirements and general functions in

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0378-7753/$ – see front matter.
doi:10.1016/j.jpowsour.2009.11.099

Nomenclature

Nomenclature

R&D research and development
DCS distributed control system
BES battery energy system
ECU electronic control unit
VCU vehicle control unit
EEPROM electrical erasable programmable read only memory
FCHV fuel-cell hybrid vehicle
HEV hybrid electric vehicle
TTCAN subsequent time-triggered controller area network
SOC state of charge
OCV open circuit voltage
V_{ocv}^{est} estimated OCV of battery
R_{bat}^{int} internal resistance of battery
V_{bat} terminal voltage of battery
I_{bat} battery current
R_{ch} internal resistance of battery charge
R_{dis} internal resistance of battery discharge
η battery charge/discharge efficiency
SOC_{ini} initial value of SOC
SOC_{ini}^{ocv} initial SOC obtained from OCV–SOC curve
SOC^{memory} the last value of SOC when we power off ECU
Q_{cur} current capacity of battery energy system
w_1, w_2 weighting function ($0 \le w_1 \le 1, 0 \le w_2 \le 1$)
V_{oc} setting value of overcharge voltage
V_{od} setting value of over-discharge voltage
T_{oc} time of overcharge status diagnosis
T_{oc} time of over-discharge status diagnosis
ΔSOC_{oc} change value of initial SOC for overcharge status
ΔSOC_{od} change value of initial SOC for over-discharge status

real-time [15,16]. The TTCAN was designed for 10 ms periods to enhance the control efficiency and to meet the rigorous requirements of its integrated subsystems.

TTCAN-based SOC estimation and battery control solutions to manage the BES online are here proposed. These solutions estimate the battery SOC based on the Ah current integration method. It is much more difficult to estimate battery SOC for HEVs in which charging and discharging occur repeatedly. Moreover, the current integration method tends to cumulate and increase errors obtained from the precision of current collection and the estimation of initial open circuit voltage (OCV). Therefore, a TTCAN-based online calibration technology for SOC estimation is here proposed also for FCHV, in order to find a method to improve the precision of lithium-ion battery SOC estimation in online operation. The details of this method will be described in Section 2.

The present experimentation utilized the Li_2MnO_4 lithium-ion battery, of which the nominal single-cell voltage is 3.8 V, and the nominal capacity, 100 Ah. The battery's energy system consists of 94 100 Ah single-battery cells in series. Since the Ah current integration method tends to increase the SOC estimation error when the foregoing issues arise, a *V–I* lock-up table combined with a first-order filter was implemented to treat this error. This treatment will be described in Section 2.

The paper is organized as follows: Section 2 presents a new SOC estimation algorithm including the estimation of SOC and an adaptive modification of SOC. Validation analysis is discussed in Section 3 by applying the proposed SOC estimation to our FCHV. Section 4 is the conclusions.

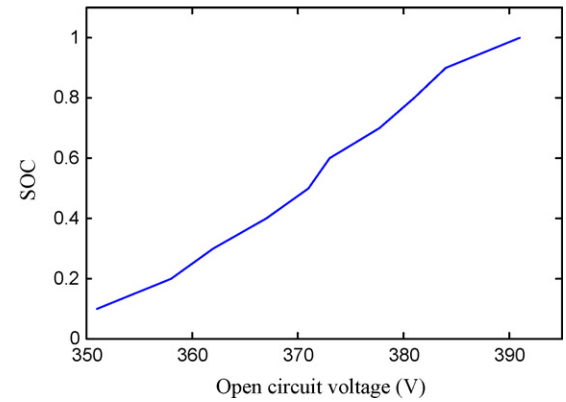

Fig. 1. Battery SOC as a function of static OCV.

2. SOC estimation

For the present experimentation, the Ah current integration method combined with filter technology was chosen to estimate the battery SOC online. Central to that method is the determination of the initial SOC and the adaptive modification of the improper SOC. Battery OCV has a simple relation to SOC, as shown in Fig. 1. Accordingly, if the battery OCV is known, the SOC_{ini} can easily be inferred from the OCV–SOC curve obtained from the pertinent experimental data. Then, based on the estimated SOC_{ini}, SOC estimation can be conducted using the Ah current integration method. However, because OCV measurement requires quite a long stabilization period, it is difficult to measure OCV directly during FCHV operation. Therefore, in this paper we propose the new SOC estimation algorithm shown in Fig. 2 to improve the precision of lithium-ion battery SOC estimation during online operation. The algorithm consists mainly of three operations, which are summarized in the pages that follow.

