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RESEARCH ARTICLE - ENGINEERING

Design of an Uninterrupted Power Supply with Li-Ion Battery Pack: A Proposal for a Cost-Efficient Design with High Protection Features

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Abstract

While decreasing their cost, lithium-ion batteries began to enter a vast domain for energy storage field, including solar systems and electric vehicles, due to their high energy density compared to other types. Besides, li-ion batteries require a safe and secure ground to reach the best performance and decrease the explosion risk. The safe operation of the battery is based on the main protection features and balancing the cells. This study offers a battery BMS design that protects li-ion batteries from overcharging, over-discharging and overheating. It is also offering passive cell balancing, an uninterrupted power source to load, and monitoring data. The used controller is Arduino mega 2560, which manages all the hardware and software protection features. Software features that include 1) variable charging speed according to the batteries charging status, 2) measuring the batteries state of health and state of charge, 3) controlling the uninterrupted driver, 4) regulating the charge and discharge voltage, and 5) measure and display all readings.

Keywords: Battery Management System (BMS); Lithium-ion Protection; Passive Balancing; Uninterrupted Power Supply (UPS)

1. Introduction

The high global demand for energy and increase in oil prices are accompanied by promising development in adopting many renewable energy sources. The last leads to high demand on the energy storage systems because the high uncertainty of the renewable energy sources depends on weather conditions. Moreover, the fast development of electric vehicle production is increasing the demand for high-density storage systems. In addition, the growth of portable electronic devices, such as phones, laptops, medical devices, and more. These aspects led researchers to develop different types of batteries [1-3], with different characteristics and capacities, like lead-acid, Nickel-cadmium, Lithium-ion, and nickel-metal hydride.

Lithium-ion (Li-ion) batteries are distinct from others that they have the following characteristics; high energy, power density, long life cycle, low self-discharge, and no effect memory[4]. Thus, many efforts have been presented to reduce the cost and raise the performance to grow their demand [5, 6] .Li-ion batteries are connected to increase the voltage in series or increase the current in parallel. Some non-linear properties reveal the variation in time; this affects each cell and decreases its capacity due to the charging and discharging operations. The surrounding factors also affect the battery pack. There are some restrictions in using lithium-ion batteries, which are voltage, current, and temperature in respect of charging or discharging, which must be considered in order not to cause damage or decrease in the number of cycles, so Lithium-ion require a safe and secure environment to reach optimum operation and performance [7-10]. Li-ion battery packs manage poverty because of the li-ion behaviour that requires controlling each cell to protect it from overcharging or over-discharging; this process is called Battery Management System (BMS) [11].

Nomenclature

BMS	Battery Management System	V_o	Output Voltage
Li-ion	Lithium-ion	V_{in}	Input Voltage
SoC	State of Charge	D	Duty Cycle
DoD	Depth of Discharge	L	Inductance
UPS	Uninterrupted Power Supply	C	Capacitance
LiCoO2	Lithium cobalt oxide	f	Frequency
NMC	Lithium nickel manganese cobalt oxide	SMPS	Switched Mode Power Supply
LifePO4	Lithium iron phosphate battery	VCCS	Voltage Control Current Source
MCU	MicroController Unit		

BMS application is essential in protecting and increasing battery life. Thus, reducing the cost and state of charge estimation works on monitoring the currents, voltages, and temperature. BMS implement the balance between cells during charge. The battery pack is operating here in a safe region [12-16]. Imbalance appears when batteries are connected in series to stave off overvoltage using passive and active methods.

2. Literature Review

In numerous previous studies on BMS design, [17] proposed a system with Li-ion. The OZ8920 chip and MCU were employed to balance cells, protect cells from overcharging and over-discharging, also monitor cell voltage and temperature. Lead-acid battery charge circuit was designed to protect the cell from an increase in the charging current, monitor it, balance the cells, and use the relay as a control switch. The relay here is impractical in many operations, and an electronic key must be used.

