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INVESTIGATION ON THE FUNCTIONALITY OF BATTERY MANAGEMENT SYSTEM (BMS) BY USING APPLICATION-SPECIFIC INTEGRATED CIRCUIT (ASIC) FOR LITHIUM ION PHOSPHATE BATTERY ($LiFePO_4$)

RINGKASAN: Secara amnya, terdapat dua cara untuk membentuk fungsi Sistem Pengurusan Bateri samada menggunakan komponen diskrit ataupun ASIC. Pada masa ini komponen diskrit digunakan untuk litar pengawasan dan litar penimbang yang menambahkan kerumitan litar. Ini meningkatkan risiko litar pintas yang akan menyebabkan kerosakan bateri atau pun letupan. Tambahan pula, komponen diskrit memerlukan lebih masa dalam merekabentuk dan memberikan bacaan dengan kejituan yang rendah berbanding komponen ASIC. Objektif kajian ini ialah untuk menyiasat kebolehan komponen ASIC untuk memenuhi keperluan keselamatan bagi Sistem Pengurusan Bateri. Keperluan keselamatan tersebut ialah membolehkan bateri berfungsi dengan selamat dengan memberi perlindungan daripada lebihan arus, lebihan voltan semasa mengecas, voltan lendut semasa dinyahcas dan suhu berlebihan. Ia juga, dapat memaksimumkan kapasiti bateri dengan memastikan setiap sel mempunyai cas yang sama dengan membuang tenaga berlebihan melalui perintang. Untuk memenuhi objektif di atas, komponen IC LTC6802-2 daripada Linear Technology digunakan dan diuji menggunakan bekalan kuasa arus terus bagi membolehkan simulasi voltan dijalankan. Hasil daripada eksperimen mengesahkan komponen ASIC boleh digunakan sebagai Sistem Pengurusan Bateri bertujuan menggantikan litar diskrit.

ABSTRACT: Generally, there are two methods to form the BMS functions; discrete components and BMS ASIC. Current methods used discrete component for monitoring and balancing circuit which increase circuit complexity. This leads to risk of short circuit that may cause battery damage and fire or explosion. In addition, discrete components require more design effort and give low accuracy measurements compared to BMS ASIC. The objective of this paper is to investigate the potential of BMS ASIC to fulfil the safety requirements of BMS. The BMS ASIC can prevent the battery from operating outside its safe operating area. The BMS provide protection for overcurrent, overvoltage during charging, undervoltage during discharging and over temperature. Secondly, to maximize the battery's capacity by ensuring that the cells battery are kept at the same State of Charge (SOC) by wasting energy from the most charged cells through a dummy load through balancing. To fulfil the safety objective, the BMS ASIC based on Linear Technology's IC LTC6802-2 is used. The designed BMS ASIC board was used and tested by using dummy load to replace $LiFePO_4$ battery. Results obtained showed that the LTC6802-2 IC can be used as replacement for BMS designed by using discrete components.

Keywords: Battery Management System (BMS), ASIC, passive balancing.

INTRODUCTION

Current BMS products used discrete component for monitoring and balancing circuit which increase circuit complexity. This leads to risk of short circuit that may cause battery damage and fire or explosion. In addition, discrete components require more design effort and gives inaccurate measurement compared to BMS ASIC (Andrea, 2010). The inaccurate measurement causes the battery to exceed the Safety Operating Area, and reduced performance and damaged the battery. In addition, it was discovered that human error was at fault, such as poor mechanical design and bad manufacturing processes of batteries but blame was put on BMS. Identifying the type of error can be determined by using BMS ASIC (Beauregard, 2008).

Advancement in semiconductor technology makes it possible to explore the role played by BMS ASIC (Xiao *et al.*, 2012). The BMS ASIC has accuracy better than 25 mV for effective balancing and protection compared to discrete components. It has an individual data acquisition circuit for each cell that is used to monitor voltage for excellent common noise rejection ratio and consist of at least one temperature sensor for every six (6) cells. The chips shall provide separate outputs for charging and discharging and manufactured by experienced manufacturer with years of BMS experience and continuous component support. In terms of balancing, it has dedicated lines separated from the lines used to measure voltage. Finally, it can be implemented as a complete BMS capable of lengthening the life of $LiFePO_4$ battery as Electrical Energy Storage (EES) (Elithion, 2011).

