DESIGN OF BATTERY MANAGEMENT SYSTEM FOR ELECTRIC VEHICLE BATTERY-BASED HYBRID METAL-ORGANIC (SOL-GEL) LITHIUM MANGANATE (LiMn$_2$O$_4$)

RANCANGAN SISTEM MANAJEMEN BATERAI UNTUK MOBIL LISTRIK BATERAI BERBASIS HYBRID METAL-ORGANIK (SOL-GEL) LITIUM MANGANAT (LiMn$_2$O$_4$)

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ABSTRAK


Kata kunci: Baterai, kendaraan listrik, Sistem Manajemen Baterai (SMB), Lithium-ion (Li-ion).

ABSTRACT

Battery-powered Electric Vehicles (BEVs) such as electric cars, use the battery as the main power source to drive the motor, in addition to lighting, horn, and other functions. Currently, Balai Besar Bahan dan Barang Teknik (B4T) has been conducting research in Lithium-ion (Li-ion) battery prototype for an electric vehicle. However, the management system in accordance with the electrical characteristics of the battery prototype is still not available. Thus, to integrate the battery prototype with electrical components of the electric vehicle, it is necessary to design Battery Management System (BMS). Two important battery parameters observed are State of Charge (SOC) and State of Health (SOH). The method used for SOC was Coulomb Counting. SOH was determined using a combination between Support Vector Machine (SVM) and Relevance Vector Machine (RVM). Based on the experiments by using BMS, the battery performance could be more controlled and produces a linear curve of SOC and SOH.

Keywords: Battery, electric vehicle, Battery Management System (BMS), Lithium-ion (Li-ion).
INTRODUCTION

Climate change has become an issue that is widely concerned around the world. On November 2015 the United Nations organised a conference in Paris with the main purpose to compile necessary actions to reduce carbon emission in all sectors of life including transportation, household, commercial, and industry [1]. One important way to realise this purpose is by reducing the use of fossil fuel.

Battery-powered Electric Vehicle (BEV) is considered as one of the solutions to deal with climate change issue since it has zero emissions in situ [2]. However, there is one major obstacle to deploy BEV widely: i.e. battery cost [3]. In order to gain commercial success, a lifetime of battery should meet or exceed vehicle lifetime. Good Battery Management System (BMS) algorithms can extend life by prohibiting battery use that over-stressed, thus preventing damage [4].

BMS research has been widely conducted by researchers in various of electric vehicles such as an electric car, electric scooter [5], and hybrid electric truck [6]. The purpose of BMS is to provide security and operational reliability of the battery. In order to maintain a secure condition and reliability of the battery, BMS implements features such as monitoring and evaluation of the state, charge control, cell balancing, and safety function.

Two important state conditions in battery that need to be monitored and evaluated are State of Charge (SOC) and State of Health (SOH). SOC is the ratio between remaining battery capacity at a certain time with a maximum capacity of the battery [7]. While SOH shows the ratio of battery capacity at a given time to the battery capacity at the beginning of its life [3]. The SOH decrement of a battery cell is mostly caused by the battery ageing and degradation [8]. As the cell ages, electrical resistance will increase and total capacity will decrease [9]. Three parameters that most affect SOH degradation speed are temperature, charge-discharge regime, and depth of charge-discharge [3].

In order to generate better performance of the battery’s two state conditions, there are commonly three variables that should be monitored: voltage, current, and temperature. The performance of lithium-ion batteries is sensitive to the cell operating temperature [10]. The recoverable power and capacity can be reduced significantly when these batteries are operated at a temperature above 50°C [10]. According to the instructions of most battery manufacturers, the reliable operating temperatures required by a majority of current automotive lithium-ion batteries (graphite/LiMn2O4) are: discharging at -20 to 55°C and charging at 0 to 45°C [8].

Battery technology used in this research is sol-gel lithium manganate. Sol-gel is an advanced powder preparation technique of ceramic material based on the colloidal system [11]. The advantage of the sol-gel technique is a need for relatively lower temperatures and is able to obtain nano-sized particles homogenously [12]. In addition, the sol-gel technique can be done simply and cheaply because it does not require sophisticated equipment.

Lithium manganate (LiMn2O4) is a battery cathode material which has a cube-shaped structure of cell unit with the type of face-centered cubic (FCC) [13]. The advantage of lithium manganate is its good thermal stability which makes the potential to be used as a battery with high power [14]. Moreover, manganese ore reserves in Indonesia is quite a lot so the lithium manganate has the potential to be produced domestically with a relatively low cost. Lithium manganate also uses manganese metal as a safe, non-toxic, and more environmentally friendly compared to other cathode materials such as LiCoO2 [15].