However, temperature monitoring was not considered [18]. In [19], the authors used a Lifepo4 connected 1P4S battery pack focused on applying passive balance, but no protective factors are mentioned, such as overcharge, over-discharge, and over-temperature. The passive balance and calculation of SoC batteries LiCoO2 1P3S battery pack were discussed in [20], with no protection features. It was overcharging and passive balancing by using a diode and monitoring current and voltages cell. Recognizing the treatment of diode in the balance produces losses that can be avoided. Furthermore, this did not work to protect from over-discharge and overheat [21]. The Passive balance has been studied and focused on balancing implantation for different battery types as in LifePO4 [22-24], Li-ion [25], and NMC[26]. Finally, all the previous studies that were covered included all kinds of battery protections, but at the same time, they did not focus on the load and how it operates during charge; For this reason, this research task on circuit design UPS has been confirmed, and the limits of battery drain. The main article's contribution is to design a BMS with full protection features, a passive balancing controller with an uninterrupted controller, and control the input and the output voltage.

The rest of the article shows the main design aspects and methodology in section 3. While section 4 presents the proposed BMS system. The software algorithms are presented in section 5, and the BMS simulation results are presented in section 6. Finally, the conclusions are conferred in section 7.

3. Design Aspect and Methodology

To securely utilize Li-ion batteries, they must be matched with protection systems able to hold them within a safe producing range. The critical faults that the batteries must be protected from are the overvoltage, overcurrent, and over-temperature conditions, as these can position the batteries in a delicate situation. Protection features can be classified into:

3.1. Electrical Protection Features

3.1.1. Over Voltage Protection

Overvoltage suited to a battery pack due to irregular charger settings is essential because it produces a thermic deserter. The system design must guarantee that the maximal charging voltage is regulated within cell guidelines to limit it. The Vmax is not always 4.2V per cell (albeit this number is most common)[27].

3.1.2. Over-current protection

The overcurrent occurs in two states: during charging issues, the charger gives currents higher than the manufacturer’s recommended rank for unusual time. Commonly the maximal charge current is submitted to be between 1C and 0.7C rates. However, it can be several cells created for high-power operation. Transcending the suggested purposes will reason overheating for the battery pack. During discharge, a device draws a current higher than the manufacturer’s recommended rating for separate periods. Remark that the rating counts on the variety of cells. Laptop and cell phone-type cells are typically rated for 1C to 2C continuous discharge: 1 hour to 30 minutes to exhaustion [27].

3.1.3. Over Charge and Discharge Protection

Overcharge befalls if the cell is charged to a state of charge more prominent than 100%. The cell voltage grows very swiftly can top the load device's limits or the monitoring system. Overcharge reason various constant depravity devices inside the cell, which can lead to dynamic failure. This is true of a single, severe overcharge event as well as repeated minor overcharging. Unlike other battery types, Li-ion cells can be overcharged by too low standards of charge current. Overcharge can lead to thermal delinquent, cell increase, venting, and other dangerous events. The robustness of various cell designs to overcharge modify significantly and should be well understood when the BMS design is undertaken. Over-discharge is the discharge of a cell exceeding 100% DOD or 0% SOC. Cell voltage reduces swiftly and can even be reversed if the over-discharge current is quite high. Reversing cell polarity can create the breakdown of management electronics and sequential malfunctions. Over-discharge can lead to significant internal cell damage, in particular dismissal of the anode foil. Subsequent efforts to recharge a cell that has been excessively and frequently over-discharged can lead to safety dangers, which decrease the life cycle and capacity [28].

