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Progressive State of Charge Estimation for Electric Bus

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Abstract

In order to use electric vehicles (EVs) and get the most efficiency out of it, the information about the battery status is significant for drivers. As a battery monitoring system is a major part in electric vehicles, a high-accuracy State of Charge (SoC) monitor is needed. The aim of this paper is to present the progressive State of Charge estimation for deep cycle lead-acid batteries powering an electric bus prototype.

In this study, the SoC of battery was estimated by means of a discharge test and a specific gravity test. An ampere-hour counting method was used in a discharge test. While this method could provide an accurate physical remaining capacity of battery, it was inconvenient in real automotive application and can only be used with flood-type lead acid battery. Alternatively, the Kalman Filter method was also considered in this study in an attempt to improve the current battery SoC estimation technique. The results of proposed study can be used initially in an electric bus prototype and can be used as a guideline for development of other electric vehicle projects in Thailand.

Key words: State of Charge, Lead-Acid Battery, Ampere-hour counting.

1. Introduction

Nowadays, electric devices have become a major part of our life. All portable electric devices use battery as electricity storage for operation. In the most basic terms, a battery is an electrochemical cell in which an electric potential (voltage) is generated at the battery terminals by a difference in potential between the positive and negative electrodes [1]. Today, there are many various types and sizes of batteries such as; Lead-acid batteries, Nickel-based batteries, Sodium-based batteries, and more recently, Lithium batteries.

Because of recent global warming phenomena and petroleum price crisis, there has been a clear sign that majority of next generation vehicles will be powered by electricity. History of electric vehicles (EVs) development dated back to

1834 [2]. In internal combustion engine vehicles, a fuel gauge is an important part for displaying the remaining fuel in the fuel tank of vehicle. Similar to electric vehicles, it is necessary to know the amount of remaining charges in battery in order to know how far the vehicle can still travel and to preserve the overall battery life. Thus, the importance of a battery monitoring system to electric vehicles is in the same way of how a fuel gauge is important to internal combustion vehicles.

In this paper, an ampere-hour counting method was used in a discharge test to estimate SoC of tested batteries. An initial study of Kalman Filter method for lead acid battery is presented. In section 2, some existing battery SoC estimation techniques are reviewed. The implementation of discharge test, the calculations for battery initial parameters for SoC estimation in Kalman Filter method are presented in section 3. During all the experiment, data acquisition tools were used to collect various battery-discharging data such as battery voltage, battery current, and battery temperature.

2. State of Charge Estimation Techniques

Technically, a unique State of Charge (SoC) definition does not exist. Accordingly, The SoC is defined as the percentage of the maximum possible charge that is present inside a rechargeable battery [3]. The determination of the SoC of a battery may be a problem of more or less complexity depending on the battery type and on the application in which the battery is used, as reviewed by Piller *et al* [4].

2.1 Specific Gravity

Batteries are electrochemical devices that convert electrical energy into potential chemical energy during charging, and convert chemical energy into electric energy during discharging [5]. When considering flooded lead-acid cells, the specific gravity (S.G.) of the electrolyte is known to be a good measure of SoC [6]. In [7], the individual cell open circuit voltage (OCV) is measured and the S.G. is calculated using the following equation:

$$OCV = S.G. + 0.845 \quad (1)$$

The S.G. measurement with the use of a hydrometer is a simple and easy way, with a high accuracy, to indicate SoC. However, it is impossible to measure the specific gravity of each battery cells during driving period and can be used only in a flooded lead-acid type.

2.2 Open Circuit Voltage

The open circuit voltage (OCV) of battery varies almost linearly to the battery SoC. For flooded lead-acid battery, the OCV can be determined from S.G. as shown in previous section. However, a direct measurement of OCV cannot be operated under loading condition. Especially in valve-regulated lead-acid (VRLA) batteries, considerable amount of times, such as several hours, are needed to reach a steady state after loading [4].

2.3 Ampere-hour Counting

Ampere-hour counting or Coulomb counting is a method to measure a delivered current during charge or discharge. The SoC of battery can be estimate as:

$$SoC(t) = SoC(0) - \frac{1}{Ah_{nom}} \int_0^t I(t)dt \quad (2)$$

Where: SoC (0) is initial SoC value;

$\mathrm{Ah}_{\mathrm{nom}}$ is the nominal battery capacity;

I(t) is the measured current.

However, this technique could present only a change in battery capacity. Lack of knowledge of initial value of SoC and an accumulated error results in a limited accuracy of the estimation.

2.4 Kalman Filter Method

Kalman filter theory was introduced In 1960 [8]. Kalman Filters are an optimal-means for estimating a present value of the time-varying “state” of a dynamic system [9].