The aim of our research is to develop a BMS to integrate battery prototype developed by another B4T’s research group with the electric vehicles. The significance of this work is to support Indonesia’s government roadmap on electric vehicles, because the development and standardization of EV’s battery also become part of the roadmap [16].

RESEARCH METHODS

BMS is designed based on device requirements and implementation. The basic theory of the applied technical solutions is determined based on device implementation possibility. It is expected that the device design solutions approach can compromise between the practicality of implementation and reliability of the theory being used.

SOC estimation method used is the Coulomb Counting (CC). This method calculates battery capacity by integrating charging and
The formula of SOC in CC method is shown in Equation 1 [8].

\[
SOC = 1 - \frac{i dt}{C_n}
\]  

Where \(i\) is the battery current and \(C_n\) is the maximum capacity that can fit the battery at a certain time. The value of \(C_n\) will progressively diminish with increasing age of the battery due to chemical reactions and imposition.

Estimation method for SOH is a combination between Support Vector Machine (SVM) and Relevance Vector Machine (RVM). RVM is a Bayesian version of SVM [17]. This method will propose a new quantity called Sample Entropy (SampEn) as input data to predict SOH as the vector target of an intelligent system. The formula of Sample Entropy is shown in Equation 2 [18].

\[
\text{SampEn}(m, r, N) = -\ln \left[ \frac{A^m(r)}{B^n(r)} \right]
\]  

Another technique that will be implemented in the BMS is cell balancing. There are two cell balancing mechanisms used: inductive shuttle and fixed resistive methods. Inductive shuttle method is an active balancing type, whereas fixed resistive is a passive balancing. The circuit diagrams are shown in Figure 1 and Figure 2.

“Electrical balancing among multiple lithium batteries in a single pack is critical for retrieving maximum energy and reducing the chance of over discharging or overcharging individual cells. If temperature gradients exist among cells, the hotter cells will be capable of discharging or charging faster than the colder cells. Hence, electrical and temperature balances are linked together” [10].
BMS Devices Workflow

Battery Pack was monitored and conditioned by the software and supported by the hardware of BMS. Battery conditions monitored include voltage, current, and temperature. These three variables were used to determine the state of the battery (SOC and SOH) and trip or danger. The data were recorded using data acquisition and processed using Matlab.

Based on this monitoring, the software then did the necessary actions include control of charge-discharge, battery protection, and cell balancing. The aims for these actions are to optimise battery performance and maintain battery operational safety. Trip or danger conditions related to safety issues i.e. overcharging, over discharging, short circuit, over current, under voltage, over voltage, and over temperature.

Table 1 shows BMS device features that were developed in this research. There are three measured input parameters: current, voltage, and temperature. The digital input channels are used as indicators for the trip (danger) and charge-discharge. There is also protection system for seven trips (danger). The functions of signal conditioning system are to do data sampling from current, voltage, and temperature sensors. Then perform analog signal conditioning which covers buffering, filtering, adjustment, TTL conversion, comparison, and voltage following process. Two cell balancing mechanisms were used: fixed resistive and inductive shuttle methods. Two analog safety devices were used: fuse and charge-discharge current block diode.

Table 1. BMS Device Features.

<table>
<thead>
<tr>
<th>Features</th>
<th>Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurable physics quantities</td>
<td>Current, Voltage, Temperature</td>
</tr>
<tr>
<td>Analog Input (AI)</td>
<td>3 channel for current measurement, 2 channel for voltage measurement, 1 channel for temperature measurement</td>
</tr>
<tr>
<td>Digital Input (DI)</td>
<td>7 channel for trip indicator, 1 channel for charge-discharge indicator</td>
</tr>
<tr>
<td>Digital Output (DO)</td>
<td>2 channel for current measurement control, 4 channel for voltage measurement control, 7 channel for trip LED indicators control, 7 channel for optocoupler actuator control, 2 channel for charge-discharge MOSFET switches control, 1 channel for current bypass control</td>
</tr>
</tbody>
</table>

1 channel for over temperature protection and cooling fan control

Table 1. BMS Device Features. (Concluded)