The lithium ion batteries in electrochemical group have become the most important storage technology in the areas of portable and mobile applications since year 2000. A cell voltage levels is up to 3.7 V and can be arranged in series to obtain the target voltage. Another advantage of $LiFePO_4$ batteries is their high gravimetric energy density, and the prospect of large cost reductions through mass production. Although $LiFePO_4$ batteries have a share of over 50 % in the small portable devices market, there are still some challenges to develop BMS for large-scale $LiFePO_4$ batteries (IEC, 2011).

Safety is a serious issue in $LiFePO_4$ battery technology. The use of lithium electrodes are thermally unstable and can decompose at elevated temperatures, releasing oxygen which can lead to a thermal runaway. In order to solve the problem, the $LiFePO_4$ batteries are equipped with a BMS. The BMS is required to limit the voltage level of each individual cell and prevent voltage deviations among them to avoid thermal runaway (Moore *et al.*, 2001).

In order to solve global environmental problems in CO_2 emission, more efficient and reliable electricity supply, renewable energies such as solar and wind will be widely used. This means that the future energy supply will be influenced by fluctuating renewable energy sources and electricity production will follow weather conditions. Surplus and deficit in energy need to be balanced by energy storage. One of the main functions of the energy storage is to match the supply and demand of energy which is essential for large and small-scale applications (Elithion, 2011 and IEC, 2011). Energy storage systems consisting of batteries are equipped with a BMS which monitors and controls the charge and discharge processes of the cells or modules of the batteries. This is necessary in order to safeguard the lifetime and ensure safe operation of the batteries (Moore *et al.*, 2001).

MATERIAL AND METHODS

In this paper, experimental development of the BMS starts with selection of BMS chip that is used to interface with programmable microcontroller. The selected microcontroller shall be capable to be programmed to ensure that improved $LiFePO_4$ BMS is able to fulfil safety requirements. The selection of BMS chip which is capable of fulfilling research safety requirements by forming BMS functions with $LiFePO_4$ battery system is very crucial. The BMS functions related with BMS are to monitor temperature, voltage and current parameters.

The first safety requirement is temperature, which states that the lifetime of $LiFePO_4$ cells will be drastically reduced if discharged outside a certain temperature range or charged outside an even tighter temperature range. The temperature range for battery pack during charging is between 0 °C to 40 °C and during discharging on load is between -20 °C to 60 °C. The thermistor is used between the battery pack to monitor the actual battery temperature.

The second safety requirement warns that $LiFePO_4$ cells will be quickly damaged and may burst into flames if overcharged above 3.7 V. The maximum voltage is set to 3.6 V and this is over the voltage limit for $LiFePO_4$. In this work, when the overvoltage occurred, the BMS chip will raise flag to microcontroller to stop charging current by using external circuitry and continue with balancing process.

The final safety requirement indicates that most $LiFePO_4$ cell will be damaged if allowed to be discharged below a certain voltage. The minimum voltage is set to 2.8 V and this is close to undervoltage limit (2.6 V) for $LiFePO_4$. In this research, when the undervoltage occurred, the BMS chip will raise flag to microcontroller. The microcontroller sends signal to external circuitry to start charging process.

BMS MODULE

The BMS Module based on Linear Technology's BMS IC LTC6802-2 was designed. The designed module has one LTC6802-2 IC that is capable of measuring 12 series connected cells with a total voltage up to 60 V and is powered directly from the $LiFePO_4$ battery pack or power supply. The designed module includes two (2) inputs for connection with NTC thermistor to measure the temperature and has a built in supply regulator. It has twelve (12) individual discharge transistors with one (1) Watt resistors that can be used to discharge overcharged cell for cell balancing through passive balancing. The BMS Module is designed to work with configuration as shown in Figure 1. Each BMS Module has 4 bit unique hardware address that can be set by the jumpers that enable maximum of 16 BMS Modules board. The number of cells that can be interfaced with BMS Controller are 192.