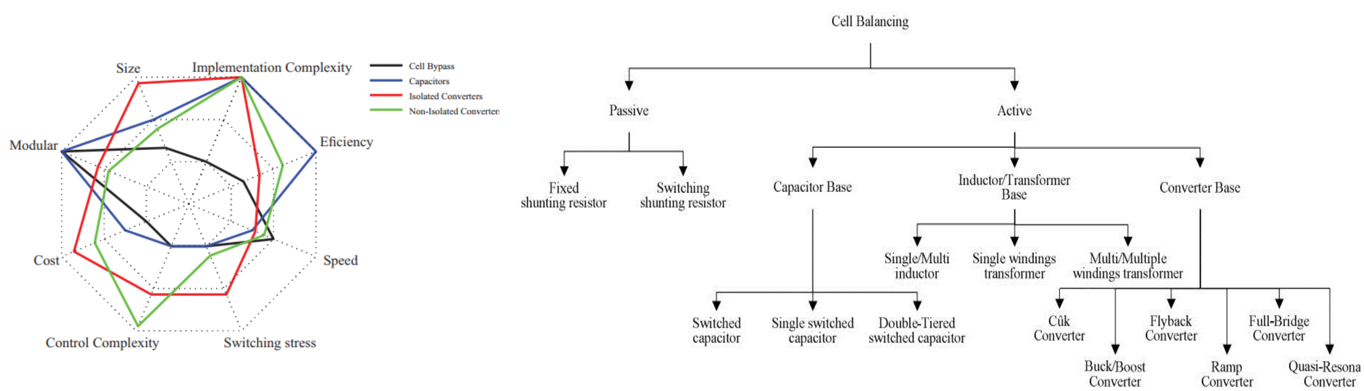
3.1.4. Over Temperature Protection

The temperature of the Li-ion pack should be within the discharge variety and charge limit. These are specified in the manufacture datasheet during charge and discharge and should not be above 60℃[29] ,but the to be more safe the system should shutdown at 55℃.

3.2. Balancing methodology

The most significant function of BMS is to balance the cells uring the charging time, the voltage varies between the cells because many factors affect it, including the charging and discharging cycles and the materials manufactured. Some cells reach the s full charge faster than other cells, and overcharge affects cells' lives and decreases the capacity. The balancing consists of passive balancing and active balancing; Fig.1b illustrated that [30].

The passive balancing strategies remove the extra charge from the fully charged cell(s) through a passive resistor element until the charge approximates those of the pack's lower cells[31, 32]. The active cell balancing strategies dismiss the charge from higher energy cell(s) and supply it to lower energy cell(s). It has different topologies according to the active element used for storing the energy, such as a capacitor and/or inductive component and controlling switches or converters[33, 34]. Fig. 1a indicates a scheme to compare the different balancing methods implementation[35]. Due to its reliability and simplicity and the point that it is a widely employed industry application, this paper has applied the passive balancing method.



(a) (b)

Fig. 1 Balancing topology a) Methods Comparison b) Type of Balancing

4. The Proposed BMS System

The proposed system was designed to protect the batteries from overcharging, discharging, or overheating, balancing circuits, measuring, and monitoring each cell's voltage. Li-ion batteries of the type 18650 connected in series (1P5S). The battery characteristic are $Vnormal$=3.7V, $Vmax = 4.2V$,$Vmin = 3V$. Figure 2 shows the block diagram for the proposed system, while Fig. 3 shows the system circuitry.

4.1. The Balancing Circuit

The first and most crucial step is to design a balanced circuit to protect the cell from overcharging. The MOSFET worked when measuring the cell's voltage reached $Vmax$. The energy is dissipated as heat in the bypass resistor, so the passive method is applied in the low voltage application but for simplicity and reliability.

4.2. Uninterrupted Power Supply (UPS) Circuit

One of the essential functions of BMS is to preserve the battery and extend its life. Protection is not only the operation of the load in all conditions. So, the circuit UPS is designed to handle the load while the batteries are charging to reduce depletion. ULN2003A was driving the relays taking signals from the controller, which turn, operates and switches between the power directed to the load either from the batteries or the source directly.

4.3. Buck Converter

Figure 4 reveals the power electronic circuit for the DC-DC buck converter, and the DC source is simulated for the SMPS input, which is 25V. The source is connected to the source of the MOSFET.IRF4905 is utilized here for the switching purpose. The transistor BC107 was used to drive MOSFET according to the pulses of the pulse width modulation circuit (PWM) from the controller, and the chosen frequency is 31 kHz. The value of inductance was calculated in Eq.1 and the capacitance value in Eq.2. The output voltage is calculated when the known duty cycle is described in Eq.3.

$$L_{min} = \frac{(1-D)R}{2f} \rightarrow L = 10 * L_{min} \quad (1)$$

$$C = \frac{1-D}{8L(\Delta V_o/V_o)f^2} \quad (2)$$

$$V_o = V_s D \quad (3)$$

4.4. Current Measurement Circuit

ACS712 equips economical and precise solutions for AC or DC currents sensing in industrial, commercial, and transmission systems. The device package allows for easy implementation. This circuit has featured a Low-noise analog signal path, a Total output error of 1.5% at TA = 25°C, and 1.2 mΩ internal conductor resistance.

4.5. Voltage measuring Circuit

Measuring voltage is done by using a differentiator op-amp to calculate voltage for each call. The circuit is illustrated in Fig 5a. The differentiator acts to measure the potential difference between the two ends of the cell. This measurement is accurate in knowing the cell voltage.