2.4.1 Battery Model

To use Kalman Filter techniques to estimate battery SOC, a mathematical state-space model of the cell is needed. A dynamic model of lead-acid battery that was necessary for Kalman Filter technique to predict the SoC is shown in “Fig.2” [6]. The battery model is consisted of two capacitors and three resistors; C_{bulk} (bulk capacitor), $C_{surface}$ (surface capacitor), R_t (terminal resistance), R_s (surface resistance), and R_e (end resistance). The V_{Cb} and V_{Cs}, are voltage across the bulk capacity and surface capacitors respectively. The SoC can then be determined from the voltage present across the bulk capacitor (V_{Cb}).

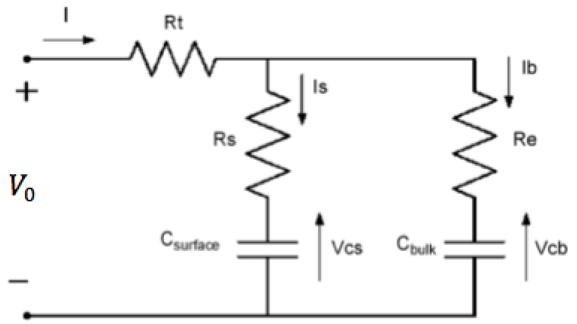

Fig. 2 RC Battery Model schematic [6]

From RC battery model schematic “Fig. 2”, the characteristics equation of voltages and currents can be express as:

$$V_0 = IR_t + I_b R_e + V_{Cb} \tag{5}$$

$$V_0 = IR_t + I_s R_s + V_{Cs} \tag{6}$$

After some algebraic manipulation and Kirchoff’s laws application, the complete state variables of the model were presented in [6]. The determinations of initial parameters in battery model in this study are presented in section 3.1.

3. Implementations

The test samples were 12 V lead-acid batteries with 130Ah capacity. In order to conveniently calculate the percentage of the maximum possible charge that was presented inside a rechargeable battery, the constant current discharge was used as battery loads. Three different rates of discharge were employed i.e. C_{10}, C_5 and C_3, among which the second rate is a common discharge rate for electric vehicles [10]. The data acquisition hardware by National Instrument (NI 9219) was used to measure battery data. Signal Express by National Instruments was used as a tool for monitoring and collect the battery data. However, a direct measurement could not be done in a high current discharge rate test. Therefore, the LEM DHR100-C10 current transformer was needed to measure the current flow. The Schematic diagram of the experiment is shown in “Fig. 3”. A hydrometer was used to measure the concentration of electrolyte in battery during discharge process. The S.G. was measured every half an hour during the tests.

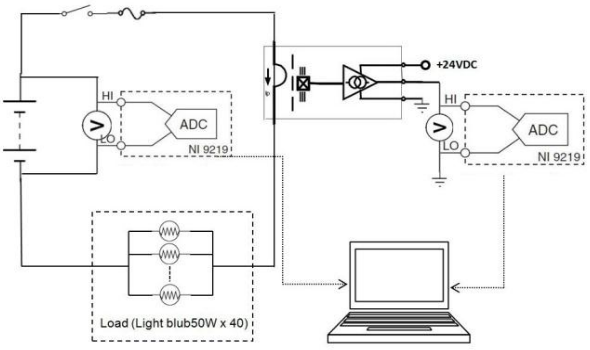

Fig. 3 Schematic diagram of the experiment

Furthermore, by using Ampere-hour counting method, a true SoC was directly obtained. The discharge test was started at fully charged condition where the SoC was considered to be 100%. The battery was discharged until the cut off voltage as presented in the battery datasheet [11] was reached. The discharge current pulses of C_5 were applied for 1800 s at 3600-s intervals. Nevertheless, in an actual electric bus prototype, batteries were connected in series to achieve a nominal 288V DC source and 130Ah. Hence, the SoC estimation in real driving conditions using Ampere-hour counting method was also investigated.

3.1 Calculation of Initial Battery Parameters

From section 2.4, the initial battery parameters are required for Kalman Filter technique. A summery of battery initial parameters is given in Table. 1.

3.1.1 Battery Resistance

The total internal resistance (R) of the battery can be estimated by [12]:

$$R = No. of\ cell \times \frac{0.022}{C_{10}} \qquad (8)$$

The R_s and R_e is assumed to be equivalent and accounted for 75% of total internal resistance [6]. Therefore, from “Fig.3” R_t can be expressed by:

$$R = R_t + \left(\frac{1}{R_e} + \frac{1}{R_s}\right) \qquad (9)$$

3.1.2 Battery Capacitors

The C_{bulk} (bulk capacitor) is obtained from OCV of battery at 0% SoC and 100% SoC, as express in “Eq. (10)”;

$$C_{bulk-initial} = \frac{Rate(Amp - Sec) \times V_{100\%SoC}}{\frac{1}{2}\left(V_{100\%SoC}^2 - V_{0\%SoC}^2\right)} \qquad (10)$$

The $C_{surface}$ (surface capacitor) is obtained from a pulse discharge test [13]. The time constant is determined by:

$$C_{surface} = \frac{\tau}{(R_e + R_s)} \qquad (11)$$

Where;

$$\tau = -\Delta T \ln\left(1 - \frac{V_4 - V_3}{V_1 - V_3}\right) \qquad (12)$$

Table.1 Summery of battery initial parameters.