FIRMWARE DESIGN

All firmware programmes for BMS Controller and BMS Display are done using CCS PCWHD C compiler version 4.104. For BMS Controller, PIC18F4685 microcontroller was chosen mainly because it has hardware CAN Module and enough Flash and RAM memory (96K Bytes of Flash and 3328 Bytes of RAM). The parameters for $LiFePO_4$ are given in Table 1 to Table 4.

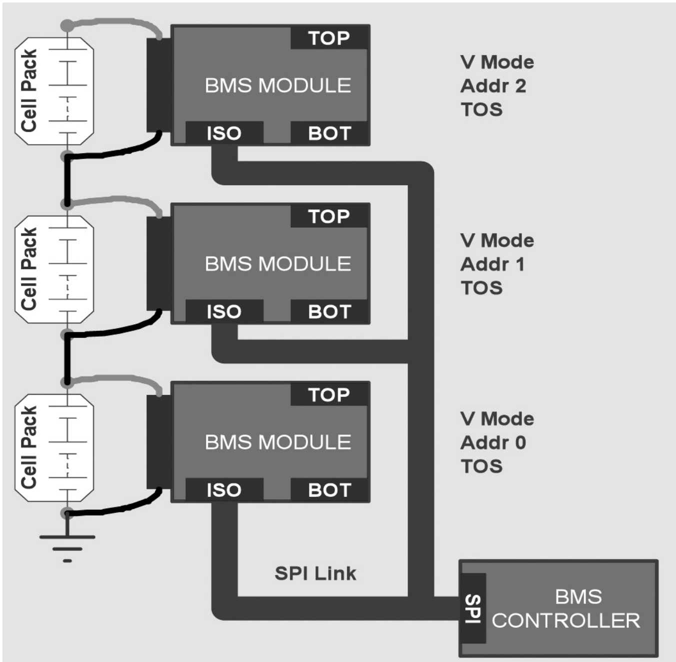

Figure 1. *BMS Configuration as Isolated Stacked and monitor cells in series.*

FUNCTION TEST

The function of the BMS Controller together with BMS Modules is to measure the cell voltages, temperature and current as shown in Figure 2.

