Design of Master and Slave Modules on Battery Management System for Electric Vehicles

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***Abstract*— Nowadays, electric vehicle usage and the use of LiFePO4 batteries in electric vehicles gradually increase. However, there are important features to be considered to use these batteries safely and efficiently. Incorrect use of these batteries can lead to burning, explosion or shortening of the life of batteries.**

In this paper, a Battery Management System (BMS) for lithium based batteries is designed that operates more efficiently and communicates with UART between master and slave modules and can communicate via CAN protocol with external devices. Micro controller based control and protection equipment is designed that help to measure and monitor the voltage, temperature and current values of the batteries. They protect the battery cells from the conditions such as over charge, over discharge, high current, high temperature. BMS balances battery cell voltages during charging process with passive cell voltage balancing. In addition to the main controller module in the BMS, slave controller modules have been added to provide high resolution voltage and temperature tracking. A modular BMS has been devised which can be used in groups of batteries of different voltage values thanks to electrically isolated slave control modules.

***Keywords*— Battery management system, battery monitoring, cell balancing, LiFePO4 batteries, electric vehicle**

I. Introduction

LiFePO4 batteries are a type of rechargeable battery that does not contain toxic substances, have high temperature stability and long cycle life. The energy density is higher than the lead acid battery. For these reasons, it has been increasingly used in electric vehicles and backup power sources in recent years. However, the batteries have important features and sensitivities to be aware of when charging or discharging. Battery cell voltage, current and temperature values must be kept within the safe zone and should be monitored continuously for this purpose so that the batteries are not damaged and can be used safely.

The battery management system (BMS) is the entirety of the hardware and software system used to make batteries safer and more efficient [1],[2]. It is a system that manages the charging and discharging processes by reading important values such as temperature, voltage and current of the battery cells [3]. Therefore, in the literature there are application-based studies which can be used in real-time applications and theoretical based studies aimed at achieving higher efficiency.

BMSs are often used with battery operated industrial, commercial devices and systems to monitor batteries more efficiently, safely. For this purpose, in [4] they proposed a new method of designing a reliable and generalized BMS that describes existing BMS techniques. In [5] the researchers conducted a study on BMSs in electric and hybrid vehicles. In this study, the latest developments in battery technology are reviewed and the challenges in BMS systems are presented and possible solution proposals are given. Gold categorized BMSs according to their different functionalities [6]. When the studies in the literature are examined, it is seen that the designed BMS are not modular and can fulfill the duties for a certain number of battery cells such as 7 [7], 22 [8], and 36 [9]. In addition to protection and monitoring, another important feature that BMS should have is balancing the voltages of the battery cells during charging. If there is no balancing, it is possible that other cells cannot be fully charged due to a cell reaching overvoltage and causing the high voltage protection. The most common of the balancing methods is the passive balancing, which is based on discharging the overcharged cell with a resistor. This method is preferred because of easy implementation and low cost.

In this study, for LiFePO4 batteries, slave and main controller system was designed and realized with a real monitoring system. The BMS, which can be used in high voltage batteries, is designed consisting of a group of electrically insulated slave control modules and a main control module. Thanks to this modular system, voltage and temperature values can be read in 12 bit resolution in high voltage applications. This system was developed and tested in an electric vehicle with 32 LiFePO4 battery cells that has 36Ah capacity. The results and design characteristics obtained with this study are presented in this publication.

This publication is structured as follows; In the first part, an introduction to the subject is given and the literature information is shared. In the second part, the characteristics of the BMS system and the tasks that need to be fulfilled are mentioned. Section III describes the design of the BMS system and the obtained results are presented in Section IV. Finally, a general evaluation has been made in Section V.

II. Battery Management System and Duties of It

A. $LiFePO_4$ Battery

Batteries are the main energy source for electric and hybrid vehicles and their performance also affects vehicle performance. In battery selection, many factors need to be considered such as; low internal resistance, no memory effect, fast charge, high level safety, high energy density, high power density, long life, high charge-discharge efficiency, high reliability in cyclical use, low cost, and the ability to be subjected to recycling processes [10].

Lithium-based batteries are preferred due to their light weight, high energy density and lack of memory effect. In addition, the safety risks of the batteries selected for use in vehicles must be as low as possible. Due to the chemical structure of $LiFePO_4$ batteries, thermal stability is better than other lithium based batteries. For these reasons, $LiFePO_4$ battery cells, a preferred battery for safety reasons, are preferred in this study. The technical characteristics of the battery cell are given in Table I.

