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Hybrid energy storage system for fast and efficient electric vehicle charging

Liew Hui Fang[1], Muhammad Izuan Fahmi Romli[1], Rosemizi bin Abd Rahim[2]
[1]Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis (UniMAP), Arau, Malaysia
[2]Faculty of Electronics Engineering and Technology, Universiti Malaysia Perlis (UniMAP), Arau, Malaysia

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ABSTRACT

The rapid adoption of electric vehicles (EVs) necessitates efficient and fast charging solutions to meet growing energy demands. This study introduces a hybrid energy storage system (HESS) designed to enhance EV charging performance. By integrating batteries and supercapacitors, the HESS leverages their complementary characteristics, optimizing energy storage and delivery. The primary problem addressed is the inefficiency and prolonged charging times of conventional EV charging infrastructure. A dynamic control strategy manages power flow between batteries and supercapacitors, significantly reducing charging times and improving system efficiency. This approach reduces battery size and optimizes power quality, utilizing a device with three 18650 lithium-ion batteries and four high-capacity supercapacitors. Simulations using MATLAB/Simulink and Proteus software demonstrate a charging time of 57 minutes for the storage system and 4.74 hours for a full EV battery charge, outperforming traditional methods. This project contributes to the design and implementation of a HESS for EVs, facilitating both efficient and fast charging capabilities.

Corresponding Author:

Liew Hui Fang
Faculty of Electrical Engineering and Technology
Universiti Malaysia Perlis (UniMAP)
Arau, Malaysia
Email: hfliew@unimap.edu.my

1. INTRODUCTION

As Malaysia strives to cut emissions and promote sustainable mobility, electric vehicles (EVs) are gaining significant traction. EV use is increasing, thanks to strong government support, expanded charging infrastructure, and cost reductions. The transition to EVs is widely regarded as a crucial strategy for combating climate change and reducing our reliance on fossil fuels. With zero tailpipe emissions, EVs offer a cleaner and more sustainable alternative to traditional internal combustion engine vehicles. However, despite their environmental benefits, the widespread adoption of EVs faces several challenges, primarily related to charging infrastructure [1]. The environmental benefits of EVs, combined with government programs and incentives, are driving the transition to greener mobility. Malaysia's dedication to creating charging networks addresses range anxiety and promotes long-distance travel.

Furthermore, with fewer running costs and maintenance requirements, EVs have become a popular choice among consumers. Malaysia's electric vehicle market is expected to grow steadily, thanks to a good outlook and a thriving domestic EVs sector [2]. Rapid charging of EVs is a difficult problem due to the considerable power consumption required, putting strain on the electrical system and causing issues with voltage and frequency stability. To address these issues, hybrid energy storage systems (HESS) combining many energy storage methods have been proposed. A popular method is to combine a fast-responding supercapacitor with a high-energy-density battery. While the supercapacitor quickly satisfies the high-power needs during charging, the battery provides the energy needed for a full charge, potentially prolonging battery life by reducing stress during rapid charging [3]–[4]. Another pressing concern with EVs is the lengthy charging time, which can range from 1 to 3 hours. Current charging technologies often struggle to meet the demands of an expanding EV market. Long charging times are a significant deterrent for potential EV buyers, as an inconvenience user and limit the practicality of EVs for long-distance travel. Moreover, the increasing number of EVs putting strain on the electrical grid exacerbates issues related to grid stability and energy supply [5]–[6].

Therefore, fast charging stations provide a solution by allowing for quick recharges without excessive wait times. This not only allows for longer trips and greater freedom for electric car drivers, but it also has the potential to minimize the need for huge, expensive batteries, cutting both vehicle weight and cost [7]. Fast charging is a critical component in the effort to increase electric vehicle adoption and address the practical issues connected with charging [8]. HESS represent a cutting-edge approach in the realm of energy storage, where multiple storage technologies are seamlessly integrated into a unified system. This innovative design aims to leverage the unique strengths of each storage medium while mitigating their individual limitations. By combining various energy storage devices such as batteries, supercapacitors, flywheels, and even unconventional options like compressed air and hydrogen storage, HESS endeavors to create a versatile and robust solution for energy storage needs [9]–[10]. In the context of EVs, HESS plays a pivotal role in revolutionizing the charging infrastructure. By incorporating diverse storage technologies, an EV's charging process can be optimized for both efficiency and speed [11]. For instance, batteries are adept at storing large amounts of energy, while supercapacitors excel in rapid energy discharge. By intelligently managing the flow of energy between these different storage mediums, HESS enables swift and efficient charging of EVs. Moreover, the integration of multiple energy storage devices within an EV charging system enhances its resilience and reliability. In scenarios where one storage medium may falter due to factors like temperature fluctuations or degradation over time, other components can seamlessly compensate, ensuring uninterrupted operation [12]–[13]. This adaptability is particularly crucial in meeting the demanding requirements of electric vehicle charging, where reliability and speed are paramount. Overall, the concept of HESS epitomizes the quest for innovation and efficiency in energy storage technology. By synergistically combining diverse storage technologies, HESS not only enhances the performance of electric vehicle charging systems but also sets a precedent for sustainable and adaptable energy solutions in various other applications.

