Wireless Battery Management System of Electric Transport

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Abstract
Electric vehicles (EVs) are being developed and considered as the future transportation to reduce emission of toxic gas, cost and weight. The battery pack is one of the main crucial parts of the electric vehicle. The power optimization of the battery pack has been maintained by developing a two phase evaporative thermal management system which operation has been controlled by using a wireless battery management system. A large number of individual cells in a battery pack have many wire terminations that are liable for safety failure. To reduce the wiring problem, a wireless battery management system based on ZigBee communication protocol and point-to-point wireless topology has been presented. Microcontrollers and wireless modules are employed to process the information from several sensors (voltage, temperature and SOC) and transmit to the display devices respectively. The WBMS multistage charge balancing system offering more effective and efficient responses for several numbers of series connected battery cells. The concept of double tier switched capacitor converter and resonant switched capacitor converter is used for reducing the charge balancing time of the cells. The balancing result for 2 cells and 16 cells are improved by 15.12% and 25.3% respectively. The balancing results are poised to become better when the battery cells are increased.

1. Background of the Study
The electric transportation is accounted for 35% of the world’s vehicles by 2040 due to its potentiity to reduce the greenhouse gas (GHG) reduction about 75% [1]. Electric vehicles curb the use of hydrocarbons and ultimately decrease greenhouse gases (GHG). This optimistic outlook is based on lower expected prices for lithium-ion batteries. In addition to being profitable in terms of the environment and the economy, the growth in the use of electric vehicles promotes the emergence of leading-edge technologies, not least energy storage devices and power optimization systems.

Continuing reductions in battery prices could bring the total cost of ownership of electric transport below that for conventional-fuel vehicles by 2025, even with low oil prices. The electric vehicle revolution could turn out to be more dramatic than governments and oil companies have yet realized. New research [2] suggests that further, big reductions in battery prices lie ahead, and that during the 2020s EVs will become a more economic option than gasoline or diesel cars in most countries. It is forecasted that sales of electric vehicles will hit 41 million by 2040, representing 35% of new light duty vehicle sales. This would be almost 90 times the equivalent figure for 2015, when EV sales are estimated to have been 462,000, some 60% up on 2014. This projected change between now and 2040 will have implications beyond the car market. The research estimates that the growth of EVs will mean they represent a
quarter of the cars on the road by that date, displacing 13 million barrels per day of crude oil but using 2,700 TWh of electricity. This would be equivalent to 11% of global electricity demand [3].

Lithium-ion battery costs have already dropped by 65% since 2010, reaching $350 per kWh last year. We expect EV battery costs to be well below $120 per kWh by 2030 [1]. The crude oil price recovering to $50, and forecasted trending back up to $70-a-barrel or higher by 2040 which might increase the sales of electric transport.[3]. Electric transport in two categories – battery electric vehicles, or BEVs, that rely entirely on their batteries to provide power; and plug-in hybrid electric vehicles, or PHEVs, that have batteries that can be recharged but have conventional engines as backup. The best-selling BEV over the last six years has been the Nissan Leaf, and the best-selling PHEV the Chevrolet Volt. Battery prices fell 35% last year and are on a trajectory to make unsubsidized electric vehicles as affordable as their gasoline counterparts in the next six years, according to a new analysis of the electric-vehicle market by Bloomberg New Energy Finance (BNEF). That will be the start of a real mass-market lift off for electric cars. The electric cars on the road will rise as its price will be equal to the price of IC engine power conventional car by 2022.

Rechargeable lithium batteries batteries are utilized extensively (Kim et al., 2014]. This technology has attracted more attention, especially for an electric vehicle, due to a clean alternative, domestic energy independence, cost and savings [5]. There are some important issues for li-ion batteries such as durability, reliability, and safety that need to be addressed in all sectors of portable application [6]. Li-ion batteries have not only the advantage of high energy density and power capacity, but also have the special features of low self-discharge rate (6%-10%), high terminal voltage, high discharge current, non-memory effect and longer life cycle [7]. In addition, if Li-ion batteries are charged and discharged partly, there is no effect on the available capacity due to free of memory effect. Since EV requires high voltage and high current, Li-ion battery can be used which has the higher voltage than other rechargeable batteries. The nominal-cell voltages of Li-ion battery, lead-acid battery, Ni-Cd and Ni-MH
battery are 3.3–3.7V, 2V, 1.2V and 1.2V respectively [8]. To supply high voltage and current to the load in the application of plug-in hybrid electric vehicle (PHEVs), electric vehicles (EVs), a large number of battery cells are connected in series (S) and parallel (P) connection [9]. The cell combination of a battery pack configuration can be 1S2P, 1S3P, and 2S2P [10,11]. A battery pack of 13 modules with 2S2P is being used in IIUM electric vehicle [12, 13].

