DESIGN OF BATTERY MANAGEMENT SYSTEM FOR ELECTRIC VEHICLE BATTERY-BASED HYBRID METAL-ORGANIC (SOL-GEL) LITHIUM MANGANATE ($LiMn_2O_4$)

RANCANGAN SISTEM MANAJEMEN BATERAI UNTUK MOBIL LISTRIK BATERAI BERBASIS HYBRID METAL-ORGANIK (SOL-GEL) LITIUM MANGANAT ($LiMn_2O_4$)

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ABSTRAK

Kendaraan listrik bertenaga baterai, seperti mobil listrik, menggunakan baterai sebagai sumber tenaga utama untuk menggerakkan komponen motor listrik dan mengatur fungsi-fungsi kendaraan yang lain seperti lampu dan klakson. Saat ini Balai Besar Bahan dan Barang Teknik (B4T) telah melakukan penelitian pada pembuatan purwarupa baterai *Lithium-ion* (Li-ion) untuk kendaraan listrik. Namun sistem yang berfungsi untuk mengatur karakteristik kelistrikan pada baterai tersebut masih belum tersedia. Oleh karena itu, untuk mengintegrasikan purwarupa baterai yang telah dibuat oleh B4T dengan kendaraan listrik diperlukan adanya Sistem Manajemen Baterai (SMB). Dua parameter penting yang diatur pada baterai kendaraan listrik yaitu *State of Charge* (SOC) dan *State of Health* (SOH). Metode pengaturan SOC yang digunakan yaitu *Coulomb Counting*. Metode yang digunakan dalam menentukan SOH yaitu kombinasi antara *Support Vector Machine* (SVM) dan *Relevance Vector Machine* (RVM). Berdasarkan percobaan yang telah dilakukan dengan menggunakan SMB, kinerja baterai dapat lebih mudah diatur dan mampu menghasilkan kurva SOC dan SOH yang linier.

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 50^0C [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 55^0C and charging at 0 to 45^0C [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 ($LiMn_2O_4$) 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 $LiCoO_2$ [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 discharging current [3]. The formula of SOC in CC method is shown in Equation 1 [8].

$$SOC = 1 - \frac{\int idt}{C_n} \quad (1)$$

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].

$$\text{SampEn}(m, r, N) = -In\left[\frac{A^m(r)}{B^m(r)}\right] \quad (2)$$

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].

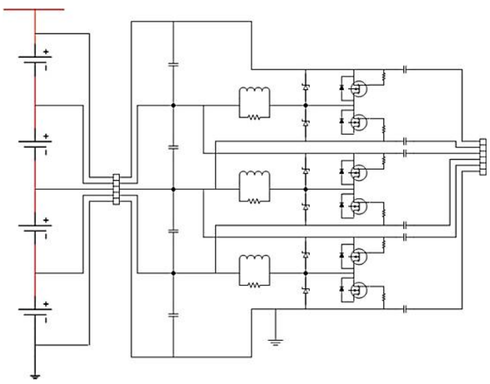

Figure 1. Cell Balancer Device: Inductive Shuttle Method.

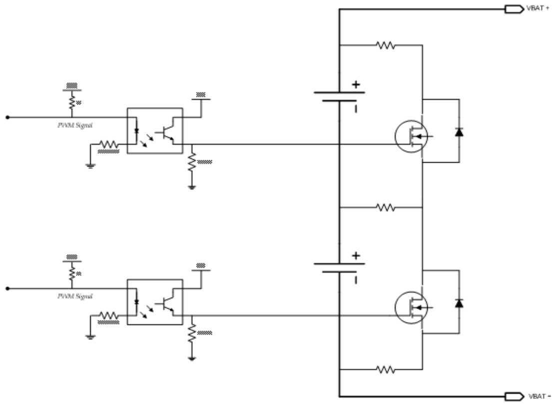

Figure 2. Cell Balancer Device: Fixed Resistive Method.

BMS which was developed consists of hardware and software, as shown in Figure 3. The hardware consists of the following units: signal conditioning, cell balancing, protection system, sensor, actuator, safety device, power supply, and Data Acquisition (DAQ). The software was developed on the Matlab platform with a display window in the form of Human Machine Interface (HMI) created on the Visual Basic (VB) platform.