2.1. Operation 1: Estimation of initial SOC

Upon shifting into the first gear when driving the FCHV, only the 24 V power source is accessed and the current of high-voltage BES is zero. In our FCHV, the time required to relay the general vehicle information to the instrument panel is almost 20 s. During this period, the OCV can first be inferred by the equation

$$V_{ini}^{ocv} = V_{bat} - R_{bat}^{int} I_{bat}, \quad (1)$$

subject to

$$R_{bat}^{int} = \begin{cases} R_{ch} = f_1(SOC) & \text{charging} \\ R_{dis} = f_2(SOC) & \text{discharging} \end{cases} \quad (2)$$

The characteristic of interior resistance via battery SOC is shown in Fig. 3. In the present study, the interior resistance of R_{bat}^{int} in Eq. (2) was determined with reference to the look-up tables based on the experimental data shown in Fig. 3.

Of course, using such an OCV estimation method, OCV estimation error is difficult to avoid. But since the current is zero during the OCV estimation period, we can easily estimate the initial SOC, neglecting for the moment the other constraints including the stabilization and temperate effects, using the above approach.

Moreover, in our designed system, the nonvolatile memory of an electrical erasable programmable read only memory (EEPROM) is used to record pertinent TTCAN network data. Thus, the online battery SOC values are periodically stored as SOC^{memory} by the EEPROM so that the last SOC value can be recorded when the electronic control unit (ECU) is powered off. The following method, as combined with the before-mentioned SOC_{ini}^{ocv} and SOC^{memory}, is here proposed

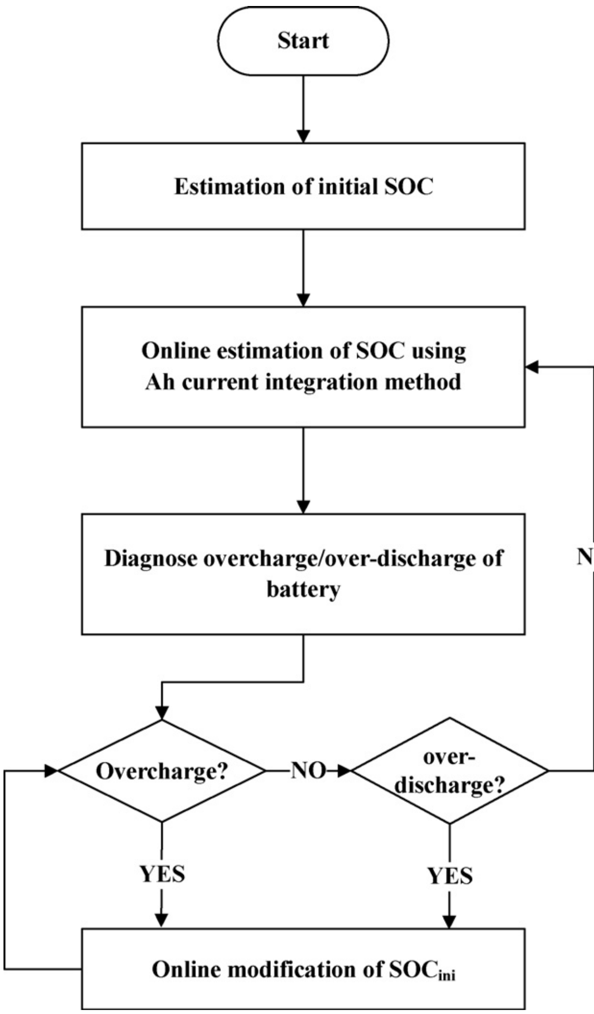

Fig. 2. Flowchart of SOC estimation.

as a means of reasonably estimating the initial battery SOC. That is,

$$SOC_{ini} = w_1 SOC^{memory} + w_2 SOC_{ini}^{ocv}, \quad (3)$$

where w_1 and w_2 are weighting functions that can be chosen simply, as shown in Fig. 4. Because the SOC_{ini} can be more accurately updated by SOC_{ini}^{ocv} after long parked durations, we can continually acquire available initial SOC values using the proposed method. A real-time clock of DS12CR887 is introduced to maintain the time and date operations when primary power is unavailable. In this way, the SOC estimation process can be easily realized.