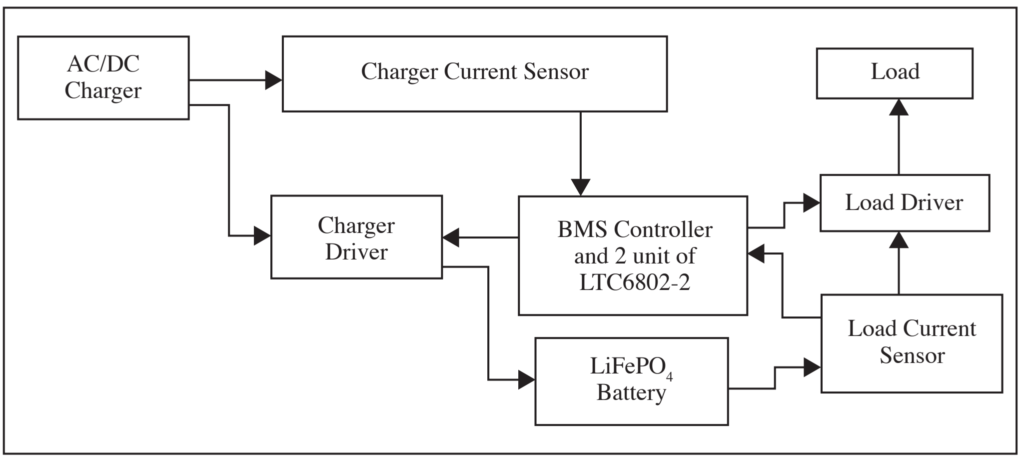

Figure 2. *BMS Functional Test Setup*

First, the programme starts by checking which input supplies are connected. At the start of loop, the programme checks for fault. If a fault is detected, programme will turn on fault output, FAULT_EN, disables both charger and load and stops the cell balancing. The programme will loop continuously in fault state until user rectifies the problem. Fault state loop can be exitted when the user turns the emergency button on and off or by resetting the programme. If there is no fault, the programme starts to measure cell voltages, temperatures and checks for open-wire connections after specified interval has elapsed (adjustable). The measurements are done by sending specific commands from the BMS Controller to LTC6802-2 chips. After cell voltages and temperature measurements are done, the BMS controller then measures the charging current (current going into the battery) from the Charger Current Sensor and load current (current going out of the battery) from the Load Current Sensor.

After all the measurements are done, the programme checks for thermal shutdown flags issued from the two BMS LTC6802-2 chips, during the temperature measurement. If BMS chip internal temperature goes above 145 ºC, thermal shutdown occurs and the programme will turn on warning output, WARNING_EN, disabling both charger and load.

Next, the measured data are compared against the parameter settings stored in EEPROM. Table 1 to Table 4 show default settings for these parameters. The settings can be adjusted by user through BMS Display. First the measured data are compared to the Fault settings as shown in Table 1. For example if any of the cell voltage already reaches fault cell overvoltage (VFault_O) BMS Controller will shut down both charger and load, disable any cell balancing and issue a fault. The BMS Controller also issues a fault when it detects any disconnected cell (open-wire).

Next the data are compared to the Charging Limits and Discharging Limits as shown in Table 2 and Table 3. If any of the cell voltage reaches maximum cell voltage (VCell_Max) or charging temperature drops below low charging temperature (TCHG_Low), the BMS Controller will shut down the charger. Similarly for discharging process, if any of the cell voltage drops below minimum cell voltage (VCell_Min) or discharging temperature increases above maximum discharging temperature (TDCH_Max), the BMS Controller will shut down the load.

Table 1. Fault limits of the $LiFePO_4$ settings stored in EEPROM.

Parameter	Symbol	Value	Description
Fault cell under voltage	VFault_U	2.5V	Low cell voltage where charging, discharging and cell balancing stops.
Fault cell over voltage	V_{Fault_O}	3.7 V	High cell voltage where charging, discharging and cell balancing stops.
Fault under temperature	T_{Fault_U}	0 °C	Low battery temperature where charging, discharging and cell balancing stops.
Fault over temperature	T_{Fault_O}	70 °C	High battery temperature where charging, discharging and cell balancing stops.
Fault charge over current	I_{Fault_Chg}	70 A	Charging current where charging, discharging and cell balancing stops.
Fault discharge over current	I_{Fault_Dch}	70 A	Discharging current where charging, discharging and cell balancing stops.

Table 2. Charging Limits of the $LiFePO_4$ settings stored in EEPROM.

Parameter	Symbol	Value	Description
Nominal charging current	I_{CHG_NOM}	50 A	Normal charging current
Peak charging current	I_{CHG_PEAK}	60 A	Battery current where charging stops
High cell voltage	V_{Cell_High}	*3.4 V*	Cell voltage where charging starts to reduce
Max cell voltage	V_{Cell_Max}	3.6 V	Cell voltage where charging stops.
High pack voltage	V_{Pack_High}	55 V	Pack voltage where charging starts to reduce
Max pack voltage	V_{Pack_Max}	60 V	Pack voltage where charging stops.
Low charging temperature	T_{CHG_Low}	5 °C	Battery low temperature where charging starts to reduce.
Min charging temperature	T_{CHG_Min}	0 °C	Battery low temperature where charging stops.
High charging temperature	T_{CHG_High}	50 °C	Battery high temperature where charging starts to reduce.
Max charging temperature	T_{CHG_Max}	60 °C	Battery high temperature where charging stops.

