

Swappable Battery Management System (BMS) For Light Electrical Vehicles (LEVs)

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Abstract - As the use of Light Electric Vehicles continues to grow, there are increasing requirements for energy-efficient solutions and quick battery charging time frames. This paper will present our proposed Battery Management System (BMS) Solution. Through our proposed BMS Solution we will achieve fast battery swaps, and reduce the total amount of idle time for these vehicles. Through the use of our BMS Solution, voltage, current, temperature and state-of-charge (SOC) can be accurately monitored to provide for safe and efficient operation. In addition, our BMS Solution provides over-charging, over-discharge and over-temperature protection. Our proposed BMS Solution is modular and supports the fast swap out of battery packs; as different battery packs can be used with our proposed BMS Solution. Lastly, there is also a capability to monitor the battery swap process over the internet through an online interface provided by our proposed BMS Solution.

Keywords – Swappable Battery Technology, Battery Management System, Relay Switch Network, Lithium-ion Batteries, State Of Charge, Thermal Management.

I. Introduction

1.1 Overview

Electric vehicles (EVs) have gained much popularity as an eco-friendly means of transport, and their battery pack acts as the energy storage component affecting performance, range, and recharge capacity. But conventional battery pack design is characterized by certain drawbacks such as insufficient range, long time to charge batteries, gradual loss in battery capacity over time, and inflexibility in operation. For this purpose, Reconfigurable and Swappable Battery Pack (RSBD) design has been proposed where there will be reconfiguration of battery cells coupled with battery swapping capability, which helps in maximizing energy efficiency and usability of the whole system.

1.2 Motivation

Electric Vehicles (EVs) are becoming more and more popular because they can help reduce reliance on non-renewable energy resources and lower the environmental impact of them. However, there are still a number of limitations with traditional batteries that affect the overall performance and convenience of electric vehicles. The limitations are due to long charge time, restricted mileage on an electric vehicle, and the challenge of replacing and repairing battery cells. Because of these reasons, it is clear that innovative solutions are needed to improve battery performance for future electric vehicle use. One possible solution could be to implement a Reconfigurable Swappable Battery System that offers dynamic battery cell configurations and allows for quick exchange of batteries. This type of system could provide better energy efficiency, improved battery performance, no downtime associated with charging, easier battery replacement and repair, and scalable solutions for all types of electric vehicles. An integral component of this type of system is a sophisticated Battery Management System (BMS) that monitors the condition of each battery cell continuously by measuring the voltage, current, and temperature to

ensure that no batteries are overcharged or undercharged or experience heat related issues, while also ensuring that they are effectively charged back up again before being removed and replaced. This will ensure the efficiency of the battery in question. Finally, this will create room for compatibility with different architectures for electric vehicles. Therefore, it is apparent that such a design is feasible. To sum up, the above-discussed design has several advantages regarding the performance of batteries.