Thus, the transition to EVs is widely regarded as a crucial strategy for combating climate change and reducing our reliance on fossil fuels. With zero tailpipe emissions, EVs offer a cleaner and more sustainable alternative to traditional internal combustion engine vehicles. However, despite their environmental benefits, the widespread adoption of EVs faces several challenges, primarily related to charging infrastructure. Current charging technologies often struggle to meet the demands of an expanding EV market [14]–[15]. Long charging times are a significant deterrent for potential EV buyers, as they inconvenience users and limit the practicality of EVs for long-distance travel. Moreover, the increasing number of EVs putting strain on the electrical grid exacerbates issues related to grid stability and energy supply. Recognizing these challenges, researchers and engineers have turned their attention to developing innovative solutions to enhance EV charging infrastructure. One such solution is the concept of a HESS. HESS integrates multiple energy storage technologies, such as batteries, supercapacitors, and potentially other emerging storage technologies, into a unified system [16]–[17].

Additionally, the key idea behind HESS is to leverage the complementary strengths of different storage technologies while mitigating their individual weaknesses. Batteries, for example, offer high energy density but may struggle with high-power demands and degradation over time [18]. Supercapacitors, on the other hand, provide rapid charging and discharging capabilities but typically have lower energy density compared to batteries [19]. By combining these technologies, HESS can deliver both high energy density and high power density, making it ideally suited for fast and efficient EV charging. Wilberforce *et al.* [20] propose a HESS that uses batteries, supercapacitors, and flywheels to improve the performance of electric and hybrid vehicles. This arrangement improves battery life by lowering workload and peak temperatures. It also includes a supercapacitor and a DC-DC converter in the power distribution system, which improves power flow and stability.

The circuit design is critical to determining HESS performance, requiring careful consideration of power and energy requirements, peak power, current fluctuations, and component characteristics in order to minimize losses and increase efficiency. Pancholi *et al.* [21] developed a parallel-connected HESS for EVs that connects lead-acid batteries and ultracapacitors via a bidirectional DC-DC converter. This system successfully controls load variances, resulting in consistent performance. Simulation studies demonstrate that the battery-supercapacitor HESS outperforms battery-only systems in a variety of conditions [21]. Bhattacharyya *et al.* [22] offered an alternate arrangement for a battery-ultracapacitor HESS, which included a diode to reduce large current surges and prevent backflow. The control approach uses peak current mode control to optimize power delivery. Simulation results confirm the system's efficacy and highlight its potential benefits [22]. Kohler *et al.* [23] emphasized the systematic approach to creating a HESS for hybrid EVs, which includes system analysis, modeling, control strategy creation, simulation, and evaluation.

Recognizing these challenges, researchers and engineers have turned their attention to developing innovative solutions to enhance EV charging infrastructure [24]–[26]. One such solution is the concept of a HESS. HESS integrates multiple energy storage technologies, such as batteries, supercapacitors, and potentially other emerging storage technologies, into a unified system. The HESS can be directly coupled to the HEV's electric machine, allowing for a variety of configurations, each with its own set of advantages. Simulation serves as the foundation for testing control strategies, resulting in increased HESS efficiency [27]. The project aims to design and develop a novel HESS specifically tailored for the efficient and fast charging of EVs. The system will integrate state-of-the-art battery technologies with high-power density supercapacitors or other suitable energy storage devices to create a synergistic hybrid solution.This research includes emphasize a HESS that combines three 18650 lithium-ion batteries and four supercapacitors to provide efficient electric vehicle charging. An Arduino UNO R3, equipped with an ATmega328 AVR Controller and a monitoring LCD display, controls power management, which includes DC/DC converters and a PWM charger. The system is programmed using the Arduino IDE, and a single A lead acid battery powers the electric car. MATLAB/Simulink and Proteus 8 are used to execute simulations for system and circuit design. The storage system charges in around 57 minutes and the electric car in 4.74 hours, with an output of 14.4 V and 2.5 A.