Table 3. Discharging Limits of the $LiFePO_4$ settings stored in EEPROM

Parameter	Symbol	Value	Description
Nominal discharging current	I_{DCH_NOM}	50 A	Normal discharging current
Peak discharging current	I_{DCH_PEAK}	60 A	Battery current where discharging stops
Low cell voltage	V_{Cell_Low}	*2.8 V*	Cell voltage where discharging starts to reduce
Min cell voltage	V_{Cell_Min}	2.6 V	Cell voltage where discharging stops
Low pack voltage	V_{Pack_Low}	45 V	Pack voltage where discharging starts to reduce
Min pack voltage	V_{Pack_Min}	40 V	Pack voltage where discharging stops
Low discharging temperature	T_{DCH_Low}	5 °C	Battery low temperature where discharging starts to reduce
Min discharging temperature	T_{DCH_Min}	0 °C	Battery low temperature where discharging stops
High discharging temperature	T_{DCH_High}	50 °C	Battery high temperature where discharging starts to reduce
Max discharging temperature	T_{DCH_Max}	55 °C	Battery high temperature where discharging stops

For cell balancing process, if any of the cell voltage is more than minimum cell voltage balancing (VBal_Min) or the difference in cell voltages is greater than Delta balancing voltage (VBal_Delta), the BMS Controller will start the balancing process to bring the voltage down for any of the cell that has higher voltage than the rest of the cells. The BMS Controller will stop the balancing process if the temperature is more than maximum balancing temperature (Tbal_Max). The parameters for balancing are shown in Table 4. Then, the programme checks for any request from serial port and Controller Area Network (CAN). If valid data is received, the programme will process the data accordingly.

The system is tested on dummy cells which consist of 250 Ω resistors in series powered by bench power supply without AC/DC charger and load. The voltage across the resistors is adjusted to simulate the range of $LiFePO_4$ cell operating voltage between 2.8 V and 3.4 V. The designed board used namely as Isolated Multiple Stacked Cells Monitor used two (2) BMS Modules with each BMS Module connected to an array of eight (8) dummy cells in series (8 + 8 configuration). The top dummy cell in lower array is attached to bottom dummy cell in upper array. The series array is powered by bench power supply with voltage settings of 48 V (2.8 V multiply with 16) and 54 V (3.4 V multiply with 16).

Table 4. Balancing limits of the $LiFePO_4$ settings stored in EEPROM

Parameter	Symbol	Value	Description
Min cell voltage balancing.	V_{Bal_Min}	3.4 V	Minimum cell voltage where cell balancing starts (depends on other conditions).
Delta balancing voltage.	V_{Bal_Delta}	50 mV	Minimum voltage difference between highest and lowest cell voltage where cell balancing starts.
Max balancing temperature.	T_{bal_Max}	55 ºC	Maximum battery temperature where cell balancing stops.

RESULT

From Table 5 and Table 6, the data shows that the cell voltages for Bank 1 and Bank 2 are consistent but each measured voltage is about 200 mV lower than theoretical value (V_{Supply} / 16). Vpack are combinations of Cells voltage from Cell1 up to Cell8 for Bank 1 and Bank 2. The ETMP1 up to ETMP3 are temperature readings from thermistor sensors and are used to measure temperature during charging and discharging.

Based on testing being conducted, the summary of test results are as shown in Table 7.

Table 5. Power Supply Test +48V, Configuration C (8 + 8).