4.6. Temperature measurement Circuit

NTC temperature thermistors have a negative electrical resistance versus temperature (R/T) relationship. An NTC thermistor's almost large negative response suggests that even small temperature changes can cause significant changes in their electrical resistance. This makes them ideal for accurate temperature measurement and control. NTC thermistor is commonly used to measure temperature also using 10K @ 25 C type.

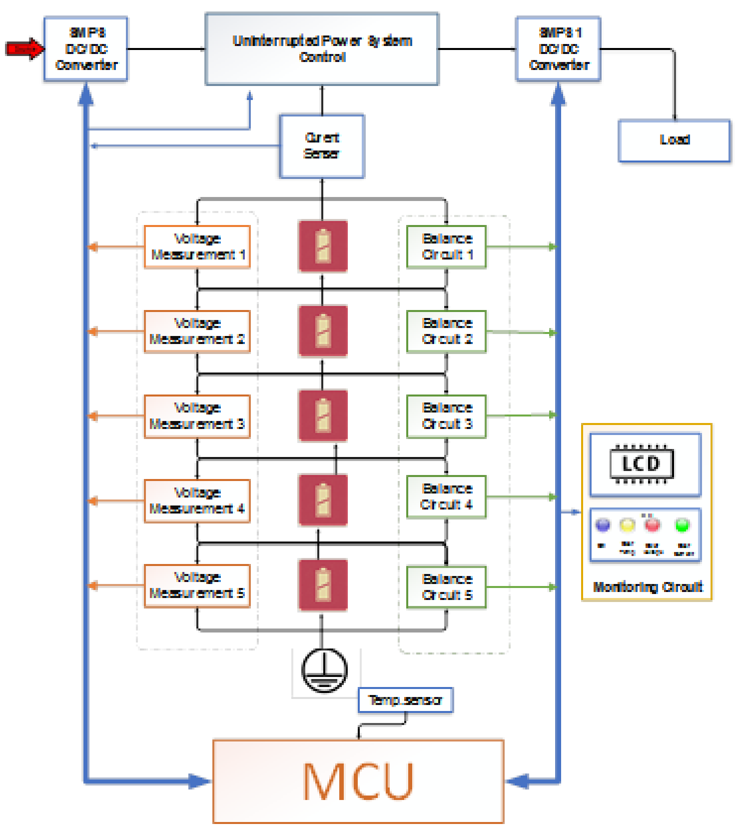


Fig. 2 The Proposed System Block Diagram

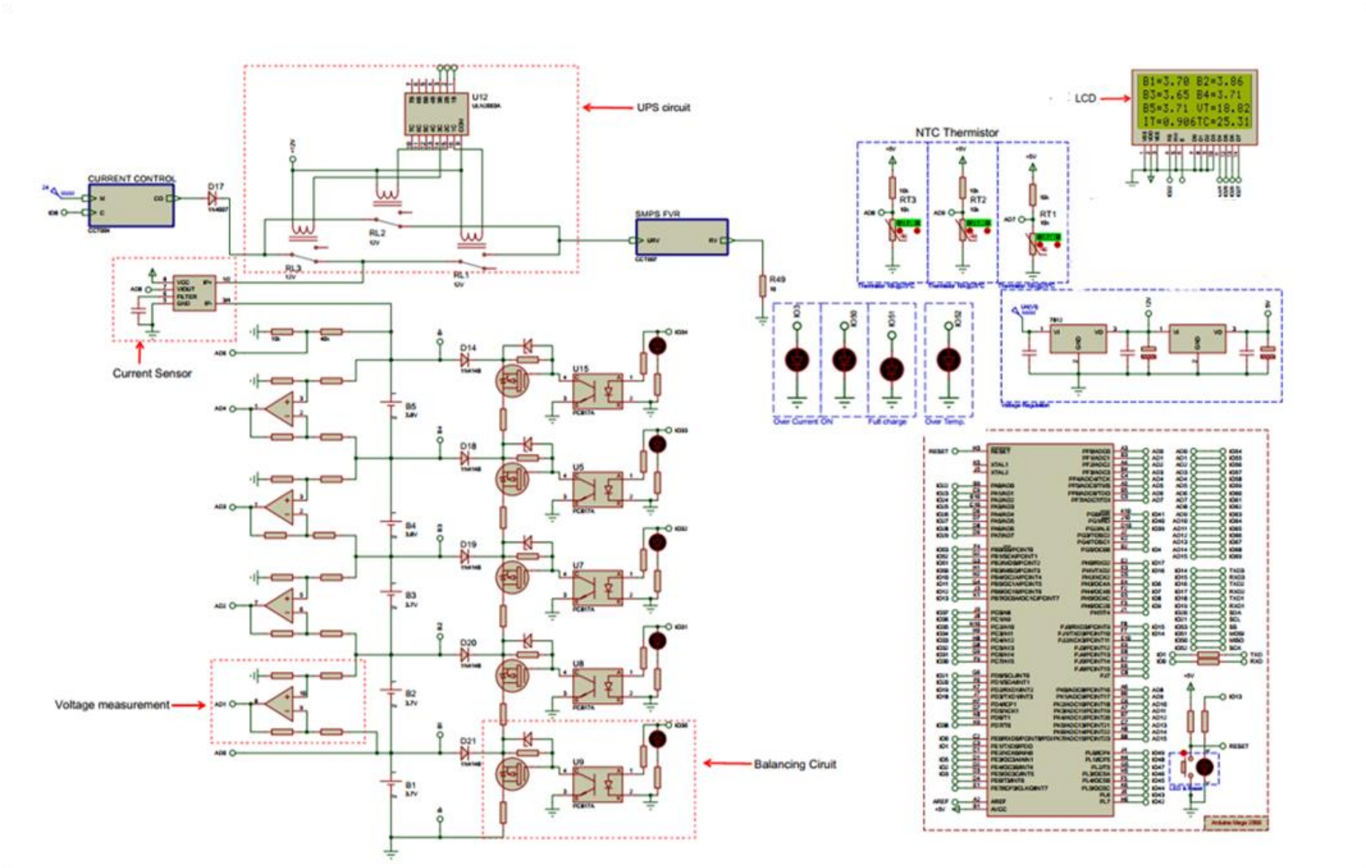


Fig. 3 The Proposed BMS circuitry

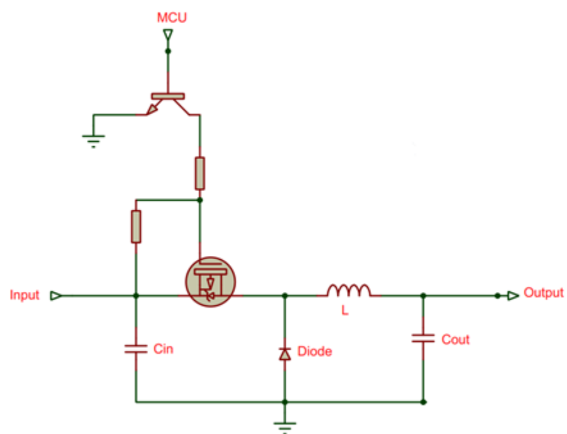


Fig. 4 The Buck Converter

5. Software Controlling Algorithms

The BMS software design is essentially based on protective algorithms, as shown in the flowchart in Fig.4. After the system is initialized, it adopts the charging or the discharging algorithm based on the primary sources' availability and the load. Moreover, it can charge and supply the load simultaneously, thanks to the adopted UPS controller. The three main algorithms that are responsible for managing the system are called initialization, charging, and discharging algorithms. A brief description of these algorithms is listed in the following sections:

5.1. Initializing Algorithm

The initializing algorithm can be concluded in the following steps:

- Checks all the sensors including voltage, current, and temperature sensors, then sets a warning if there are any faults.
- Measure the batteries' initial SoC to be used later in the other algorithms.

- Measure the batteries' initial temperature. If the temperature is not in the allowable limit for the battery operation, the system will not start.
- Checks the main source availability to be used later in the other algorithms.
- By default, the system will connect the battery to the load. The reason for that is to detect the load availability by detecting the current.
- Suppose a current is detected and the source is available. In that case, the system will connect the load directly to the source by energizing it and adopting the charging algorithm. Otherwise, it will keep supplying the load with power by adopting the discharge algorithm.
- Monitor cell voltage, current, and temperature. Then they are compared with the values assigned to them.
- According to the specified values, a decision is progressed to continue or stop discharging and start charging.