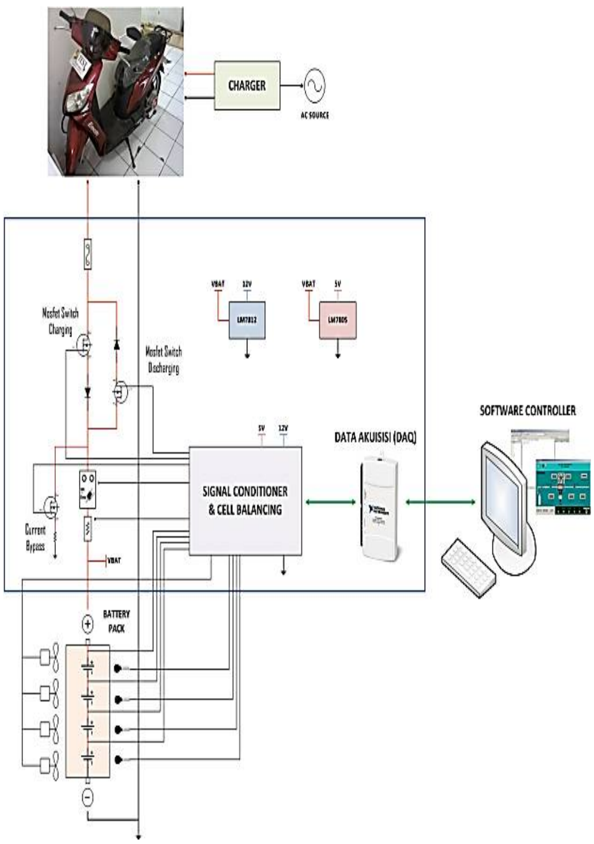

Figure 3. BMS Device Diagram.

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.

Features	Items
Measurable physics quantities	Current
	Voltage
	Temperature
Analog Input (AI)	3 channel for current measurement
	4 channel for voltage measurement
	4 channel for temperature measurement
Digital Input (DI)	7 channel for trip indicator
	1 channel for charge-discharge indicator
Digital Output (DO)	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
	1 channel for over temperature protection and cooling fan control

Table 1. BMS Device Features. (Concluded)

Trip (danger) protection system	Over charge protection
	Over discharge protection
	Over voltage protection
	Under voltage protection
	Over current protection
	Short circuit protection
	Over temperature protection
Protection system redundancy	Analog protection system
	Controlled protection system (by software)
Estimated battery state	SOC (State Of Charge)
	SOH (State Of Health)
Signal conditioning	Voltage signal buffering
	Signal filtering
	Signal adjustment
	TTL signal conversion
	Signal comparator
	Voltage signal following
Cell Balancing (CB)	Passive CB: Fixed Resistive
	Active CB: Inductive Shuttle
LED indicator	Trip LED indicators
	Power DC indicators
Peripheral actuator	Charge/discharge MOSFET switch
	Cooling fan
	Bypass current
Analog safety device	Fuse
	Charge-discharge current block diode
Power rating	5 VDC
	12 VDC
Data acquisition (DAQ)	NI-USB 6216 (National Instrument)
	Arduino Mega R3
Communication protocol	Serial USB
	Serial RS232
Software Controller	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

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 2. BMS Device Testing Parameters.

No	Type of Test	Testing Parameters
1	Calibration of sensor measurement	Current measurement of current sensor ACS712
		Current measurement of current sensor R-Shunt
		Voltage measurement of voltage sensor Divider
		Temperature measurement of temperature sensor Thermistor NTC
2	Signal conditioning and communication	Noise filtering Analog Input (AI)
		TTL signal conversion Analog Output (AO)
		Serial communication of data acquisition system
3	Evaluation methods of determining battery states	SOC estimation method using Coulomb Counting
		SOH estimation method using SVM and RVM
		Battery charging method using Constant Voltage or Constant Current
4	System commissioning of Digital Input and Digital Output	Digital Output (DO) drive of signal conditioner
		Digital Input (DI) read of signal conditioner
5	Protection system commissioning	Overcharge protection system
		Over discharge protection system
		Over-voltage protection system
		Under voltage protection system
		Over current protection system
		Short circuit protection system
		Over temperature protection system
6	Cell balancing system testing	Passive cell balancing using Fixed Resistive method
		Active cell balancing using Inductive Shuttle method
7	Peripheral system testing	Battery power consumption rating
		Fuse rating
		Bypass current protection system

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.