Date	Bank	Cell1	Cell2	Cell3	Cell4	Cell5	Cell6	Cell7	Cell8	Vmin	Vmax	Delta	Vpack	ETMP1	ETMP2	ITMP
15/07/15 11:41:59	1	2.816	2.814	2.814	2.817	2.811	2.811	2.816	2.874	2.811	2.874	0.063	44.94	20.2	19.6	25.5
	2	2.801	2.792	2.799	2.792	2.795	2.793	2.796	2.796	2.792	2.801	0.009		19.8	19.9	28.4
15/07/15 11:42:15	1	2.814	2.814	2.814	2.817	2.811	2.813	2.816	2.876	2.811	2.876	0.065	44.94	20.1	19.6	25.4
	2	2.801	2.793	2.799	2.792	2.795	2.792	2.796	2.796	2.792	2.801	0.009		19.8	20.1	28.4
15/07/15 11:42:31	1	2.816	2.814	2.814	2.817	2.809	2.813	2.816	2.876	2.809	2.876	0.067	44.94	20.0	19.7	25.5
	2	2.799	2.793	2.801	2.792	2.793	2.792	2.795	2.796	2.792	2.801	0.009		19.9	20.1	28.4
15/07/15 11:42:47	1	2.816	2.814	2.814	2.817	2.811	2.813	2.816	2.876	2.811	2.876	0.065	44.94	20.1	19.6	25.5
	2	2.799	2.793	2.801	2.792	2.795	2.793	2.796	2.796	2.792	2.801	0.009		19.9	20.1	28.7
15/07/15 11:43:03	1	2.814	2.814	2.814	2.817	2.811	2.813	2.816	2.876	2.811	2.876	0.065	44.94	20.1	19.5	25.5
	2	2.799	2.793	2.799	2.792	2.793	2.793	2.796	2.796	2.792	2.799	0.007		19.7	19.7	28.5
15/07/15 11:43:19	1	2.816	2.814	2.814	2.817	2.809	2.813	2.814	2.876	2.809	2.876	0.067	44.94	20.1	19.6	25.5
	2	2.801	2.793	2.799	2.792	2.793	2.793	2.796	2.796	2.792	2.801	0.009		19.8	19.9	28.5
15/07/15 11:43:35	1	2.816	2.814	2.814	2.817	2.811	2.813	2.816	2.876	2.811	2.876	0.065	44.94	20.1	19.7	25.5
	2	2.801	2.793	2.801	2.792	2.795	2.793	2.796	2.796	2.792	2.801	0.009		19.9	20.0	28.5
15/07/15 11:43:51	1	2.816	2.814	2.816	2.817	2.811	2.813	2.816	2.876	2.811	2.876	0.065	44.95	20.2	19.7	25.5
	2	2.801	2.793	2.801	2.792	2.795	2.793	2.795	2.796	2.792	2.801	0.009		19.9	20.1	28.5
15/07/15 11:44:07	1	2.816	2.814	2.816	2.817	2.811	2.813	2.816	2.877	2.811	2.877	0.066	44.95	20.3	19.7	25.5
	2	2.801	2.793	2.799	2.792	2.795	2.793	2.796	2.796	2.792	2.801	0.009		19.9	20.1	28.5
15/07/15 11:44:22	1	2.816	2.814	2.816	2.817	2.811	2.813	2.816	2.876	2.811	2.876	0.065	44.94	20.2	19.6	25.5
	2	2.799	2.793	2.801	2.793	2.795	2.793	2.795	2.796	2.793	2.801	0.008		19.7	19.9	28.5
15/07/15 11:44:38	1	2.816	2.814	2.816	2.817	2.811	2.813	2.816	2.877	2.811	2.877	0.066	44.95	20.2	19.7	25.5
	2	2.801	2.793	2.801	2.793	2.793	2.793	2.796	2.796	2.793	2.801	0.008		19.8	19.9	28.7

Table 6. Power Supply Test +54V, Configuration C (8 + 8)..