II. Literature Review

Research has grown significantly in recent years concerning the development of Electric Vehicles (EVs), including Research on Battery Technologies, Battery Thermal Management, and Battery Power Systems. Battery Swapping Systems (BSS) are now being heavily investigated because of their potential to replace current battery charging methods and have become a popular method for storing energy due to high-energy densities, long cycle life, and very low self-discharge rates. However, the Batteries' Performance has been dependent on and affected by Temperature Ranges, Battery Operating Strategies, as well as System Integration when used with Swappable Battery Technologies. As an example, some of the paramount challenges studied in the literature surrounding the thermal management of Batteries for Two-Wheel Electric Vehicles (EVs) will include the overall size and packaging of compact battery designs. A recent empirical study (2022) that investigated Air Cooling for Battery Thermal Management Systems (BTMS) for Swappable Lithium-Ion (Li-ion) Batteries in Electric Motorcycles provided various configurations for Airflow through the Battery Packaging Systems at different locations of the Inlet(s) and Outlet(s). Finally, maintaining a battery temperature of less than or equal to 35°C greatly increased both the Safety and Performance of the Batteries. Through the use of the air-cooling strategy, the efficiency of the heating system was improved (by as much as 14%) and the distance travelled by the vehicle increased (by as much as 12%). As well as being unique in its method of measuring vehicle range, this study is also unique in its approach to the development of battery packs for two wheeled electric vehicles; it does not reference battery packs used with four wheeled electric vehicles. The use of thermal imaging and thermal patterns on the surface of the battery structure enables the identification of where the majority of heat resides within the battery structure and the movement of heat within the structure [1]. In addition to the increase in popularity of the battery swapping concept as a potential option for reducing charge times and increasing practicality of EVs, IEEE Transactions on Intelligent Transportation Systems conducted a comprehensive review of the BSS through examining BSS operations and decision-making processes. Currently, the BSS architecture can be broken down into four general categories: single-station BSS; multiple-station BSS; integrated charging-swapping stations; and hybrid BSS Systems have distinct properties/abilities depending on the circumstances (e.g., environmental). In addition, there are five separate decision domains associated with BSS development. In addition, there has also been an increase in the acceptance of the battery swap model as an alternative means of decreasing EV charge time and improving the practicality of EVs, leading to a comprehensive review study published in the IEEE Transactions on Intelligent Transportation. The study was designed to evaluate the business operations and decision-making processes associated with BSS. Presently, BSS models can be classified into four categories: 1) one station BSS, 2) multiple station BSS, 3) integrated BSS, and 4) hybrid BSS. These architectures offer varying levels of functionality based on requirements and situations. In addition, there are five decision domains to consider [2]. An additional significant field of research is the incorporation of battery swapping technology into energy storage systems. In particular, a federally funded study done in the United States in 2024 assessed the use of second-life batteries to create a new design framework for a system that enables both to drive electric vehicles and to store energy from those vehicles. This type of design framework uses a combination of series and parallel connections of batteries that are centrally controlled via BMSs, PDUs, and VCU devices; thus eliminating the need for additional equipment, while simplifying and reducing the cost of production. Experimental results demonstrated that real-time current and voltage control could be implemented for multiple battery systems without experiencing problems related to inrush currents or state-of-charge imbalances. Furthermore, the study pointed out the possibilities for prolonging battery life using intelligent techniques and also suggested the possibility to use used batteries in applications related to supporting power grids. Battery lifetime optimization strategy discussed here fits perfectly into the discussion about sustainability and circular economics by ensuring that resources are reused