Initial Parameters				
$R_t(\Omega)$	$R_s(\Omega)$	$R_e(\Omega)$	$C_{bulk}(\mathrm{F})$	$C_{surface}(\mathrm{F})$
0.00073	0.00087	0.00087	268016.9	597.54

4. Result and Discussions

The observed relationship between specific gravity and OCV is shown in “Fig. 4”. The graph shows the discharge characteristics of battery under 5-hours rate, C_5 constant discharge current. At the maximum capacity, corresponding OCV at measured S.G. of 1.25 was calculated to be 12.57V. After being discharged at C_5, the OCV was continuously decreasing to 11.07V after a terminal voltage of 10.2V was reached (i.e. cut-off) and S.G. was decreasing to 1.0. The battery SoC is decreased from 100% to 0% as shown in the graph. Nonetheless, in EVs the initial SoC is not always beginning from 100%. A study of S.G. can be used for identifies the initial SoC.

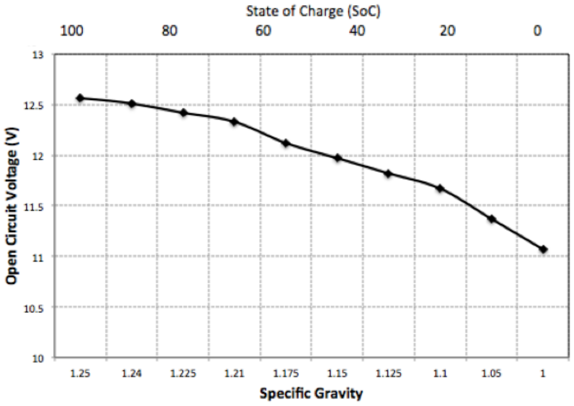

Fig. 4 OCV versus S.G. and SoC

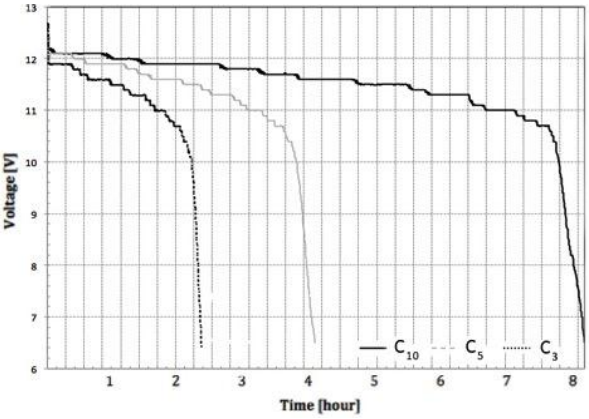

Fig.5 Discharge Characteristic of Battery

In "Fig.5", the result shows the discharge characteristics of battery under 3 different constant discharge rates (C_{10}, C_5, and C_3). By using ampere-hour counting method, the initial SoC was set to 100%. The result of SoC was determined by integral of current over the time as stated in "Eq. (2)". At constant current discharge, the SoC of battery continuously decreased. This experimental result indicated a capacity consumption of 93Ah, 83Ah, and 80Ah at C_{10}, C_5, and C_3 respectively. The relationship between SoC and time was almost linear-relationship under constant current discharge as shown in "Fig. 6". The battery voltage rapidly dropped at a cut-off voltage (0%SoC) in 8 hours, 4 hours, and 2.5 hours for C_{10}, C_5, and C_3 respectively.