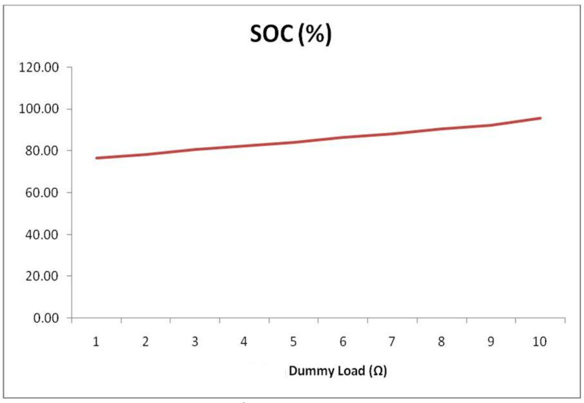

Figure 4. Graph of Correlation Between SOC and Dummy Load.

During testing, the data taken only battery voltage at the end of each test after a duration of t (time). From the Equation 1 formula of SOC in Coulomb Counting method, $\int i\,dt$ defined as the battery capacity which has been consumed by the load for the duration *t*. Hence:

$$\int i\,dt = C_{consumed} = C_{con} \quad (3)$$

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

$$C_{con} = C_n - C_k$$
$$C_k = C_n - C_{con} \quad (4)$$

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:

$$SOC = 1 - \frac{\int i\,dt}{C_n}$$

$$SOC = 1 - \frac{(C_n - C_k)}{C_n}$$

$$SOC = 1 - \frac{C_n}{C_n} + \frac{C_k}{C_n}$$

$$SOC = 1 - 1 + \frac{C_k}{C_n}$$

$$SOC = \frac{C_k}{C_n} \quad (5)$$

Next, based on the capacity equation:

$$C = \int i\,dt \quad (6)$$

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:

$$C = i \,.\, t = \frac{V}{R} \,.\, t \quad (7)$$

Substituting (7) to (5) to give:

$$SOC = \frac{C_k}{C_n} = \frac{V_k/R_k \;.\; t}{V_n/R_n \;.\; t} = \frac{V_k/R_k}{V_n/R_n}$$

$$SOC = \frac{V_k \,.\, R_n}{V_n \,.\, R_k} \quad (8)$$

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 $\frac{R_n}{R_k}$ can be eliminated so that the Equation 8 approximated by the equation :

$$SOC \approx \frac{V_k}{V_n}$$

$$SOC \approx \frac{V_k}{V_n} \text{ x } 100\% \quad (9)$$

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.

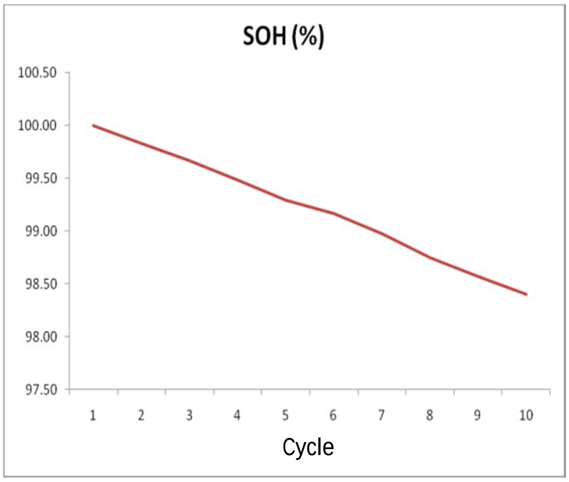

Figure 5. Graph of Correlation Between SOH and Testing Cycle.

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.

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