rather than being wasted. The verification of the suggested method by means of experimental tests on two- and three-wheeled vehicles makes the practical application of such a system more possible [3]. In addition to advancements in batteries themselves and how they work in relation to their control systems, the switching of batteries has drawn much attention from researchers due to its dependability and user satisfaction with the switching process. In a study conducted in 2024, researchers proposed the development of an intelligent control system for battery swap stations and stressed aspects of automation, fault tolerance, and user friendliness for the battery swap stations. This system will be made up of various components that can monitor the entire process of switching batteries in real-time (i.e., battery recognition, alignment of the two batteries for fit, locking the batteries together, and detecting any faults). Sensors will collect data to be supplied to the IoT system, which will provide an analytical capability for the data collected. Additionally, HMI components will provide information to users who are switching their batteries, both with instructional messages as well as providing user feedback. One of the major findings of this study is that by employing redundancy and safety features, the overall system will be made more reliable and reduce the chances of malfunctions. In addition to the technical aspects of this study, there was significant attention given to the human factors associated with the operation of the swapping stations. This study emphasizes the design of an intuitive system with capabilities for automation, which will reduce the amount of human interaction and thus increase the efficiency of the overall system. The results of this study are significant because it represents the first step toward commercializing battery swapping systems[4]. All of these research papers indicate the multidisciplinary nature of the research being done on electric vehicle batteries. In all of these research papers, one of the common aspects discussed is that there needs to be a system-level approach, where all of the individual components, such as the battery, controllers, and infrastructure, work together to optimize performance. The shift from traditional charging systems to battery swap technology presents new issues relating to standardization and interoperability, which demand innovative methods and technologies, including the Internet of Things, artificial intelligence, and digital twin. In addition, the trend towards small-size and modularized battery packs highlights the increasing role of two-wheel and three-wheel electric vehicles in high-density urban centers, especially in emerging markets, where small EVs are more practical and cost-effective[5]. Another important factor that is mentioned in the existing literature is related to decision-making based on big data analysis. The application of big data analysis and real-time control can help to optimize performance in terms of changes in the load, temperature, and battery condition. It is important to take into account that the implementation of decision-making based on big data helps to ensure the reliability and sustainability of the battery system and its operation. Furthermore, the application of machine learning algorithms can be useful in optimizing performance and reducing the probability of equipment failure. Such approaches can be seen as one of the major trends in the development of EV infrastructure in line with Industry 4.0[6]. The idea of using second-life batteries, however, opens up additional possibilities when it comes to improving the sustainable performance of the EV system. With this technology, the life cycle of the batteries will be extended as they can be used in other areas, thereby minimizing environmental impact. Furthermore, these technologies can play a vital role in the integration of alternative energy sources like solar and wind energy since they offer an efficient way to store energy and balance the supply and demand side of the system[7]. Despite advances in battery systems and battery swap stations, many issues remain to be resolved. One such issue is the lack of standardization on batteries and battery communication systems; the lack of standardization is one of many factors hindering the acceptance of these systems; Additionally, the high cost of building and installing new infrastructure and the technical nature of this activity restrict the use of battery swap stations. Solving this problem will require both government regulatory support and joint action of both the academic and industrial sectors. Based on the current studies published to date, it could be concluded that the majority of the literature has focused primarily on the performance and safety of battery swap stations, with most efforts focused on optimization of design and control. Thus, as the market for battery swap stations continues to grow, the market will require the development of new approaches to meet the changing needs. All studies referenced provided valuable information regarding the relationship between the various components of battery swap stations, and highlight the importance of using a holistic approach when designing such systems [8].