Battery pack is a non-linear system, the available capacity affected by the charging-discharging cycles, over charging, under discharging, and excessive temperature. The battery pack should be supervised by battery management system (BMS) to offer safe operation and optimum performance [14]. In other words, BMS provides appropriate battery utilization, guaranteed maximum performance, monitoring present battery pack’s condition and diagnosis [15]. A BMS acts as a medium among the battery and other modules (charging source and load) in improving vehicle performance and optimizing operation safely [16]. A battery management system (BMS) with hardware and software controlling should consist several parts: charging, discharging, thermal management, charge balancing, SOC estimation and communication. In practice, a BMS collects the all information from the sensors (voltage, current, temperature, and SOC) connected to a battery pack and take a specific action by activating the precise circuitry during charging and discharging operation.

The objective of this article is to develop wireless battery management system to control the operation of evaporative thermal management system to maintain the battery temperature ≤ 40°C and balance the SOC of the cells with the maximum variation of (0.75 ± 5%) Ah.

2. DEVELOPMENT OF ELECTRIC VAN

The electric van is developed from this study by using a 14 kWh LiFePO4 battery of nominal voltage 148 V and capacity of 86 Ah. The 14 kWh battery pack is made with 88 cells. Each cell has nominal voltage of 7.5 V and capacity of 86 Ah. The van is powered by an 48 kW AC motor and a 550 A controller. A two phase evaporative thermal management system has been developed to control the battery temperature in the range of 30-40°C with the wireless battery management system. A wireless battery management system has been used to maintain the cell’s SOC variation of (0.75 ± 5%) Ah.

2.1 Two-phase thermal Management System

The IIUM has developed a battery thermal management system (Fig.2) to cool the battery pack by a direct refrigerant-based evaporative cooling. Heat generated from the battery is absorbed by the evaporating refrigerant inside the cooling duct and then dissipated heat to the surrounding air at the condenser. Thus the proposed system was able to maintain the temperature of the battery in the range of 30-40°C. The combined effect of our battery cell’s charge balancing system and battery thermal management system could enhance the battery life from 8 years to 10.5 years (projection based on field experimental result both in IIUM campus and Sepang F1
circuit). In this project, we have done the required modification of our final evaporative thermal management system by extensively testing the performance with employing wireless battery management system to maintain the battery temperature in the range of 25 -35°C.

2.2 Wireless Battery Management System

The central control system of BMS communicates with its sub-systems through the Controller Area Network (CAN) bus or serial bus to provide safe and efficient performance [17]. BMS collects the information from the sensors (voltage, current, SOC, impedance, internal and ambient temperature) relate to battery cells or pack, process, controls its sub-systems and send that information to the user end to monitor through communication interface. Two types of communication system are being employed with BMS, which are wired and wireless communication. For wired communication, each battery cell connected to BMS. Since, battery pack consists of a large number of cells, the complex connection causes the correction of the electric contact, which may lead to whole system failure [11]. Instead of wired, wireless communication is more preferable because of low cost, reliable, easy implementation. This study presence the wireless battery management system which has been built with sensors and ZigBee.

Wireless network deployed in BMS to monitor instantaneous current, voltage, SOC, capacity (AH) and temperature of battery cell or module. It provides wireless bidirectional communication between BMS and monitoring (user end control) units where BMS can be controlled from the user end. Fig.3 shows battery management system with ZigBee wireless communication. The design model is divided into two parts: battery management system (BMS) and monitoring/user end controlling unit. The BMS mainly consists of a thermal management system, a charging system and a balancing system, a battery pack, different kinds of sensors (SOC, voltage, current,
and temperature), two master controllers, and four slave controllers. The monitoring/user end controlling unit is made of a display unit, a user controlled unit. To communicate between two parts, two ZigBee wireless communication devices are used because of its special feature such as, low power consumption, low cost, high reliability and low data rates [19,20, 21].