2. METHODS

The HESS system's pivotal role in facilitating efficient EV charging is elucidated through the accompanying block diagram. This diagram intricately outlines the components and processes involved in the charging process. At the heart of the system lies a DC power supply, which serves the crucial function of converting the rated terminal voltage of the main power supply (240 V) down to a lower voltage level of 12.6 V. This voltage reduction is imperative to match the requirements for charging within the HESS framework. Following this voltage conversion, the output values from the HESS system are carefully regulated through a pulse width modulation (PWM) charge controller. This controller plays a critical role in adjusting the output voltage to an optimal level conducive for charging the EV battery pack efficiently and rapidly. To provide real-time feedback and visualization of the charging process, the output values are displayed on an LCD display interfaced with a microcontroller. This display not only offers a visual representation of the charging status but also allows for monitoring and control of the charging parameters. Figure 1 serves as a comprehensive visual representation of the HESS architecture, specifically tailored and engineered to facilitate efficient and rapid charging of EVs. Through this block schematic, the intricate interplay of components and control mechanisms within the HESS system is highlighted, underscoring its significance in advancing the field of electric vehicle charging technology.

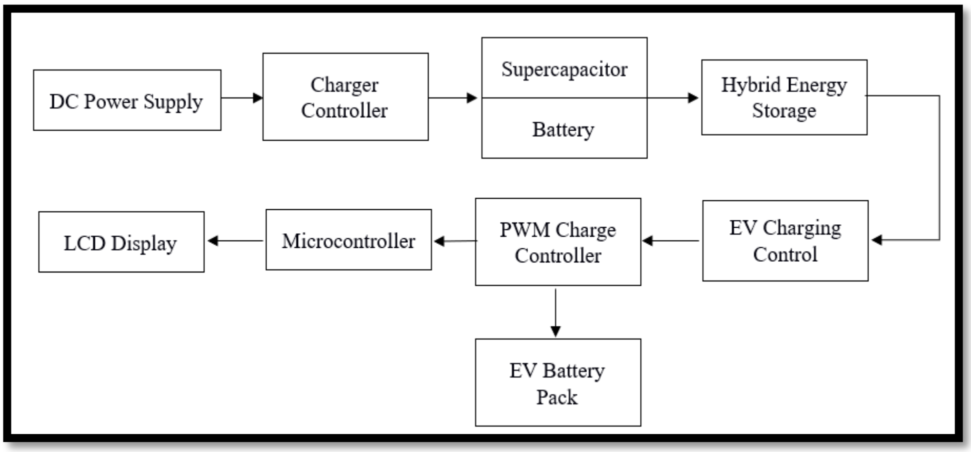


Figure 1. Block diagram of designing a HESS system and efficient electric vehicle charging

2.1. Design of hybird energy storage system

The efficient rapid charging control system circuit is comprised of three primary components: a DC voltage source, a bidirectional DC/DC converter, and a common load. In this setup, the DC voltage source is configured to operate at 48 V to fulfill the 12 V input requirements of both the battery and supercapacitor, necessitating a higher power input. The bidirectional DC/DC converter is activated through three series RLC branches and two MOSFETs. During the charging process, this converter efficiently reduces the high DC voltage from the source to the level necessary for the electric vehicle's battery pack. It meticulously manages the charging current and voltage, ensuring optimal charging performance while simultaneously monitoring and controlling the battery's state of charge (SOC) and temperature. Additionally, the common load is engaged when the voltage source is deactivated, allowing the HESS to supply power to the EV battery pack seamlessly. This smooth transition guarantees uninterrupted power delivery to the vehicle, thereby enhancing user convenience and reliability. Figure 2 illustrates the circuit design of the efficient rapid charging control system, meticulously crafted and simulated using MATLAB software. This design serves as a blueprint for implementing a robust and efficient charging infrastructure capable of meeting the demands of modern EVs.