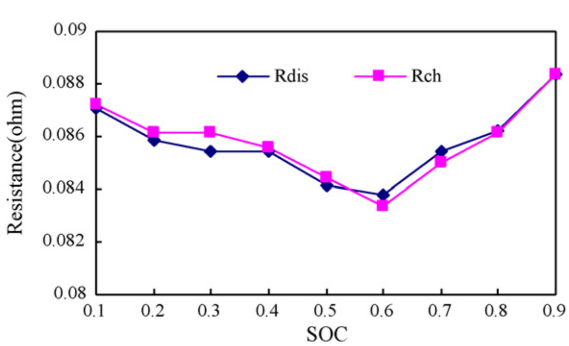

Fig. 3. Interior resistance via battery SOC.

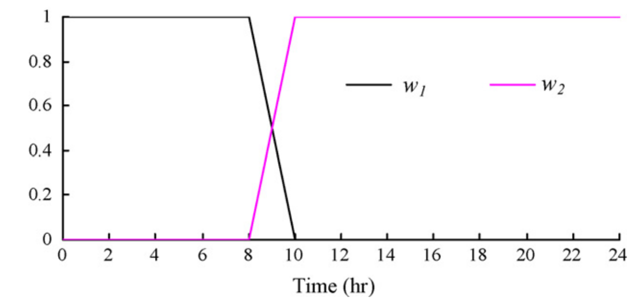

Fig. 4. The determination of weighting functions.

2.2. Operation 2: Online SOC estimation

In the proposed SOC estimation method, a current integration module computes the online SOC value using the Ah current integration method, as follows:

$$SOC = SOC_{ini} - \int \frac{\eta I_{bat}}{Q_{cur}} dt. \quad (4)$$

For our case, we used the sign "−" for the charging current and "+" for the discharging current. Moreover, Q_{cur} was assumed to be the same as the standard capacity value, as the change of capacity was not considered in this study.

2.3. Operation 3: Adaptive SOC modification

FCHV undergoes repetitive acceleration and deceleration under normal driving conditions. So the estimation error also cumulates and increases. Moreover, the OCV is not necessarily a single-valued function of the SOC. As a result, we cannot precisely calibrate the SOC from an OCV–SOC curve online. Therefore, we propose here an SOC calibration method based on voltage diagnoses. By this method, the initial SOC is modified to avoid battery overcharge or over-discharge. The purpose of this protection is to diagnose the battery status during operation and then to apply an adaptive modification method that leads to error reduction in online SOC estimation. A modification flowchart is shown in Fig. 5. The allowable maximum charge voltage of the battery is around 400 V,

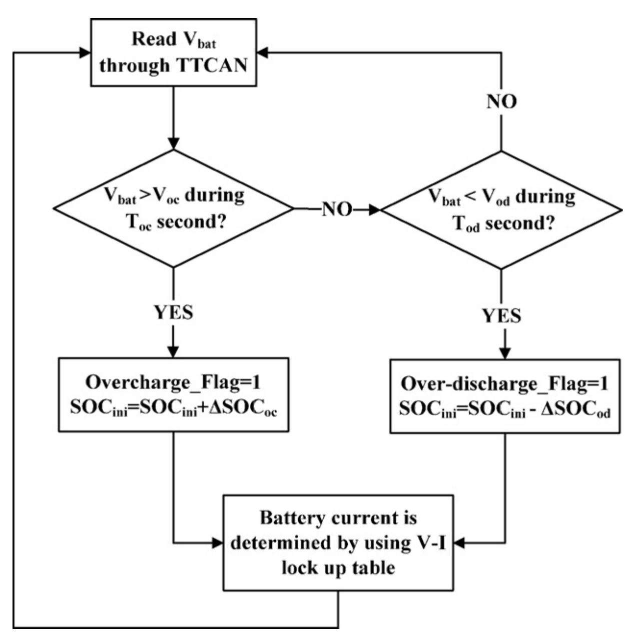

Fig. 5. Adaptive modification method of initial SOC.