![BMS with wireless communication.](image)

Charging and discharging operation are very common phenomena of battery monitoring and controlling in order to provide safety and better performance. In the BMS part, slave controller 1 (106) collects the information regarding a battery pack from the employed analog sensors (SOC 107-1, voltage 107-2, current and temperature 107-3) and mapped into its specific ranges. After that, slave controller (106) sends the processed information to the master controller (A) (101) as shown in Fig.4. On basis of the receiving information, the master controller (A) (101) takes two decisions: communication and control signal generation. To communicate with the monitoring device, master controller (A) (101) activates ZigBee coordinator 1 (100) to send the information. Besides, it sends a control signal to the slave controller 2 (102) to turn ON/ OFF switches for the thermal management, charging operation, charge balancing system after checking the allowable range of voltage (2.7-4.2V), temperature (<46°C) and SOC (30%-85%). On the monitoring and user controlled side, Master controller (B) 109 receives the sending information via ZigBee coordinator 2 108. Then Master controller (B) (109) processed the information and sent signal to slave controller 1 106 to display information or show a warning message. Slave controller 2 111 receives two information either copy of information from Slave controller 1 (110) or user command (ON/OFF) (115) and sends to the
master controller (B) (109). Then master controller (B) 109 receives the request and sends to master controller (A) (101) to take necessary actions on maintaining the battery temperature.

$$\text{Fig.4. Point to point topology base network model for BMS.}$$

$$\text{Fig.5. Wireless battery management system (for Single battery module: 2 Cells in series and 2 in parallel)}$$

**3. RESULTS AND DISCUSSION**

The wireless battery management system (WBMS) has been developed with developing an algorithm based on the battery electro chemistry (LiFePO}_{4} for maintaining the accurate state-of-charge (SoC) and state-of-discharge (SoD) of the
individual cells. This allows the vehicle to utilize the maximum energy available from the battery for a given drive cycle whilst maintaining pack balance within the range of optimal functionality. This system is capable of preventing overcharging and over-discharging of LiFePO₄ cell. The battery was made with 22 modules (M) each of nominal voltage (NV) of 7.5V and capacity of 86Ah connected in series. Based on the topology, the experimental work has been setup and shown in Fig 5. The performance of developed WBMS was conducted in laboratory and measured the voltage of the 1st module and 22nd module. The difference was found from 1st M to 22nd M: 0.66% at full charge and 0.95% at full discharge.

**Charge Balancing with WBMS**

The simulation results are carried by using PSIM 9.3 on multistage LC networks for a four series connected battery cells with and without individual resistance (1.5Ω). Considering the simulation time limits, the battery cells are modeled with 10F of electrolytic capacitor. The values of LC networks are 5uH of inductor and 10uF of capacitor. The cell voltage is intentionally made different that are 3.2V, 3.5V, 3.4V and 3.6V respectively. The switching frequency 22 kHz has been chosen for all balancing process.

![Balancing Profile](image)

**Fig. 6: Module SOC during discharging.**

Experiment has been conducted for a module, which SOC was recorded before using the modules to power the motor as 83.82%, 83.8%, 83.78% and 65.25% of the cell B1, B2, B3, and B4 respectively. During discharging the modules with the other modules about 55 minutes in laboratory to power the motor, the cell’s SOC was recorded and presented in Fig. 6. All cells were in balance in 53 minutes during discharging. The result indicates that the potentiality of the wireless cell balancing is not highly effective. However, it has positive effect on the battery lifespan by preventing the cells from damage or even fire.
Battery Temperature with WBMS

Battery temperature has been measured based on the sensors employed evaporative control battery thermal management system (ECBThMS) during discharging current for the 60-70 A and 220-240 A by two different mode: with and without WBMS. The results are presented in Table 1 and 2. The positive difference shows that the modules SOC were in the range of 83-84%, which were uniformly discharge current and temperature goes up uniformly while the negative module shows that the module has SOC below 70%, which contribute more temperature. In overall, the temperature difference was not significant.