III. Control Strategy and Circuit Operation

3.1 Circuit Diagram:

The figure above illustrates a smart swappable battery configuration for Electric Vehicles. This system comprises Li-Ion batteries, a switch matrix controlled by relays, and a Battery Management System, which exchanges information with the EV controller or charging station.

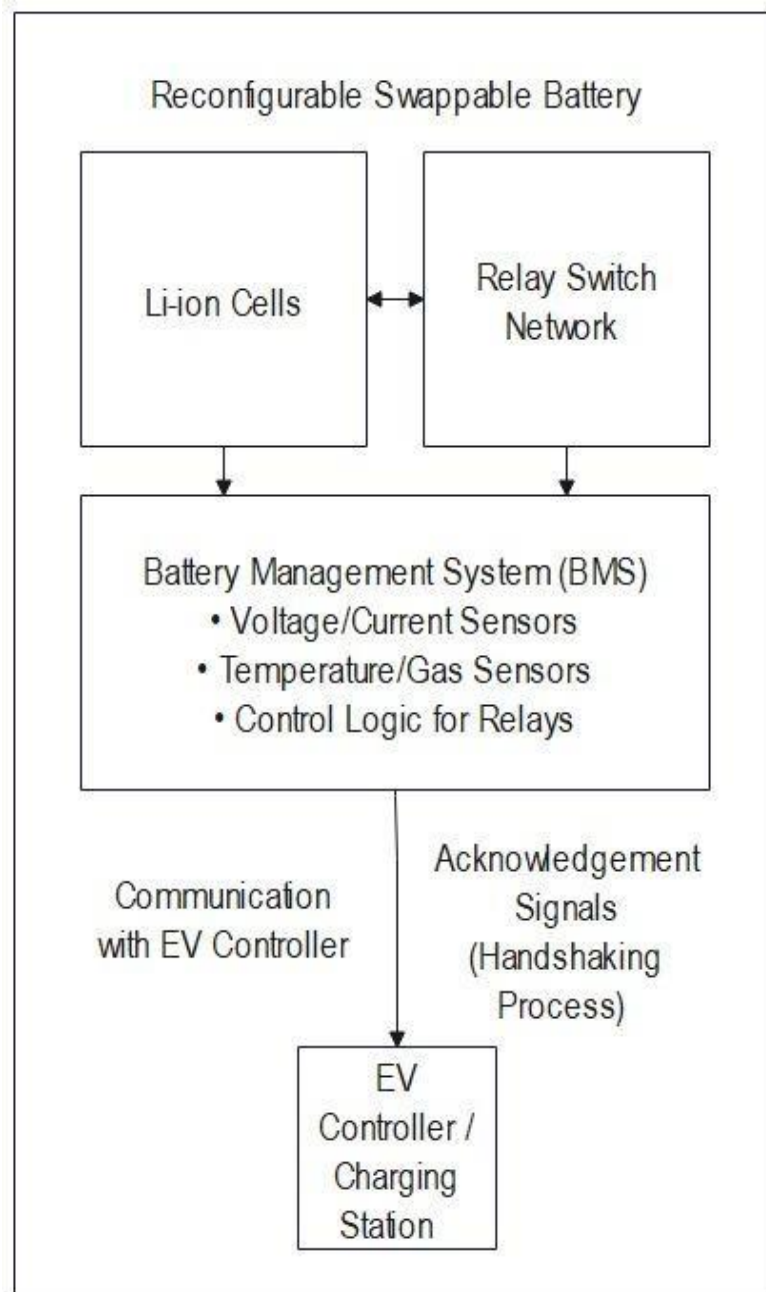


Fig 1: Block Diagram

Li-ion Cells

The individual lithium-ion batteries, integrated together, make up the primary energy storage for the overall system. The lithium-ion batteries can be connected in series or parallel configurations to achieve the voltage and capacity needs of the overall system. In addition, the system is dynamic, allowing for changes in how the lithium-ion batteries are configured based on the current state of the battery or the requirements of the vehicle.

Relay Switch Network

Managing how the lithium-ion batteries in the battery system are interconnected is the responsibility of the relay switch network. Depending on usage, the batteries may be connected in either a series, parallel, or hybrid configuration using relay switches. Relay switch control signals (inputs) come from the Battery Management System, which controls how the relay switch opens and closes circuits in order to maximize the efficiency and reliability of battery usage while also providing the ability to isolate any failed lithium-ion batteries, thus providing a more efficient, reliable, and cost-effective operation.

Battery Management System (BMS)

As a key component of the entire good battery system, the BMS acts as the control centre of the battery so that the whole system may operate at maximum safety and efficiency. The BMS tracks batteries for important information, including individual cell voltages and total current being consumed by the total battery pack; this information helps to maintain a balanced performance of all battery components and avoid the risk of problems. The BMS also guarantees that there are no unsafe conditions within the battery; unsafe operating conditions would include overcharging, deep discharging, and overheating. In addition to maintaining battery protection from unsafe conditions, the BMS facilitates communication between system components and assists in making decisions.

Communication with EV Controller

The BMS communicates with an EV (Electric Vehicle) controller (also referred to as the Vehicle Control Unit or VCU) to provide a linkage between the battery and the controller. The communication between the BMS and the VCU allows for the exchange of critical information such as the state of charge, temperature, and energy capacity of the battery. Additionally, charging and discharging modes will be communicated to the VCU by the BMS to ensure that the vehicle operates within the battery system's parameters.

Acknowledgement Signals (Handshaking Process)

The handshaking procedure is executed when the battery pack is plugged in or substituted to guarantee that the connection is safe and compatible. The procedure includes verifying the voltage level, authenticating the battery module, and synchronizing the BMS with the EV controller. This ensures that there will be no chance of a wrong connection and improves the entire system's safety and reliability.

EV Controller / Charging Station

The EV controller or the charger acts as the control centre of the system, working together with the Battery Management System to control the energy flow inside the system. In the process of charging, it controls the flow of current and voltage, while getting real-time information about the batteries state. On the other hand, during vehicular operations, it distributes energy depending on the demands of the driver and the batteries state.

3.2 System Description

The purpose of this system is to measure and improve the operation of the battery pack made up of many 18650 cells. These cells are arranged in a combination of series and parallel, using a 3S2P layout, giving a nominal voltage around 11.1 volts and a capacity of about 5000mAh. 2 battery packs will be connected to one another using a two - bay installed in the battery rack meeting the standards for both Ola Electric/Tesla/VIDA. In addition to this, there will also be a charging and discharging circuit installed for the purpose of testing how the power is discharged when it's reconfigured into and from this circuit's load, as well as to test power dissipated when charging/discharging at the same time. Included within this electronic system will also be all necessary functionality required by the Battery Management System (BMS) to monitor temperatures within, voltages, current amounts, etc. The BMS will ensure that all critical parameters of the batteries are monitored using a logger device. The loggers will record all essential performance measurements, including State of Health (SOH), State of Charge (SOC), & Internal Resistance.