5.2. Charging Algorithm

This algorithm is responsible for charging the batteries safely. Its duties can be concluded in the following steps:

- Energized the source to battery relay to start the charging process.
- Keep monitoring the batteries' temperature and make sure the charging process within the allowable operation limit.
- Monitoring the voltage of every single cell and controlling the balancing system as required.
- According to the battery SoC, the system selects the suitable charging mode as recommended by the manufacturer.
- For the lithium-ion battery, the charging process has three stages. At the first stage, a 1C constant current is used when SoC $\leq$80%. While in the second stage a constant voltage mode is used for the rest of the charging process. Finally, in the last stage, the system will compensate the voltage and delivers it to the permitted limit with a low current, approximately 0.1C, and this is called the floating mode.

5.3. Discharging Algorithm

The lithium-ion battery and the other types of batteries had a limited amount of cycles. Besides that, the manufacturers recommend a specific level for the deep of discharge DoD. Moreover, it is highly recommended to keep the operating temperature within the operating temperature. The discharging algorithm adopts the following steps to manage all of these recommendations:

- Checks if the main source is available to avoid excessive battery discharge and deliver the power to the load directly from the source by energizing the source to load relay.
- Keep detecting the load current, and if there is no load, the system will go to sleep mode to save the power consumed by the system itself.
- Make sure that all the cells temperature is within the recommended limit. Otherwise, the system will shut down to protect the batteries.
- It simultaneously measures the delivered current to ensure that it is within the allowable limits.
- Measure the depth of discharge to ensure it did not discharge below the allowable limit.

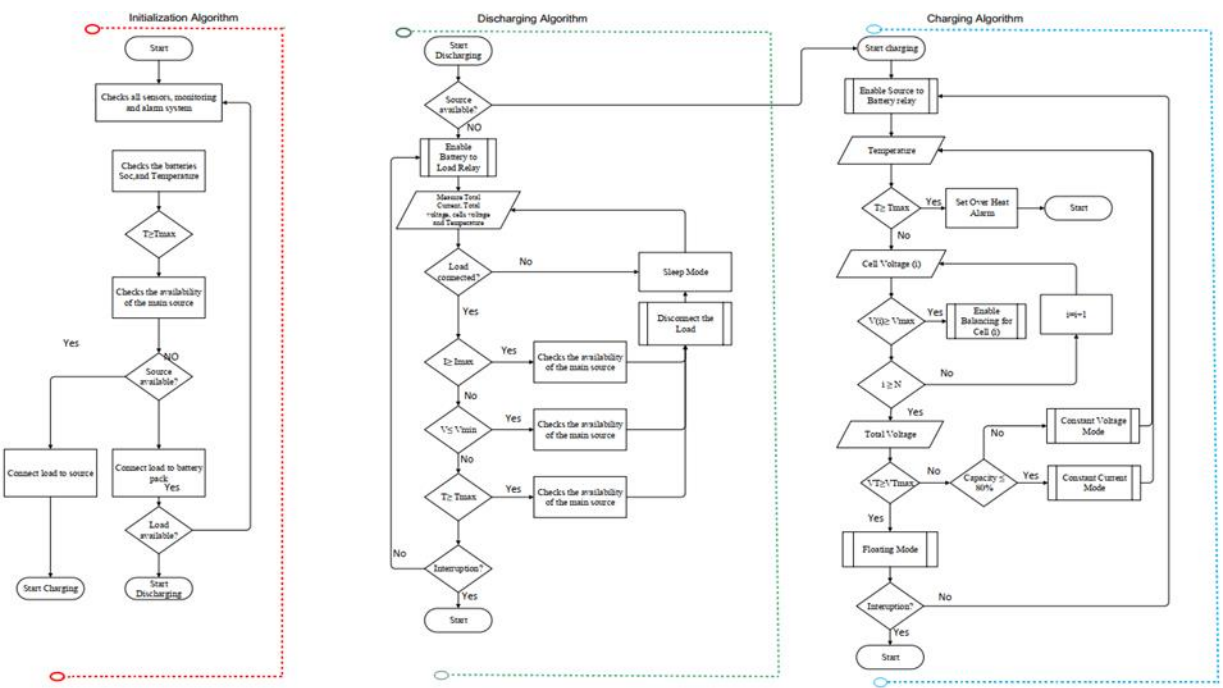


Fig. 5 Flowchart for the software management strategy

6. Results and Discussion

The BMS design was simulated in Proteus software; Simulation results will be presented and discussed in this section. All the proposed system feature will be described briefly in the following sub-sections:

6.1. Over Charge Protection Test

To allow charging, the battery pack was supplied from a DC source. All cell's voltage was specific, such as $V_{cell\ 1} = 2.5V$, $V_{cell\ 2} = 3V$, $V_{cell\ 3} = 3.91V$,$V_{cell\ 4} = 2.25V$, and $V_{cell\ 5} = 1.2V$. These four cells' voltages are increased during the charging process, as well as for the other cell is stored at the reference balance voltage by dissolving energy (overcharge) through to the resistance and internal resistor of the MOSFET. At this point, when the maximum voltage $V_{max} = 4.2V$ was reached, the BMS system began the passive balancing process for each cell. This strategy is shown by overvoltage protection in Fig. 6a.