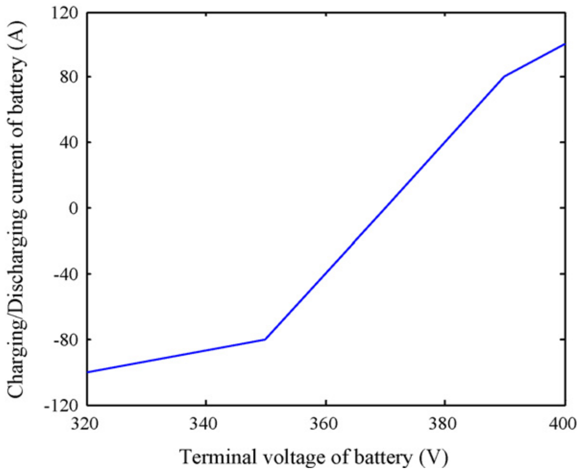

Fig. 6. *V–I* lock-up table to determine battery current during the states of overcharge and over-discharge.

Fig. 7. Fuel-cell hybrid vehicle.

and the allowable minimum discharge voltage is around 310 V. In our work, the voltages V_{oc} and V_{od} correspond to the overcharge and over-discharge, which were set to 380 and 320 V, respectively. The T_{oc} and T_{od} were set to 5 and 3 s, respectively. The ΔSOC_{oc} and ΔSOC_{od} were set to 0.005 s^{-1} when overcharge or over-discharge occurred, respectively. In addition, the fundamental sample time of the real-time SOC estimation program was 10 ms.

Moreover, as shown in Fig. 5, when the overcharge or over-discharge condition, namely Overcharge_Flag = 1 or Over-discharge_Flag = 1, was diagnosed, we dealt with the battery charge/discharge current I_{bat} by reference to the proposed *V–I* curve combined with a first-order filter used to filter the terminal voltage of battery voltage V_{bat}, as shown in Eq. (5). The *V–I* V_{bat} vs I_{bat} curve is presented in Fig. 6. The central idea behind it is to maintain the battery SOC at around 70% until SOC self-modification is completed, by which time the states of overcharge and over-discharge have been diagnosed. In the present study, additionally, the maximum charge or discharge current for the *V–I* curve was 1 C.

$$V_{filter} = \frac{V_{bat}}{1 + \tau_{vol} s}, \quad (5)$$

where τ_{vol} is the time constant for the battery voltage filter. This constant was set to 5 s, because in our FCHV, the output current of the fuel-cell engine is controlled by a first-order filter using 5 s time constant, the time constant required in order to extend the lifetime of the fuel-cell system. Moreover, it was considered that the means