1 Voltage-Based Reconfiguration

The battery configuration is chosen dynamically depending on the voltage levels that have been recorded to achieve efficient operation, proper use of energy, improve the reliability of the system, and its safe operation.

| Voltage Range | Configuration | Description |
|---------------|---------------|-----------------------|
| 3 – 4.2 V | 1S7P | All cells in parallel |
| 7 – 8.4 V | 2S3P + 1 open | 6 cells used |
| 10 – 12.6 V | 3S2P + 1 open | 6 cells used |
| 14 – 16.8 V | 4S | 4 cells in series |
| 18 – 21 V | 5S | 5 cells in series |
| 22 – 25 V | 6S | 6 cells in series |
| 25 – 30 V | 7S | 7 cells in series |

Table 1: Voltage-Based Dynamic Configuration of Li-ion Battery Pack

2. Safe Switching Mechanism

A method for safe switching is adopted to avoid the possibility of short circuiting that could occur during the process of battery connection change. At first, all the relays are switched off to ensure isolation from any circuit. Then a short time interlock delay of around 100 milliseconds is added before switching on the necessary relays.

Voltage Measurement System

A voltage measuring circuit based on a voltage divider circuit with a combination of 100 kΩ and 9.8 kΩ resistors is used. To ensure high accuracy during the process of measurement, several measurements are made to obtain average data. Further, measures such as noise elimination are used to avoid any fluctuations, which ensures the stability of the readings obtained.

Charging Monitoring Subsystem

The battery charging control subsystem uses a secondary microcontroller to monitor the various parameters during the charging process. The system continuously monitors the reference battery voltage and charging voltage. The current during the charging process is monitored through an ACS712 current sensor. Similarly, the ambient conditions, i.e., temperature and humidity, are monitored by the DHT11 sensor. Through these readings, it is possible to trigger a reset relay under certain conditions.

3.3 Hardware Components:

3.3.1 Batteries Swapable rack:

Designing and developing a universal dual-slot battery rack that would be capable of hosting any of the following lithium-ion batteries: Ola, Tesla, and Vida. The main purpose of having such a rack would be to provide an interface through which different types of batteries will have a common connection point for easy installation and

compatibility with minimal loss of efficiency. The rack is designed to have strong mechanical support for holding the batteries, ensuring there are minimum vibration and stress on them during their use.

Apart from offering strong mechanical support, the rack is also designed with good electrical connections to make sure there are no resistance losses in the flow of electric current from the battery to the system. In addition, there is incorporation of basic temperature management in the battery rack to ensure that there is very less heating of the batteries. Furthermore, the system incorporates user-friendliness and modularity such that batteries can easily be put inside, pulled out, or substituted without having to undergo extensive alterations. This is especially useful when it comes to battery swapping because saving time is crucial at such times. All in all, the suggested system of swappable batteries not only adds to its flexibility but also facilitates interoperability of various battery systems.

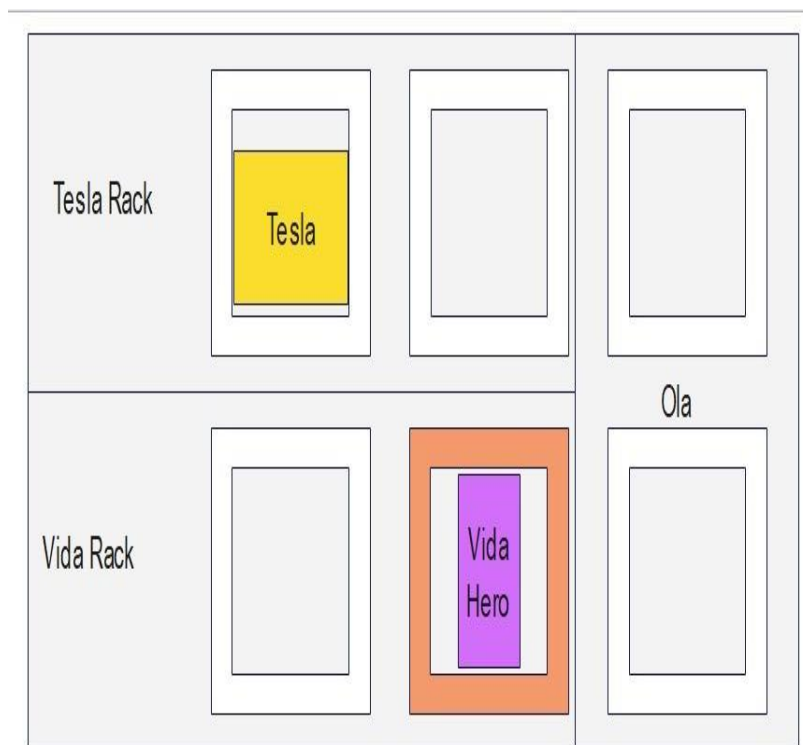


Fig 2: Batteries Swappable rack

| Feature | Specification |
|-------------------|--|
| Rack Capacity | 2 battery modules (swappable) |
| Compatible Brands | Ola Electric, Tesla, Vide Motors |
| Mount Type | Horizontal slide-in slot with lock mechanism |
| Material | 4 mm Mild Steel frame with aluminium base plate and insulation coating |
| Slot Type | Custom adjustable cradle with sliding rails and connector alignment guides |
| Cooling | Forced air (dual axial fans at rear) with vent holes for airflow |