Date	Bank	Cell1	Cell2	Cell3	Cell4	Cell5	Cell6	Cell7	Cell8	Vmin	Vmax	Delta	Vpack	ETMP1	ETMP2	ITMP
15/07/15 11:46:32	1	3.189	3.188	3.189	3.192	3.184	3.186	3.191	3.261	3.184	3.261	0.077	50.94	20.2	19.7	25.7
	2	3.176	3.168	3.176	3.167	3.168	3.168	3.170	3.171	3.167	3.176	0.009		19.9	20.2	28.7
15/07/15 11:46:48	1	3.191	3.189	3.189	3.192	3.184	3.186	3.191	3.261	3.184	3.261	0.077	50.95	19.9	19.7	25.7
	2	3.176	3.168	3.174	3.167	3.168	3.168	3.170	3.171	3.167	3.176	0.009		19.9	20.1	28.7
15/07/15 11:47:04	1	3.191	3.189	3.189	3.192	3.184	3.186	3.189	3.261	3.184	3.261	0.077	50.94	20.0	19.8	25.7
	2	3.176	3.167	3.176	3.167	3.168	3.168	3.170	3.170	3.167	3.176	0.009		19.9	20.1	28.9
15/07/15 11:47:20	1	3.191	3.189	3.189	3.192	3.184	3.186	3.191	3.263	3.184	3.263	0.079	50.95	20.2	19.7	25.9
	2	3.176	3.168	3.176	3.167	3.168	3.168	3.170	3.171	3.167	3.176	0.009		19.9	20.1	28.9
15/07/15 11:47:36	1	3.189	3.189	3.189	3.192	3.184	3.186	3.191	3.263	3.184	3.263	0.079	50.95	20.2	19.7	25.9
	2	3.177	3.168	3.176	3.167	3.168	3.167	3.170	3.171	3.167	3.177	0.010		19.8	20.0	29.1
15/07/15 11:47:52	1	3.191	3.189	3.189	3.192	3.184	3.186	3.191	3.263	3.184	3.263	0.079	50.95	20.2	19.7	25.9
	2	3.176	3.168	3.176	3.167	3.168	3.168	3.171	3.171	3.167	3.176	0.009		19.8	20.1	28.9
15/07/15 11:48:08	1	3.189	3.189	3.189	3.192	3.184	3.186	3.191	3.264	3.184	3.264	0.080	50.95	20.2	19.7	25.9
	2	3.177	3.168	3.176	3.167	3.168	3.168	3.170	3.171	3.167	3.177	0.010		19.9	20.0	29.1
15/07/15 11:48:24	1	3.189	3.189	3.189	3.192	3.184	3.186	3.191	3.264	3.184	3.264	0.080	50.95	20.2	19.8	25.9
	2	3.176	3.167	3.176	3.165	3.168	3.168	3.170	3.171	3.165	3.176	0.011		19.9	20.1	29.1
15/07/15 11:48:40	1	3.191	3.189	3.191	3.192	3.184	3.186	3.191	3.266	3.184	3.266	0.082	50.95	20.2	19.8	25.9
	2	3.177	3.167	3.176	3.167	3.168	3.167	3.171	3.171	3.167	3.177	0.010		20.0	20.2	29.1
15/07/15 11:48:55	1	3.191	3.188	3.189	3.192	3.184	3.186	3.191	3.264	3.184	3.264	0.080	50.95	20.2	19.8	25.9
	2	3.176	3.168	3.176	3.167	3.168	3.167	3.170	3.171	3.167	3.176	0.009		19.9	20.2	29.1
15/07/15 11:49:11	1	3.191	3.189	3.189	3.192	3.184	3.186	3.191	3.266	3.184	3.266	0.082	50.95	20.2	19.7	26.1
	2	3.176	3.168	3.176	3.167	3.168	3.168	3.171	3.171	3.167	3.176	0.009		19.9	20.0	29.3

Table 7. Summary of test results.

Test Parameters	Function test	Measurement	Result
Supply voltage 63 V.	Check for fault over voltage.	Cell voltages > 3.70 V.	Load = Off Charger = Off Balancing = Off
Supply voltage 43 V.	Check for fault under voltage.	Cell voltages < 2.50 V.	Load = Off Charger = Off Balancing = Off
Supply voltage 48 V. Applied hot air blower to ETMP1 thermistor.	Check for fault over temperature.	Cell voltages ~ 2.8 V. Temperature = 80 °C.	Load = Off Charger = Off Balancing = Off
Supply voltage 48 V. Update CFGR1 register value for both LTC6802-2 from 0 to 0xFF.	Test for cell balancing.	None.	All cell discharge LEDs on both BMS Module boards lit up.

CONCLUSION

It is found that the Battery Management System was successfully measured and monitored the voltage and temperature. However, the load current and the charging current parameters were not tested because there was no suitable charger and load for testing. The difference between measured voltages for each cell was too small and can be ignored during measurement. This indicated that the balancing circuit is working perfectly.

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