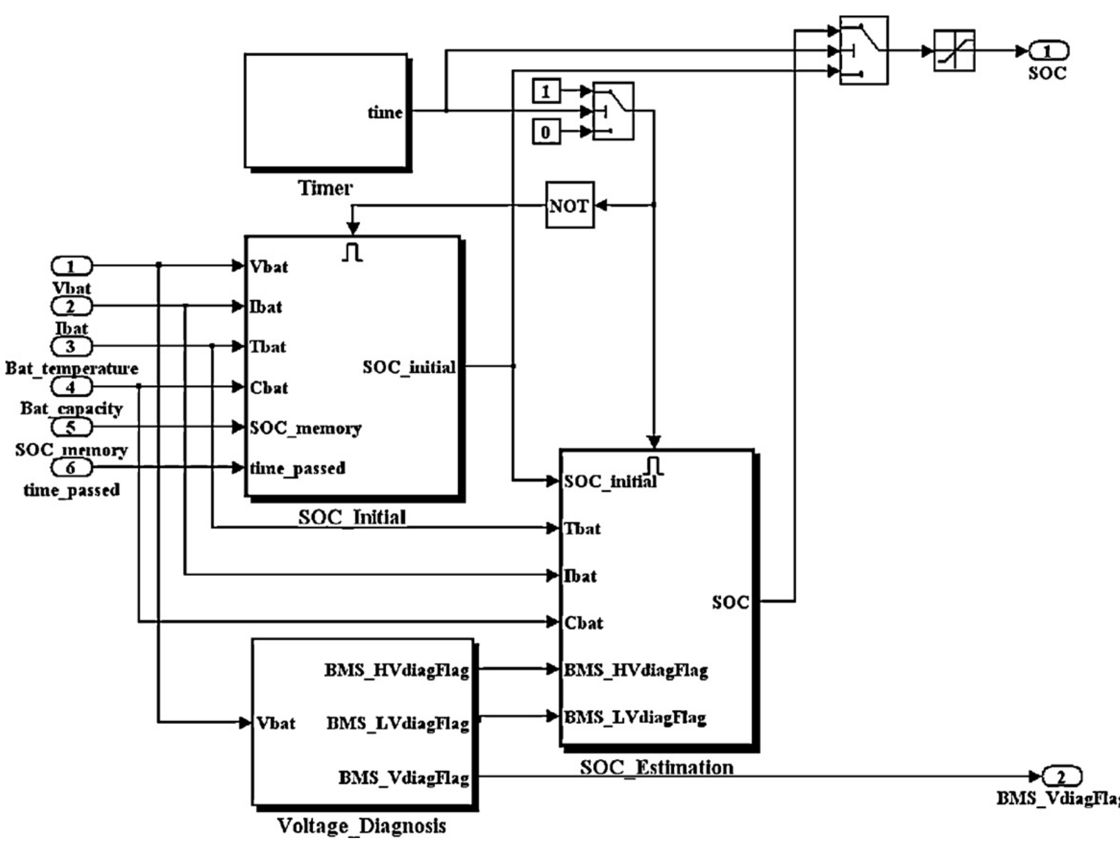

Fig. 8. Schematic structure of SOC estimation system by Matlab/Simulink.

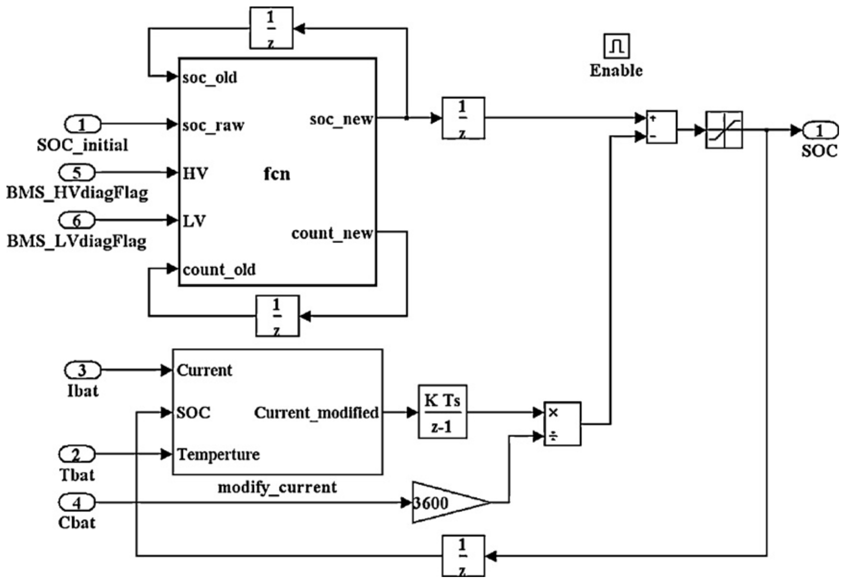

Fig. 9. . Detailed SOC estimation block presented in Fig. 8.

to determine this parameter τ_{vol} must be compatible with the characteristics of the control system and the set ΔSOC_{oc} and ΔSOC_{od} values. In this work, the estimated SOC value was adaptively modified to around 2% per 5 s when overcharge or over-discharge of the battery occurred.

3. Validation and analysis

To evaluate the performance of the proposed battery control strategy, some road tests were conducted using the FCHV as shown in Fig. 7. The schematic structure of SOC estimation as implemented by Matlab/Simulink software is illustrated in Fig. 8. As can be seen, the voltage diagnosis unit was used to determine the overcharge/over-discharge status, and the timer unit was introduced to mark the VCU power-on time. The Simulink schematic for Operations 2 and 3, presented in Fig. 9, is a detailed schematic module of the SOC estimation shown in Fig. 8. As shown in Fig. 9, an embedded Matlab function model was introduced to implement the adaptive SOC modification described in Operation 3 of Section 2. The target range for SOC control in this work was 40–70%. The initial SOC was determined by SOC initial unit taking into account the memorized SOC, the current battery statistics, and other measures. The online estimation and adaptive modification of the battery SOC were executed by the SOC estimation unit.