| | |
|----------------------|--|
| System | |
| Protection | Rubber vibration isolators, thermally insulated housing, IP54 casing |
| Electrical Interface | Universal Anderson-type connectors, 200 A rating, with keyed orientation |

Table 2: Specifications of Swappable Battery Rack System

3.4 Analytical & Mathematical Design

3.4.1 Sensors

As for the design of this prototype using 18650 lithium-ion batteries (3.7V/2500mAh), several types of sensors have been implemented in order to constantly monitor the operating conditions of each individual cell in the battery pack. A voltage measuring sensor has been implemented in order to monitor voltages of individual cells as well as voltages of the battery pack as a whole in order to ensure safe operations between 3.0V and 4.2V. In order to prevent overheating and other thermal issues, temperature sensors have been placed in order to detect excessive heat beyond the 60 degrees Celsius. Current measurement has also been performed using the ACS712 current sensor in order to monitor charging and discharging currents.

3.4.2 Experimental Design.

The proposed experimental setup aims at testing and improving the performance of a battery pack that is designed by using reconfigurable battery cells of type 18650. The battery module configuration considered in this case includes a 3S2P connection, which leads to the formation of a nominal voltage of about 11.1V and a capacity of 5000mAh. Two such battery modules have been integrated into a dual-slot battery rack capable of meeting the battery standard of Ola, Tesla, and Vide batteries. The system consists of the battery charging and discharging circuit for the analysis of the battery performance and a load simulator for evaluating the performance during loading and reconfiguration process. The system also includes the battery management system (BMS) that constantly monitors the performance of the battery including its temperature, current, and voltage level. Moreover, a data acquisition system has been designed that would record SOC and internal resistance values of the battery module under consideration.

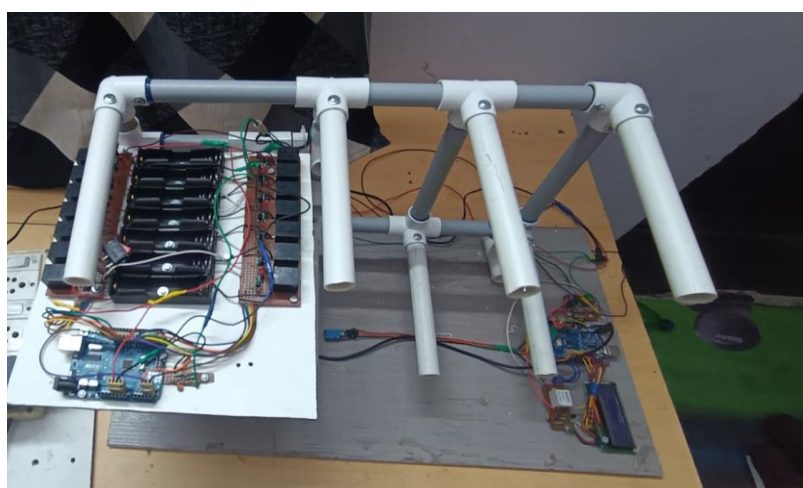


Fig 3: Experimental Setup of Swappable Battery Management System

3.5 Mathematical / Statistical Analysis

To evaluate battery performance, several analytical relationships are derived:

1. Energy Capacity (wh):

$$E = V \times I \times t$$

Where,

$$V = 3.7V \text{ (nominal voltage per cell)} \quad I = 2.5A \text{ (rated capacity)}$$

t = discharge duration (hours)

$$\text{For 1 cell} \rightarrow E = 3.7 \times 2.5 = 9.25 \text{ Wh}$$

For 3S2P configuration \rightarrow 6 cells = $9.25 \times 6 = 55.5$ Wh total energy capacity per module.

Efficiency (η): $\eta = (\text{Output Energy} / \text{Input Energy}) \times 100$

Battery Pack Power Output (P):

$$P = V \times I_{\text{load}}$$

4. Thermal Analysis:

$$Q = I^2 \times R_{\text{internal}} \times t$$

This expression estimates internal heat generation per cell during charging/discharging.