TABLE I
Some Technical Characteristics of Used WN36AH $LiFePO_4$ Battery.

Nominal Voltage	3,2 V
Nominal Capacity	36 A
Max. Cell Voltage	3,8 V
Min. Cell Voltage	2,5 V
Operating Voltage Interval	2,8 - 3,7 V
Internal Resistance	<2 mΩ
Cycle Life	>2000
Weight	1,3 kg

B. SOC Estimation

The BMS calculates how much energy is left in the battery by looking at the voltage, current, and temperature of the batteries. Important information such as how many kilometers the car can go for electric car application and how many more hours of energy it can provide for backup power supply applications is calculated by the BMS circuits. The ratio of the instantaneous capacity of the battery to the total capacity, which is called state of charge (SOC), is calculated as a percentage and displayed to the user.

LiFePO4 battery cell nominal voltage is 3.2V. At most of the interval of battery capacity the voltage remains at 3.2V. This feature of LiFePO4 batteries makes it difficult to calculate capacity with voltage. One of the capacity calculation methods is the current counting method. For the capacity calculation algorithm, the current drawn from the charger is collected every second during charging. The sum of current in amperesxhour and the total capacity of the battery can be found. During discharging, the SOC of the battery can be calculated by subtracting the current drawn every second from the battery bank from the total current. Relations related to this method, called the current count, are given in Eq. (1) and (2).

$$q(t) = q_0 + \int I(t).dt \tag{1}$$

$$q_k = q_0 + \Delta t.\sum_k I_k \tag{2}$$

In these methods, it is difficult to precisely determine the remaining capacity of the battery due to reasons such as the loss of PCB materials, the difference of each produced battery cell, the failure to form a definite battery cell model, the chemical characteristics of battery cells vary according to battery age and ambient temperature.

C. Safety and Protection

One of the most important tasks of BMS is to ensure that batteries are used safely. For this reason, the temperature, voltage and current information of the battery should be kept under constant control. If this data goes out of the safe zone, the battery may be damaged. If the necessary precautions do not taken in case of high current or high voltage, the battery cells may become very hot and flame. The basic tasks that should be included in a BMS system in general are described below.

- *Voltage Protection*

During battery charge and discharge operations, the cell voltages must be read continuously to keep the cell voltage values in the safe zone, to detect cell voltage differences and to calculate battery remaining capacity.

The safe zone for the LiFePO4 battery cell voltages is between 2.5 V and 3.7 V. During charging, the cell voltages are read continuously and charging is terminated when the cell voltage reaches the charging voltage maximum limit. During discharge, when the cell voltage reaches the discharge termination voltage of 2.5 V, the load is disconnected from the battery bank and the cell is protected from over discharge. When the cell voltage drops below minimum voltage limit, the maximum capacity value the cell can store can reduce or eliminate.

- *Current Protection*

The limit values of the current to be drawn from the batteries must be considered. The maximum instantaneous current and continuous current that can be drawn from the batteries will vary depending on the battery type and capacity. In the batteries used in this study, the continuous current value is 108 A and the instantaneous current value is 180 A (current that can be drawn for 5 seconds). Batteries may heat up, explode, or reduce their service life if these conditions are exceeded. During charging and discharging, the current value is read continuously. When the current values go out of the safe zone, the BMS circuits separate the charger or load from the battery pack.

- *Temperature Protection*

The overheating of the batteries can cause the chemical bonds in the cell to break. This can cause the batteries to lose their life, deteriorate or explode. Since the chemical structure of $LiFePO_4$ batteries is predominantly iron, thermal stability is higher than other lithium batteries. The Fe - P - O bond in the chemical structure of LiFePO4 batteries is stronger than the chemical bonds in other lithium batteries. $LiCoO_2$ batteries have a high temperature explosion limit of 175ºC while $LiFePO_4$ batteries have an explosion limit of 250ºC. The temperature value for efficient use during discharge is between -20 and +45 degrees. During charging, the temperature should be between 0 and 45 degrees.

The battery temperature is read continuously during charging and discharging in the BMS cycle and the user is warned in critical situations. The charging unit or load is separated from the battery pack if necessary. At the same time, the Voltage-Capacity curve changes according to the temperature value. Therefore, the battery cell temperature and the battery cell temperature are also taken into account when calculating the remaining capacity of the battery.