6.2. Deep discharge protection

This test was established to present the BMS system's ability to protect the batteries from deep discharging. The cells' voltages are monitored during the discharging process until any cell reaches the minimum voltage $V_{min} = 3V$, the discharge process is stopped, as illustrated in Fig. 6b.

6.3. Overtemperature Protection

The protection of the cells from over temperature through the charging and the discharging is presented in Fig. 5c. The system monitors the cells temperature via NTCs planted in the battery pack, usually there are three sensors, in the first cell, the middle cell, and the last cell. If any of these sensors measure 60℃, the system will stop the charging or discharging process immediately.

6.4. The UPS Response and Load Management

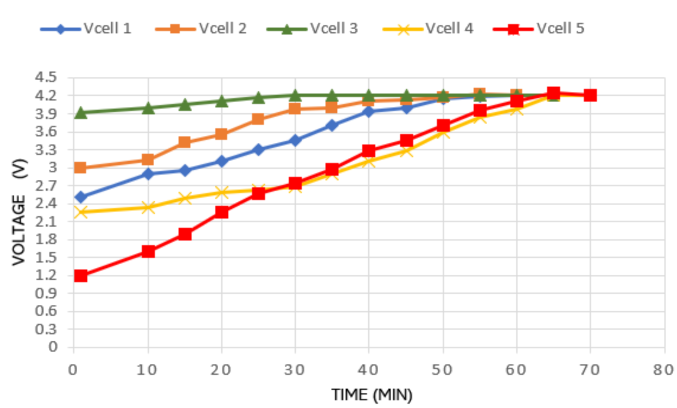
Unlike most of the battery pack, this system is designed to charge the battery and bypass the power from the source to the load simultaneously, thanks to the adopted UPS. Two buck convertors are responsible for these processes. The first DC-DC buck convertor is laying between the source and the batteries. It has a regulated output controlled by the microcontroller and works as a VCCS. As the BMS controlling the charging current via the delivered PWM signal to this DC-DC Convertor. The second DC-DC buck convertor is at the output stage. It is responsible for supplying the load with a regulated voltage within the allowable limits for the batteries, or the supply voltages. Fig. 6d shows the output voltage of the system and the battery voltage vs time.

6.5. The charge Process

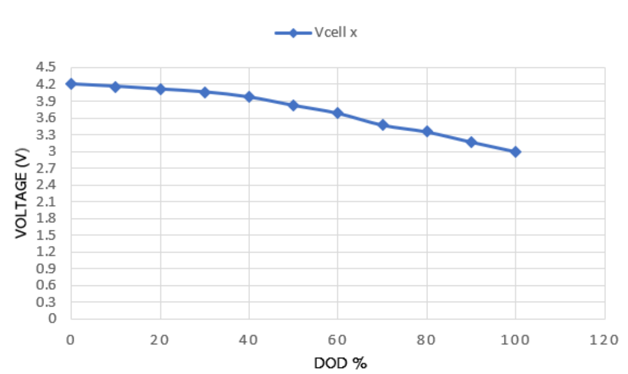
In the test, all three charging stages are presented. Fig. 6e shows these stages, where it starts at fast charging until the SoC reaches 80%. The fast charge is accomplished by charging the battery at a constant current. In the second stage, with constant voltage, the charging current is reduced until it reaches 100% SoC. Finally, the floating stage is adopted to compensate for the SoC degradation due to the battery shunt resistance.

6.6. The discharge Process Mode

Fig .6f illustrates the discharge mode. The results show that the system supplies the load with a fixed power as the battery voltage decreases, the supplied current increase. The system will keep discharging until it reaches the specified deep of discharge recommended by the manufacturer. This discharge process may interrupt if the batteries supply current or the temperature exceeds the normal operating limits.