5. Statistical Evaluation:

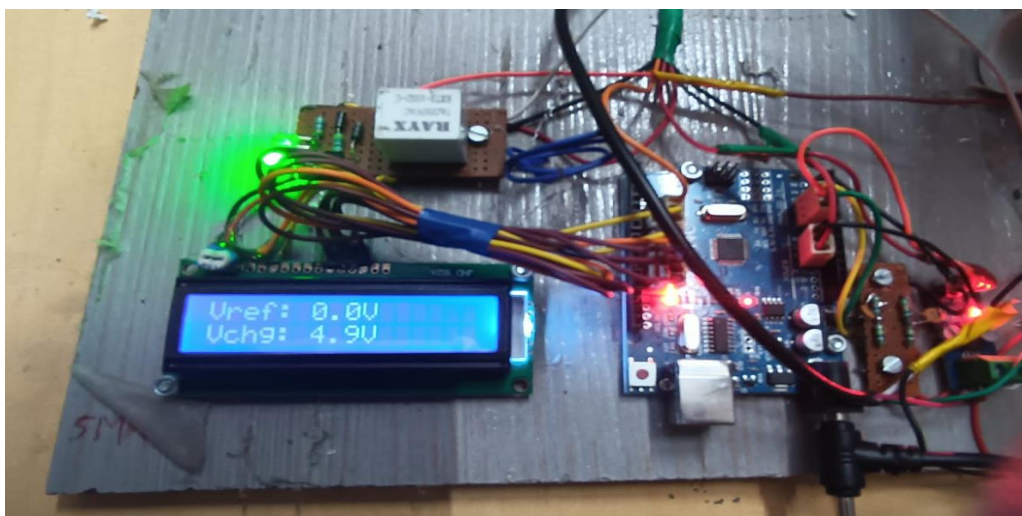
Repeated discharge-charge cycles are analyzed using standard deviation and mean values of temperature and voltage readings: $\sigma = \sqrt{(\sum(x_i - \bar{x})^2 / N)}$

Mean deviation helps assess consistency of cell performance across modules.

These formulas support experimental evaluation, efficiency calculation, and ensure optimal reconfiguration control for maintaining balance and safety in the battery system.

IV. Result and Discussion

4.1 Before swapping



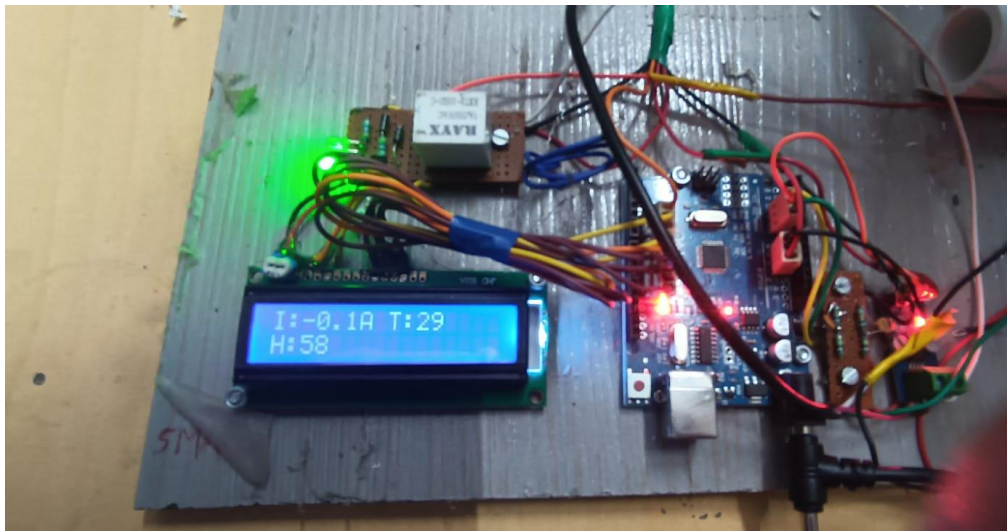


Fig 4: Before swapping

This is when the battery is connected to the charging circuit and disconnected from the load and represents the condition “before swapping.”