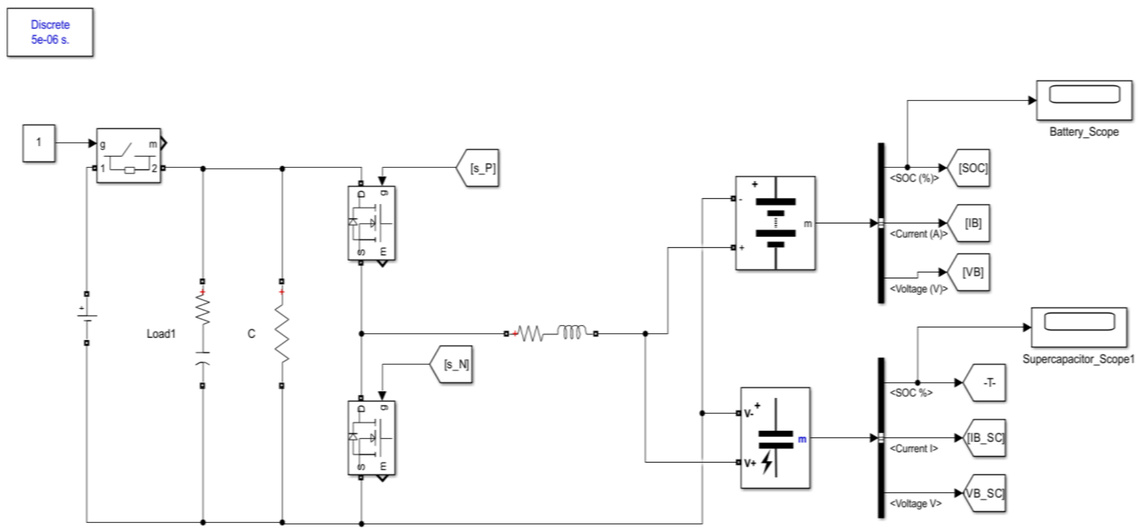


Figure 2. Efficient fast charging control system design using MATLAB

2.2. Specification of parameter battery setup in MATLAB

When three batteries are connected in series to form a lithium-ion battery, each individual battery contributes its standard voltage of 3.7 V. In a series connection, the total voltage is the sum of the voltages of each battery, resulting in a combined voltage of 11.1 V for the lithium-ion battery. Moreover, while the series setup increases the total voltage, the overall power capacity remains the same as that of a single battery, which is 2000 mAH. This means that although the voltage increases, the total energy storage capacity remains unchanged. In Simulink, a software platform used for modeling and simulating dynamic systems, the parameters required to set up a lithium-ion battery are specified in Table 1. These parameters include the nominal voltage and capacity of the battery. Based on these set values, Simulink calculates additional important parameters such as the cut-off voltage, fully charged voltage, nominal discharge current, and capacity at nominal voltage. These parameters are critical in determining various aspects of battery performance and behavior, including its charging and discharging characteristics. For instance, the cut-off voltage determines the minimum voltage level at which the battery should be discharged to prevent damage, while the fully charged voltage signifies the maximum voltage the battery can reach during charging. Additionally, the nominal discharge current represents the maximum continuous current that the battery can deliver under normal operating conditions. Understanding these parameters is essential for designing efficient charging systems and predicting the duration, power, and current required to charge the battery effectively while ensuring its longevity and safety.

After calculating the battery value in Simulink, the charging and discharging processes were simulated. During the charging procedure, a constant current (CC) is employed as the charging method. The proposed charging system achieves the desired output current by setting the charging current to 5 A. The observation and determination of the charging time are conducted through data analysis of SOC against time and voltage against time. The charging and discharging times of the battery can be calculated using in (1) [28].

$$\tau = \frac{C_{bat}}{I} \quad (1)$$

τ is representing the charging time of battery in hour, C_{bat} is representing the capacity of battery in mAh and I is representing the charging or discharging current in Ampere.

Table 1. Specification parameter for lithium-ion battery

Nominal voltage	11.1 V
Rated capacity	2 Ah
Initial state-of-charge (SOC)	0 %
Cut-off voltage	8.325 V
Fully charged voltage	12.9203 V
nominal discharge current	0.8696 A
Capacity at nominal voltage	1.8087 Ah

2.3. Specification of parameter supercapacitor setup in MATLAB

For the supercapacitors, a configuration is established where 12 V and 10 F supercapacitors are arranged in series with four 3 V, 40 F supercapacitors. Each supercapacitor possesses an equivalent series resistance (ESR) of 0.015, resulting in a total ESR of 0.075. In Simulink, Table 2 illustrates the specification parameters of the supercapacitors. The number of capacitors in series is specified as four supercapacitors connected in sequence. Since there is only one row of five supercapacitors, the number of parallel capacitors is set to 1. The initial voltage for the charging process is set at 2.4 V, with a default operating temperature of 25 degrees Celsius. With these parameters defined, it becomes feasible to conduct an in-depth investigation into the charging time of supercapacitors.