- *Voltage Balance*

Cell voltage balancing is a process in which a lot of cells are taken care of while charging the battery. When the battery voltage reaches the upper limit, charging stops. The internal resistance of the battery cell may vary for each cell. When power is drawn from a series of connected battery packs, the energy consumed on each battery cell will be different. In a same way, when the battery pack connected in series is charged, the stored energy will be different. In this case, voltage differences may occur between the batteries during charging and discharging operations. Although there is no problem in total voltage during charging, some of the voltages per cell may have reached the critical voltage level. Therefore, when the batteries are charged, the voltages of all the batteries must be measured separately and the battery voltages should be balanced when necessary. If one of the batteries reaches high voltage without reaching the required total voltage level, the charging operation is stopped and the balancing operation is started. The battery with higher voltage is discharged through the discharge resistor until the voltage level returns to normal. When voltage level reaches the same level as other cells, balancing is stopped and charging is continued. As shown in Fig. 1, the battery cell with excessive voltage is discharged by the passive balancing method and the voltage level is reduced. If the voltage of Bat2 cell is higher than Bat1 cell, SW2 is turned off and excess energy is wasted on Discharge Resistor2 equalizing resistor. This process continues until the voltage levels are equalized.

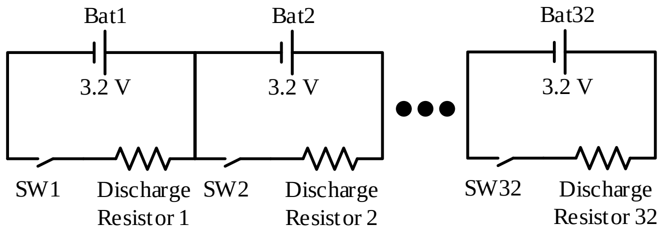


Fig. 1 Passive balancing method connection diagram

III. Design of BMS System in Electrical Vehicle

The BMS is designed and implemented as part of ALATAY-EV project that is a fully electric vehicle prototype for the urban use.

The vehicle's supply unit consists of 32 LiFePO4 battery cells with a capacity of 36Ah connected in series and the DC bus voltage is 102.4V. The BMS for this battery module is designed and manufactured.

Because of the high number of batteries in this high voltage application, instead of a centralized system, a system is designed in which the slave controller modules and the master controller module that controls these modules work together as shown in Fig. 2. Thus, a BMS is installed which is highly efficient and easy to install in battery pack. Battery cell voltages and temperature values can be read at high resolution. General topology of proposed BMS system is illustrated in Fig. 2.

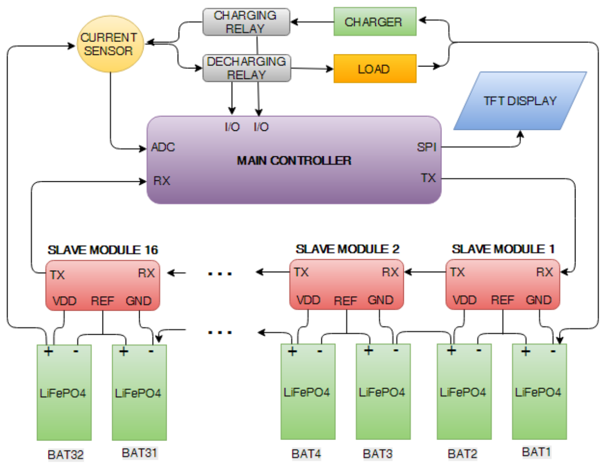


Fig. 2 General topology of proposed BMS system

A. *Slave Module Design*

Slave controller modules are auxiliary cards that read the current, temperature, and voltage values of the batteries they are connected to and send this data to master module, perform management processing commands such as balancing from the master controller. Application circuit block diagram of the slave modules are illustrated in Fig. 3.