- Voltage (V_{ref}): 0.0V
- Charging Voltage (V_{chg}): 4.9–5.0V • Current (I): 0 A (load disconnected)
- Temperature (T): 28–30°C
- Humidity (H): 55–60%
- Relay Status: OFF (relay not energized)

Zero current value shows that no power is drawn by the load and that the battery is safe because it is only connected to the charging circuit and is not drawing any power. Also, the charging voltage confirms the fact that the battery is charged via the charging circuit without any breaks in the connection. Temperature and humidity are within the allowed and safe values and will ensure that battery efficiency remains high during this phase since no thermal damage will occur. Thus, this controlled environment provides a secure and efficient charge phase, increasing battery life span due to lack of stress from the load or possible failures in the circuit. The OFF status of the relay guarantees safety through electrical insulation of the circuits from each other, reducing risks of failure.

4.2 After Swapping

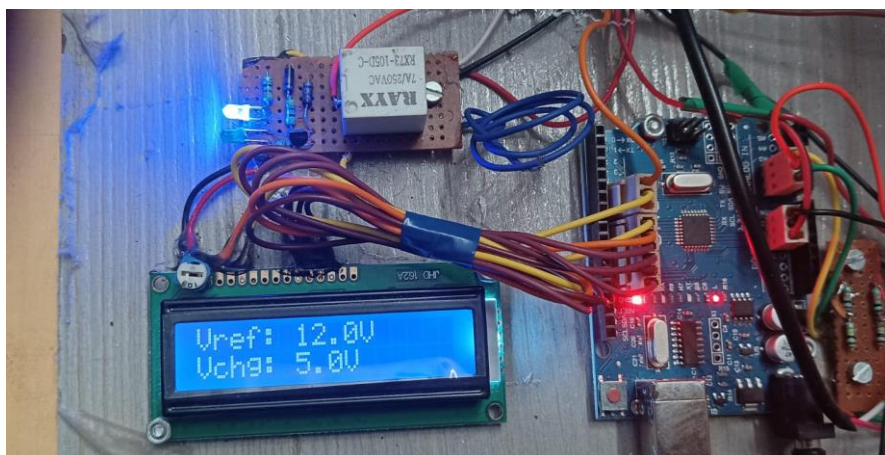




Fig 5: After swapping

In this case, the charged battery is coupled to the load via relay switch-on; this represents after swapping state.

- Voltage (V_{ref}): 11.9 – 12.0V
- Charging Voltage (V_{chg}): Approximately 5.0V
- Current (I): 0.3 – 0.8 A depending on load
- Temperature (T): 29 - 32 °C
- Humidity (H): 55 – 60%
- Relay status: ON

The fact of positive current proves the delivery of energy from the battery to the load. The recorded voltage level proves that the battery is fully charged. Relay is needed to make a connection between the battery and load to ensure safe work of the system.

There is a slight increase in temperature because of the ongoing load work and battery resistance. Temperature values are not critical, which means that the system functions efficiently. The humidity value doesn't change significantly.

Moreover, all the system parameters are monitored online, which allows making sure that there are no failures in energy supply. It will be possible to identify any deviations in voltage, temperature, or current levels.

V. Conclusion

The successful implementation of an EV battery swap and conf. system reflects a functional prototype of the above mentioned features that will automatically change the battery configuration in order to improve power delivery, based on what voltages are present at each connection. A relay switching method was used to allow for a safe and smooth transfer process between the batteries; this function also continuously monitors battery status as well as its environmental surroundings using different parameters (i.e., current, voltage, temperature). Therefore, many of the conditions that might create potentially dangerous situations (such as overcharging, over-discharging, and overheating) can be ruled out. In addition to how data is monitored and reported on, the means for providing a visual representation of the state (as seen by the visual indicator) are in real time.

Additionally, it was found that charging and discharging operations were clearly delineated during observation of the created system: charging operations would have the load disconnected from the battery being charged, and during discharging operations, an established stable source of power would be used.

Additionally, the proposed method has great potential for further application in terms of scalability as a result of being able to increase the battery module size and to provide an overall practical solution for EV usage. Swappable

batteries allow for more flexible use than traditional batteries because they can be swapped out easily and are designed for optimal usage of available energy. Additionally, low-cost microcontrollers and simple circuit designs make the swappable battery management system inexpensive to implement on a larger scale and thus, cost-effective. In conclusion, the swappable battery management system is an innovative solution that allows users to charge their batteries much faster, as well as improve the overall efficiency of the system. The design of the system can also be easily expanded with additional features, creating an even smarter product.

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