(a)



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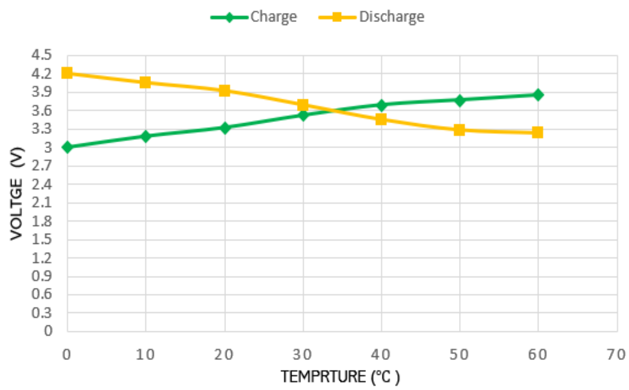
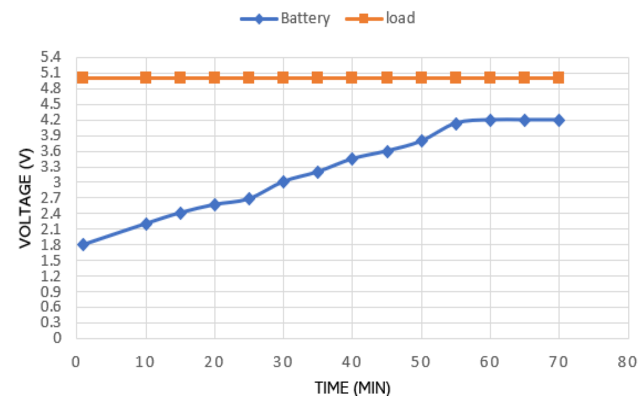
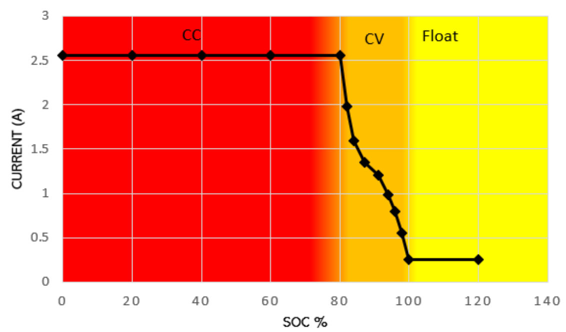
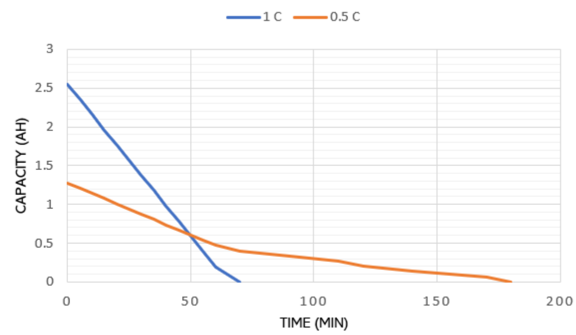




(c)

(d)





(e)

(f)

Fig. 6 The system results, a) Overcharge protection, b) Deep discharge protection, c) Overtemperature protection, d) The UPS response, e) The Charge process mode, and f) Discharge process mode

7. Conclusion

This article presents a BMS system with features that meet all the recommendations by the manufacturer of the Li-ion battery. A 5S-1P Li-ion batteries string is simulated with Proteus software. An Arduino Mega 2560 used as the main controller, is responsible for managing all the hardware and the software algorithms in the system. The simulated prototype results presented power resistors and power MOSFET as central components to disintegrate energy deficit for fast balancing of five series-connected Li-ion cells. The simulation results for particular discharge/charging tests confirmed that the proposed BMS could control the cell's voltages according to the datasheet's rated value. The critical downside of passive balancing is that the power resistors and MOSFET convert the excess energy into an amount of heat, so the function point's productivity is low. While using active cell balancing can solve the heat and low-efficiency problems but with increased difficulty and increased cost of balancing circuits and DC-DC converters. The proposed BMS's key benefit is that the balance time is many times shorter than the presently offered BMS. They also include another attribute. They were also presented in the outcome section, specifically over-discharge protection and overheating protection. The used fast charging mode shows a preference over typical charging methods because it shortens charging time and preserves battery life. The relays utilized in the UPS circuit proved efficiency in operating and switching between the charging and discharge processes. The UPS delivers power to load in all conditions.

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