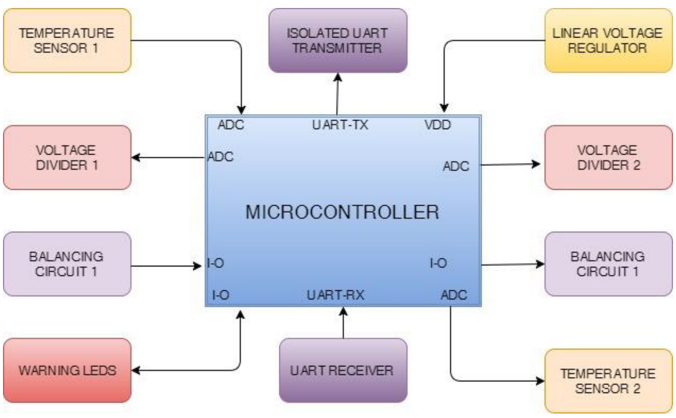


Fig. 3 Slave module block diagram

The slave controller card is connected to two battery cells and receives the energy required for operation from these battery cells. It has two temperature sensors, voltage divider circuits, voltage balancing circuits, user warning LEDs and electrically isolated communication circuits. Completed slave module design can be seen from the Fig. 4. Voltage balancing can be performed up to 2A using a 5W stone resistance. Balance current can be adjusted between 0A and 2A with balancing of PWM equipment. In the event of increased temperature or precise balancing, the duty cycle can be reduced by reducing the duty ratio of the PWM.

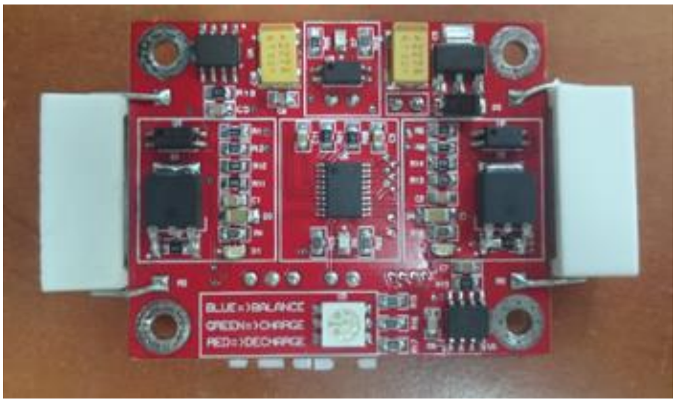


Fig. 4 Designed BMS slave module

B. *Master Module Design*

The main controller module is the card that evaluates the current, temperature and voltage information coming from the slave module and carries out the operations of the BMS. The master module sorts the information of temperature and voltage from the slave module from the largest to the smallest and takes the average of them. The controller marks the battery cells that are at critical values. Master module decides whether to start or stop balancing and charging and calculates and displays the remaining battery capacity. Protect the batteries from being overcharged or over discharged by loading or disconnecting the battery when necessary. The main controller module block diagram can be seen from the Fig. 5.

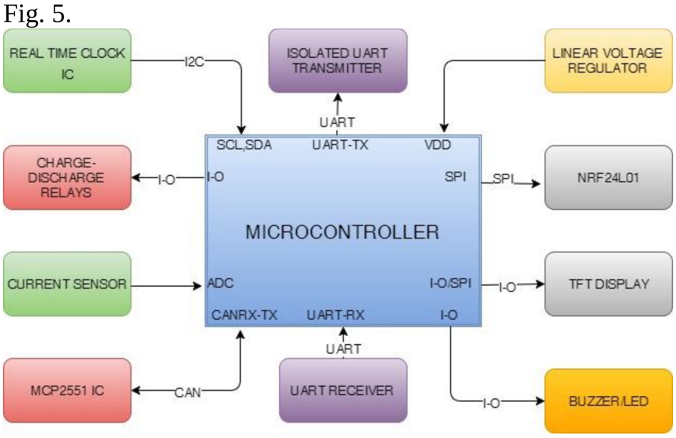


Fig. 5 Main controller module block diagram

Fig. 6 shows the control flow diagram of the main controller circuit. When the BMS system is turned on, initial settings for the microcontroller are made. After this, the main controller sends the initial communication signal to the slave modules to receive the battery data required for the BMS operations. Then, by evaluating the data coming from the slave module card, it finds the data such as the highest and lowest battery cell, the highest and lowest temperature value, the total voltage value and decides the BMS commands.