<table>
<thead>
<tr>
<th>Protection system redundancy</th>
<th>Analog protection system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated battery state</td>
<td>SOC (State Of Charge), SOH (State Of Health)</td>
</tr>
<tr>
<td>Signal conditioning</td>
<td>Voltage signal buffering, Signal filtering, Signal adjustment, TTL signal conversion, Signal comparator, Voltage signal following</td>
</tr>
<tr>
<td>Cell Balancing (CB)</td>
<td>Passive CB: Fixed Resistive, Active CB: Inductive Shuttle</td>
</tr>
<tr>
<td>LED indicator</td>
<td>Trip LED indicators, Power DC indicators</td>
</tr>
<tr>
<td>Peripheral actuator</td>
<td>Charge/discharge MOSFET switch, Cooling fan, Bypass current</td>
</tr>
<tr>
<td>Analog safety device</td>
<td>Fuse, Charge-discharge current block diode</td>
</tr>
<tr>
<td>Power rating</td>
<td>5 VDC, 12 VDC</td>
</tr>
<tr>
<td>Data acquisition (DAQ)</td>
<td>NI-USB 6216 (National Instrument), Arduino Mega R3</td>
</tr>
<tr>
<td>Communication protocol</td>
<td>Serial USB, Serial RS232</td>
</tr>
<tr>
<td>Software Controller</td>
<td>HMI (Human Machine Interface) Windows, State estimation, Trip protection system, Advanced, smart, and model based implemented algorithm, Charge/Discharge control, Data logging, Serial communication protocol, Matlab based software analysis, HMI created on Visual Basic (VB) platform</td>
</tr>
</tbody>
</table>

Current Measurement Procedures

There were two current sensors used: current sensor ACS712 and R-Shunt. The use of two sensors intended for redundancy and calibration of each other. The current measurement in R-Shunt began with connecting line signals by using the MOSFET switch controlled through Digital Output (DO) Control. The ACS712 line measurement was always connected.
Through the mechanism of signal conditioning, the data signal from both sensors eventually became TTL analog signal and delivered to DAQ as Analog Input (AI). Data signal from the R-Shunt processed through comparison mechanism to determine the current state whether it was charging or discharging. The result was a Digital Input (DI) indication of charge or discharge.

Voltage Measurement Procedures

Voltage measurement was conducted using Voltage Divider (VD) sensor. There were four VD sensors to measure four cell batteries. Line data signal was connected by a MOSFET switch controlled through DO Control. The next data signal was processed through the signal conditioning to become TTL signal and sent to DAQ as AI data.

Temperature Measurement Procedures

Temperature sensor used was NTC thermistor 10 Kelvin. The advantage of thermistor sensor is having small time constant so the sensitivity is high and reactive to temperature changes. Four NTC thermistors were affixed to the surface of the battery cell to measure its surface temperature. Data signal then processed through signal conditioning to become TTL signal and delivered to DAQ as AI data.

Table 2 shows BMS device testing parameters that were developed in this research. The testing experiment of this research was conducted in Energy Management Laboratory and assisted by Electronics Workshop Unit, Engineering Physics, Bandung Institute of Technology. Testing was conducted in October until November 2015.

The batteries used in this research were one cell Lithium-ion batteries with rated of 12V and 26Ah. The obtained data was recorded by data acquisition and processed using Matlab.

<table>
<thead>
<tr>
<th>No</th>
<th>Type of Test</th>
<th>Testing Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calibration of sensor measurement</td>
<td>Current measurement of current sensor ACS712</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Current measurement of current sensor R-Shunt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Voltage measurement of voltage sensor Divider</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature measurement of temperature sensor Thermistor NTC</td>
</tr>
<tr>
<td>2</td>
<td>Signal conditioning and communication</td>
<td>Noise filtering Analog Input (AI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TTL signal conversion Analog Output (AO)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Serial communication of data acquisition system</td>
</tr>
</tbody>
</table>

RESULT AND DISCUSSION

SOC Measurement

On the measurement of SOC, the method used is Coulomb Counting. The batteries were burdened with a load of 1 ohm to 10 ohms. After each measurement, the batteries were charged until full. The test result can be seen in Figure 4. Based on Figure 4 it can be seen that by using BMS, the SOC as one of the battery performance indicator can be more controlled and generates a linear curve. The conventional batteries, with no BMS, tend to generate a chainsaw-like curve.
battery capacity which has been consumed by the load for the duration $t$. Hence:

$$\int i \, dt = C_{\text{consumed}} = C_{\text{con}}$$  \hspace{1cm} (3)

From $C_{\text{con}}$ data, the value of the current battery capacity ($C_k$) can be known:

$$C_k = C_n - C_{\text{con}}$$  \hspace{1cm} (4)

where $C_n$ is the battery maximum capacity.