Fig. 10 shows a vehicle speed profile for a road test driving period of around 2400 s. Fig. 11 shows the test result for the SOC profile, and Fig. 12 shows that for the battery V/I profiles, where the battery SOC was estimated and modified according to the proposed battery management strategy. From Figs. 11 and 12, it can be seen that the battery SOC can be maintained around the target conditions through real-time power flow control for FCHVs.

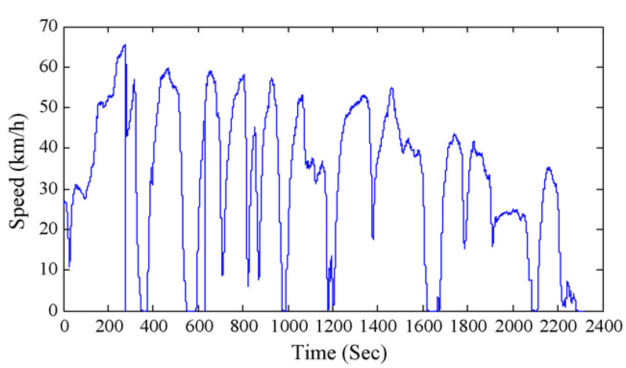

Fig. 10. Vehicle speed profile during road test driving period.

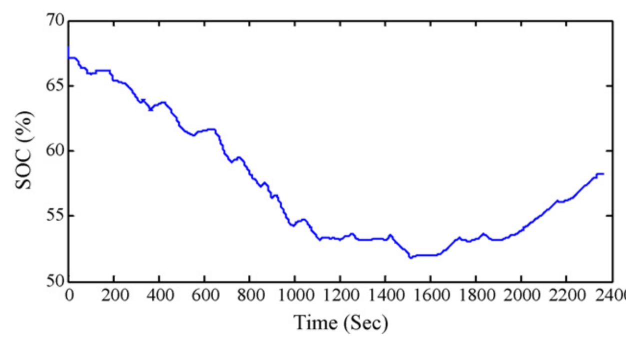

Fig. 11. Test result of SOC profile for FCHV.

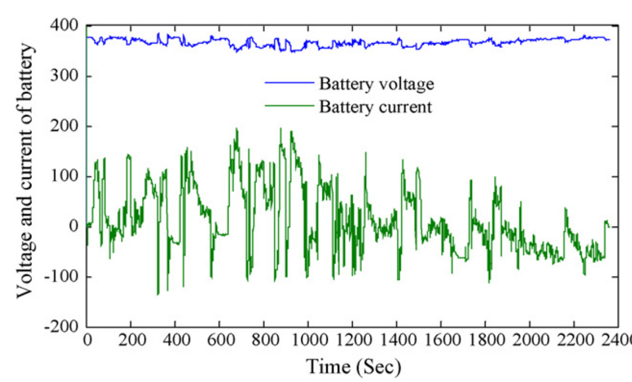

Fig. 12. Test result of battery V/I profiles.

4. Conclusions

Avoiding overcharge/over-discharge and making sure that there will be a consistently sufficient state of charge, are the main considerations governing the efficacious use of automotive batteries.

Therefore, in this paper, a TTCAN-based battery management strategy that prevents overcharge and over-discharge of automotive batteries and maintains the precision of SOC estimation is proposed for the hybrid fuel-cell vehicular power system. Road tests demonstrated that the proposed method can estimate battery SOC for online operation and can maintain the SOC around the target conditions. The efficient use of batteries, in consideration of a detailed battery model and battery SOH, among other parameters, will be discussed in the near future. In addition, it is considered that battery equalization is an important issue and it mainly divided to active or passive equilibrium method. A novel battery management system including active battery equilibrium technology will be also reported in the near future.

Acknowledgements

This work is supported by the National Energy-efficient and New Energy Vehicle Program – the R&D of Fuel Cell City Bus Power System Technology Platform and the R&D and industrialization of ECU for New Energy Vehicle Powertrain, which belong to the eleventh five year "863" program-the hi-tech research and development program of China. The author X. Li also thanks to the China Postdoctoral Science Foundation (Grant No. 20090450354).

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