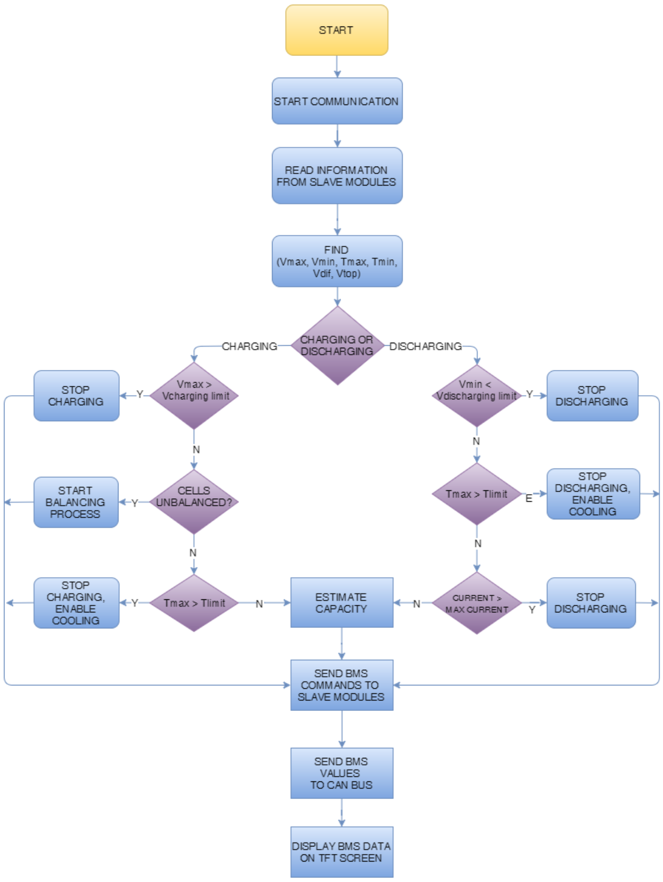
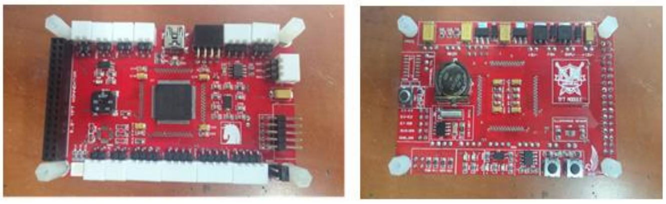


Fig. 6 Flow chart of the main controller

In the main controller system; if the highest voltage of the battery cells reaches the upper limit of 3.7V during the charging process, the charging relay is opened and charging is stopped. Likewise, if the battery temperature reaches the upper temperature limit, the charging process must be stopped again to avoid battery failures.

The master card compares the voltage values of all the battery cells and calculates the voltage difference between the cells. If the difference value of cell voltages is more than 0.1V, battery cells with higher voltage are discharged by passive voltage balancing method. The balance process continues until all the battery cell voltages are balanced. Once all cell voltage levels are equal, the system will start charging again.

If the voltage of the battery cell with the lowest voltage level during discharge is less than the lower discharge limit of 2.5V, the load relay is opened and the battery is protected from over discharge. If the current drawn from the battery pack is greater than the instantaneous current value or if the temperature of the battery pack reaches the upper temperature limit, the load is separated from the battery pack and the user is notified with the sound and visual warning.The final version of the main module is shown in Fig. 7.



(a) (b)

Fig. 7 BMS main module with a) front face, b) rear face

C. *Communication and Monitoring*

The communication between the slave controller modules and the main controller module is carried out by the UART communication protocol. Slave controller modules receive their energy from the battery cells they are connected to. This creates voltage reference differences between the series-connected modules. The slave and main controller modules must be electrically isolated from each other for communication. The BMS circuits are isolated from each other by using the optical isolator integration at the slave controller module communication output.

In addition to the BMS is connected to the CAN BUS communication network and sends important battery data such as maximum and minimum voltage, current and SOC to the in-vehicle display screen, motor drive circuits and on board charging unit. After these operations, the BMS sends the necessary commands to the slave module. All of these BMS data are displayed on the TFT display of the user interface.

A 3.2-inch TFT screen is placed on the main controller module so that all battery information can be displayed on a single screen. This screen shows all the battery cell voltages and which of these battery cells has the highest or lowest voltage value. When the BMS enters the sleep mode, the TFT backlight can be turned off to save energy.

IV. Implementation Results and Discussions

A BMS design that can be used in both low voltage and high voltage battery groups has been made with master and slave controller card designs. Because the two circuits are very close to the battery cells, the cable length connecting the circuits to the battery cells is very shortened. At this point, cable losses are prevented to cause problems in reading analog data. Thanks to the modular design, mounting of the BMS circuits on the battery is facilitated. The use of the isolated UART protocol in serially connected slave controllers allows communication between modules with different references. With this communication method, all the battery data can be transmitted smoothly to the main controller module.

One of the important features of the design is its ability to be used in battery groups with different specifications. As shown in Fig. 8, the properties of the battery cells can be entered via a setup screen.