The current battery capacity ($C_k$) is the remainder of the battery maximum capacity after deducted by the amount of battery capacity consumed by the load for the duration of the $t$ test. Furthermore, by inserting Equation 4 to the Equation 1 yields:

$$\text{SOC} = 1 - \frac{\int i \, dt}{C_n} = 1 - \left(\frac{C_n - C_k}{C_n}\right) = 1 - \frac{C_n}{C_n} + \frac{C_k}{C_n} = 1 - 1 + \frac{C_k}{C_n} = \frac{C_k}{C_n}$$  \hspace{1cm} (5)

Next, based on the capacity equation:

$$C = \int i \, dt$$  \hspace{1cm} (6)

Because the measurements only made at one point, at the end of each test after a duration of $t$, it is assumed that $i$ constant so that Equation 6 approximated with the equation:

$$C = i \cdot t = \frac{V}{R} \cdot t$$  \hspace{1cm} (7)

Substituting (7) to (5) to give:

$$\text{SOC} = \frac{\frac{V_k}{R_k} \cdot t}{\frac{V_n}{R_n} \cdot t} = \frac{V_k}{V_n} \cdot \frac{R_n}{R_k}$$  \hspace{1cm} (8)

$R_n$ value cannot be defined because there is no load attached at the moment of maximum battery capacity. Because of the undefined $R_n$ value, the part $\frac{V_n}{V_k} \cdot \frac{R_k}{R_n}$ can be eliminated so that the Equation 8 approximated by the equation:

$$\text{SOC} = \frac{V_k}{V_n} \cdot 100\%$$  \hspace{1cm} (9)

From Equation 9 noted that for calculating the SOC only requires data of battery voltage $V_k$ and $V_n$. $V_k$ defined as the sampled battery voltage after testing for the duration $t$. $V_n$ defined as the maximum battery voltage, i.e. 12 Volt. By using data $V_k$ from measurement test results and Equation 9 then SOC value was obtained as shown in Figure 4.

When testing, the smaller the load ($R$), the greater the current consumption ($i$). Because the duration of the test is the same for each load, the battery capacity will reduce faster at a smaller load. Thus the smaller the load, the greater the current consumption, the faster the battery capacity decreases, the smaller the SOC value (heading to a value of 0%), and vice versa. In the testing of this research, the measurements were conducted with the increasing load from 1 ohm to 10 ohms. Hence SOC plotting on a graph in Figure 4 against the increasing R value yields an ascending curve.

The curve of SOC value is also relatively linear. This linear curve is the result of BMS application. “When the ignition switch of the vehicle is turned on, the BMS initializes its main operating software and algorithms. Then once every measurement cycle, current, voltage, and temperature are measured. Estimation of SOC and SOH are updated. Then a decision is made as to whether cells in the pack require equalization (moving charge into/out of specific cells to achieve the same voltage or SOC in each cell in the series string). This process repeats until the vehicle is turned off, at which time the appropriate data is saved in non-volatile memory for the next time the vehicle is turned on.” [19].

SOH Measurement

On the measurement of SOH, the batteries were not charged again after each testing cycle. Batteries were tested with the same load on every cycle using dummy load of 5 ohms. Test time for each cycle was 60 minutes. The method used is Support Vector Machine. The test result can be seen in Figure 5. Based on Figure 5 it can be
seen that by using BMS the SOH can be more controlled and generates a linear curve. The conventional batteries without BMS tend to generate a curve that goes down drastically.

The SOH value will decrease with the growing cycle of testing, because SOH is strongly related with battery ageing [8]. Hence SOH plotting on a graph yields a descending curve (see Figure 5).

The BMS can produce such a linear curve by detecting battery parameters such as internal resistance, impedance, conductance, voltage, capacity, discharge rate, charge rate, and a number of charge-discharge cycles to control the SOH value. The controlled parameters then can be implemented in the form of Power Width Modulation (PWM) signal as BMS output in the process of battery charge-discharge.

CONCLUSION

A design of BMS for electric vehicle battery-based sol-gel lithium manganate has been made and implemented. This BMS was tested on the electric motor and observed the SOC and SOH. Based on the experimental results, the BMS can control the battery performance so as to produce linear curves of SOC and SOH. Further research collaboration with other institutions needs to be established for future development of the BMS.

ACKNOWLEDGEMENTS

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