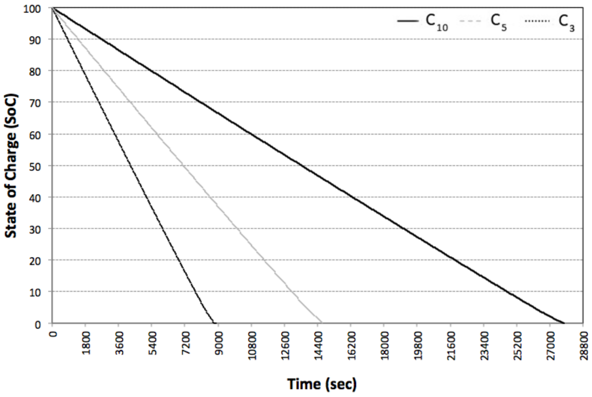

Fig.6 Calculated SoC of Battery using ampere-hour counting method

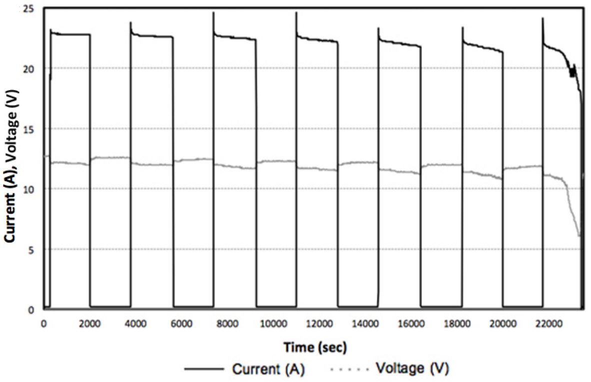

Fig.7 Battery voltage and current variation from pulse discharge test

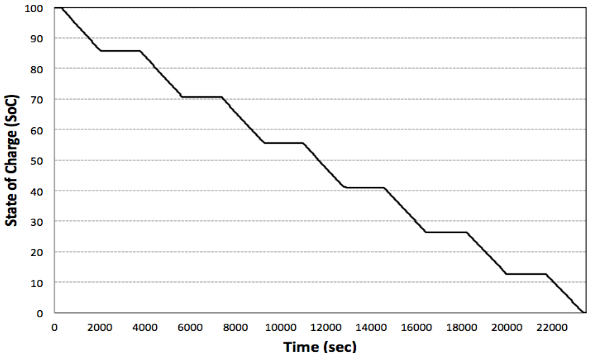

Fig.8 Calculated corresponding State of Charge from pulse discharge test

"Fig. 7-8" display a battery voltage, current and SoC obtained from a pulse discharge test. While a discharge current pulse of C_5 was applied, a battery voltage was inversely proportional to a drawn current as shown in "Fig. 7". During an open circuit, there was some voltage recovery in battery. However, after 50%SoC a gap between open circuit voltages were increased and a terminal voltage continuously decrease after 20%SoC was reached. Then, the battery could no longer supply electric charge to loads. As shown in "Fig. 8", the SoC results showed that the ampere-hour counting method could predict the remaining available run-time of the vehicle.

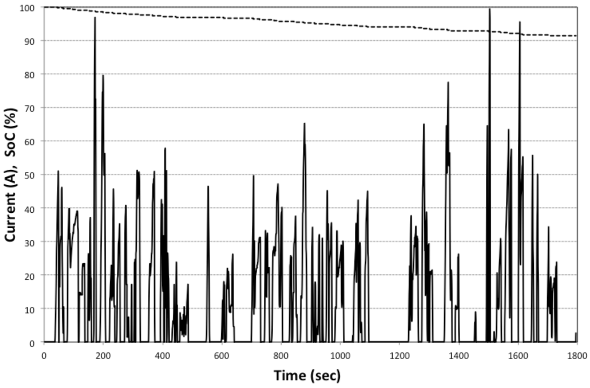

Fig.9 Battery current and SoC in real driving conditions

The parameters obtained from a real traffic condition are shown in “Fig. 9”. The battery current varied from 0-100A, depending on the driving situations. The results were obtained from a 30-minutes test drive. Battery SoC was determined to decrease slightly from 100%SoC to 90%SoC over a travel distance of 7km resulting in an average consumption of 1.4Ah/ km. From this information, a remaining range could be determined to be 63km or a maximum operating range of 70km per charge.

In addition, there were some discrepancies in the battery capacity consumption between that of theoretical specification and that observed during the lab-scaled tests. The decreasing rates of SoC were changed by battery consumption and directly affected a total capacity. Therefore, the necessity in carrying out individual battery capacity study was obvious in order to develop a potent SoC monitoring system for any EVs applications.

5.Conclusion

All modern electronic devices that used battery as a main power source required battery status to display battery capacity or remaining run-time information. There are many techniques for estimating the battery status. Some techniques are appropriated with electric vehicles while some techniques are not.

- An ampere-hour counting method could predict the remaining available run-time of the vehicle.
- The S.G. measurement could be employed to identify an initial SoC and, by combining with ampere-hour counting method, could be used to estimate the real-time SoC.
- The constant current and pulse discharge test result showed that the rate of discharge could directly affect to the available charge in battery and also affect the estimation of SoC.

In future work, the Kalman Filter Method would be considered in this study in an attempt to improve the current battery SoC estimation technique. By using the battery model and initial battery parameters as presented in this paper, the estimation by Kalman Filter technique will be presented.

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