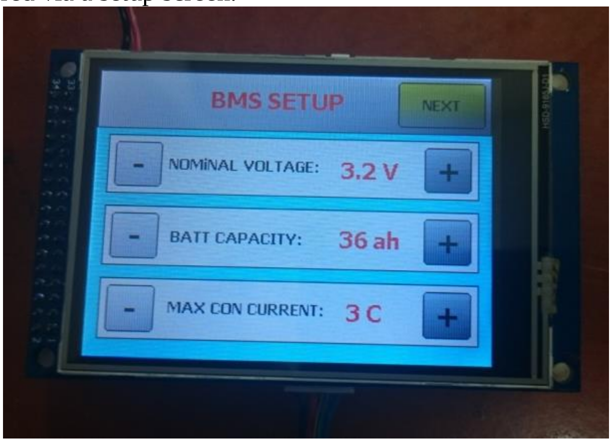


Fig. 8 BMS module setup screen

Besides, many information (nominal voltage, battery capacity, temperature values etc.) and status of the battery can be read through the created graphic screens. Some screenshots of the BMS module are given in Fig. 9.

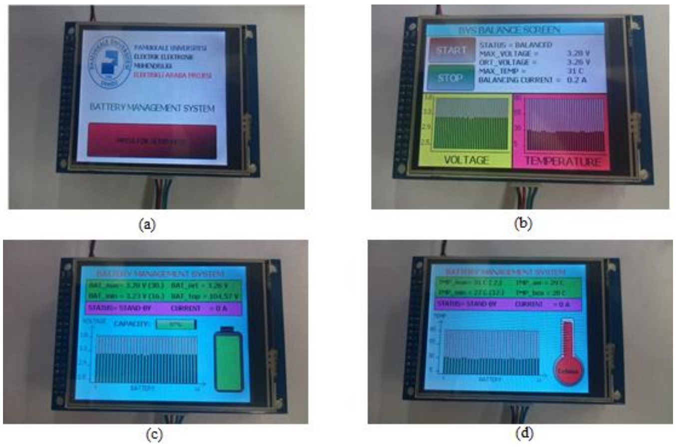


Fig. 9 BMS main module screenshots a)BMS startup screen, b)BMS balance screen, c)BMS voltage monitoring screen, d)BMS temperature monitoring screen.

The designed BMS box provides short circuit protection for both the battery and the BMS circuits. The protection box simplifies the installation of the entire system into the electric vehicle by keeping together elements such as controller circuits, current sensor, circuit breakers and display screen used in the BMS system. It is also understood that it is very important to use this box because it protect components from dust and external impacts. With the cooling fans mounted on the battery box, the battery cooling process can be done easily during the battery voltage balancing process. The designed battery module and the BMS system are shown in Fig. 10.

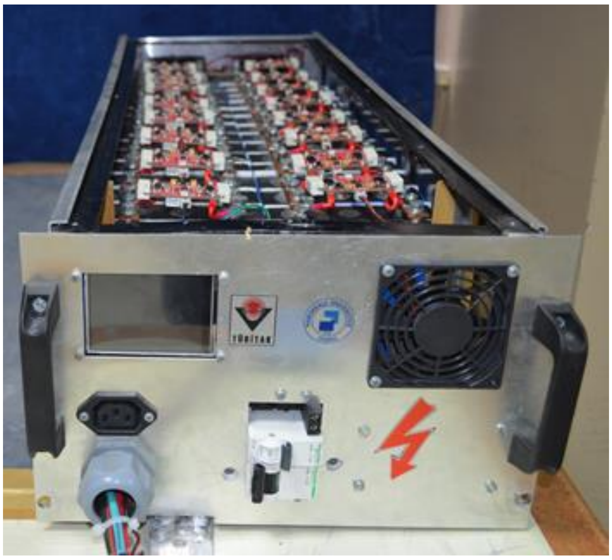


Fig. 10 Designed and manufactured battery system

V. Conclusions

In this work, a modular BMS for electric vehicle is designed to help and measure the voltage, temperature and current values of the batteries. The designed BMS consists of a main controller and slave modules connected to it. Thus, a modular BMS system is designed to be used in applications with different numbers of battery cells. This BMS operates more efficiently and communicates with UART between master and slave modules and communicate via CAN with external devices. The BMS protect the battery from conditions such as over charge, over discharge, high current, high temperature. BMS balances battery cell voltages during charging process with passive cell voltage balancing.

Designed BMS has been tested on 32 serially connected LiFePO4 battery cells which are used in the international ALATAY-EV project. Successful results have been achieved in this application.

Acknowledgment

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