Table 1: Battery temperature for the discharge current 60-70A

| Battery Discharging Time (min) | Battery Temperature Control by ECBThMS | With WBMS | Without WBMS | Difference |
|-------------------------------|----------------------------------------|-----------|--------------|------------|
| 0                             | 26.1                                   | 26.16     | 0.06         |
| 10                            | 26.3                                   | 26.41     | 0.11         |
| 20                            | 26.9                                   | 27.15     | 0.25         |
| 30                            | 27.6                                   | 27.59     | -0.01        |
| 40                            | 28.4                                   | 28.45     | 0.05         |
| 50                            | 29.3                                   | 29.33     | 0.03         |
| 60                            | 30.1                                   | 30.13     | 0.03         |
| 70                            | 31.2                                   | 31.20     | 0.00         |
| 80                            | 32.8                                   | 32.74     | -0.06        |
| 90                            | 34.4                                   | 34.51     | 0.11         |
| 95                            | 35.0                                   | 35.14     | 0.14         |

Table 2: Battery temperature current for the discharge current 220-240A

| Battery Discharging Time (min) | Battery Temperature Control by ECBThMS | With WBMS | Without WBMS | Difference |
|-------------------------------|----------------------------------------|-----------|--------------|------------|
| 0                             | 26.4                                   | 26.27     | 0.1          |
| 5                             | 34.5                                   | 34.31     | 0.2          |
| 10                            | 39.1                                   | 38.87     | 0.2          |
| 15                            | 44.3                                   | 44.11     | 0.2          |
| 18                            | 46.4                                   | 46.42     | 0.0          |

(a) Vehicle operating speed of 60 km/h  (b) Vehicle operating speed of 120 km/h

Figure 7: Battery temperature of the electric vehicle with WBMS equipped EC-BThMS
Figure 7 shows the temperature of the modules has been recorded experiment by using the WBMS for the vehicle speed of 60 km/h and 120 km/h. The result shows that the temperature spike of the battery is proportional with the discharge current (i.e., $T \propto I$, where $I$ is current and $T$ is temperature), which is mainly for the ohmic affect ($i^2R$). It is found that the 48 kW motor has drawn 200 A current to speedy the e-coaster 120 km/h and the battery temperature spike to 49°C in 20 minutes. While the battery temperature is recorded maximum of 35°C for the vehicle speed 60 km/h due to the current drawn by the motor from the battery about 70 A.

The energy efficient of the developed EC-BThMS has been compared with two other EVs using air cooling battery thermal management system (AC-BThMS 1 and AC-BThMS 2). For these AC-BThMS, the all fans for air blowing were kept running during operation of the vehicles. The result of the cooling systems has been shown in Table 3. Table 3 indicates that the EV with EC-BThMS can save 17.69% more energy than the EV with AC-BThM 1 and 23% than the EV with AC-BThMS 2. This is because the potentiality of the EC-BThMS which is able to maintain the temperature of the battery pack in the range of 20°C – 40°C. The result of Table 5.2 shows that the EV with EC-BThMS can save 25% more time than the EV with AC-BThM 1 and 23% than the EV with AC-BThMS 2 for the quarter mile acceleration; 20.21% more time than the EV with AC-BThM 1 and 21.28% than the EV with AC-BThMS 2 for the two laps travelling.

### Table 3: Performance analysis of EC-BThMS over two others AC-BThMS I

| Type of BCThMS          | 1/4 mile acceleration (sec) | Time for 11.2 km traveling (Sec) | Max. velocity (within fastest time in 11.2 km) (km/h) | Farthest distance (km) | Energy saving with EC-BThMS (%) |
|-------------------------|-----------------------------|---------------------------------|---------------------------------------------------|-----------------------|---------------------------------|
| EV with EC-BThMS        | 22                          | 17:15                           | 119                                               | 68.62                 | -                               |
| EV with AC-BThMS 1      | 51                          | 26:51                           | 119                                               | 59.94                 | 17.69                           |
| EV with AC-BThMS 2      | 25                          | 26:19                           | 91                                                | 57.75                 | 23                              |

The correlations between measured (experimental) and predicted (simulation) values of temperature profile has been illustrated in Figure 5.19. The correlation coefficient of temperature profile at discharge current 80 A or the goodness of fit is found as 0.9730. It indicates that the predicted data over the measured data have a closed agreement and thus, validity of the simulation result. However, the mean relative error of measured and predicted values from the mathematical model on temperature profile is found as 9.027%. The relative error of simulation values over the experimental values is due to the effect of outdoor environment.
4. Conclusion
The Evaporative cooling battery thermal management system is found to be an efficient for the enhancement of battery lifespan. The enhancement of the battery lifespan would be more by using the wireless battery management system which balance the battery cells in shorter time with keeping the cells variation about 2.5 to 5%. The WBMS is important for the electric vehicle battery mainly to balance the charge while for controlling the battery temperature it is not so efficient or otherwise.

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