Table 2. The parameters of supercapacitor

Rated capacitance	10 F
Equivalent DC series resistance (ESR)	0.075 Ω
Rated voltage	12 V
Number of series capacitors	4
Number of parallel capacitors	1
Initial voltage	0.08 V
Operating temperature	25 ℃

The steady current charging method was employed to model the charging of a supercapacitor. In this experiment, a charging current of 5 A was applied. The initial voltage of the supercapacitor, used in the charging process, was set to 0.08 V. To determine the required charging duration, one can analyze the SOC and voltage over time. By utilizing in (2), it becomes possible to calculate the duration needed for the charging process [29].

$$\tau = (V - V_0) \cdot \frac{C}{Ic} \quad (2)$$

The symbol τ represents the charging time or discharging time of a supercapacitor in seconds. V denotes the rated voltage of the supercapacitor in volts, while V_0 signifies the initial voltage of the supercapacitor at τ, also measured in volts. C represents the capacitance of the supercapacitor in Farads, and Ic represents the charging current in Amperes.

2.4. Battery charging circuit with voltage regulator and current limitter for energy storage system

In the system, a DC power supply with a rated voltage of 13.4 V is utilized to charge a series of three batteries with a combined output of 12 V. A battery management system (BMS) is employed to balance individual cells during the charging process. Figure 3 illustrates the voltage regulation and current limit circuit designed for charging lithium-ion batteries in this configuration. The circuit incorporates an LM317T integrated chip, which functions both as a current limiter and a voltage regulator. U1 represents the current limiter, with the charging current limited to 0.625 A, as recommended for lithium-ion battery charging. U2 represents the voltage regulator, which regulates the voltage level to 5 V. This is achieved by fixing the value of resistor R5 to 320 Ω, and adjusting the value of the 10 kΩ potentiometer RV3 until the voltage level reaches 5 V.

The BMS plays a crucial role in facilitating fast charging by dynamically adjusting parameters such as voltage and current. It manages temperature to prevent overheating, accurately estimates SOC to avoid overcharging, actively balances cells to optimize efficiency, implements safety protocols to mitigate risks, and ensures compatibility with diverse charging standards. This comprehensive approach enables efficient and safe charging while preserving battery health and longevity across various applications and charging environments.

Furthermore, fast charging exacerbates any existing imbalances between individual cells within a battery pack, leading to uneven charging and reduced efficiency. To address this challenge, the BMS performs active cell balancing by redistributing charge among cells to maintain uniform SOC levels. This optimization enhances charging efficiency and prolongs battery lifespan. Additionally, the BMS provides short circuit protection, monitors temperature, and regulates voltage and current during both charging and discharging phases. It fosters effective communication through data logging interfaces, enabling real-time monitoring and informed decision-making based on historical performance. Moreover, the BMS's capacity to estimate SOC provides valuable insights into remaining energy capacity, while alarm and protection indications offer users a clear understanding of the battery's status. The BMS exercises precise control over the charging process, seamlessly transitioning between CC and constant voltage charging modes for optimal efficiency and prolonged battery life. In essence, the BMS emerges as an indispensable component, addressing multifaceted challenges and contributing significantly to the advancement of battery technology. Figure 4 illustrates the connection setup in the experimental battery charging system.

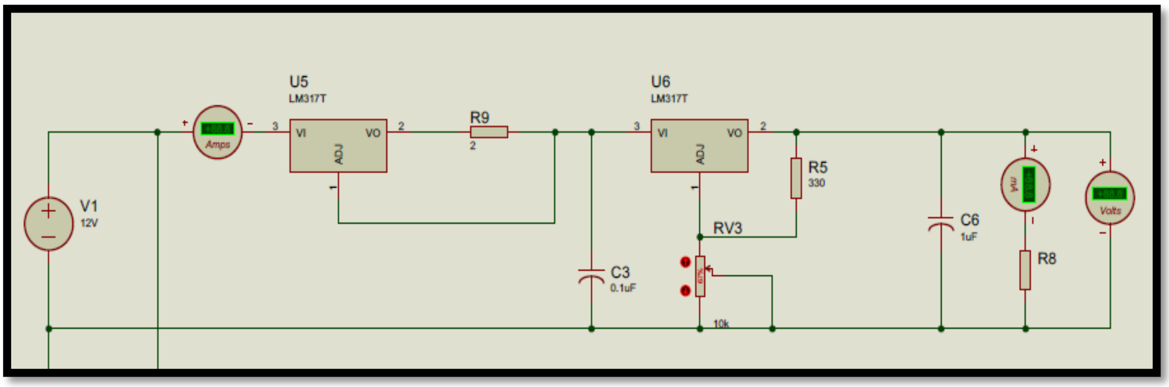


Figure 3. Battery charging circuit with voltage regulator and current limitter

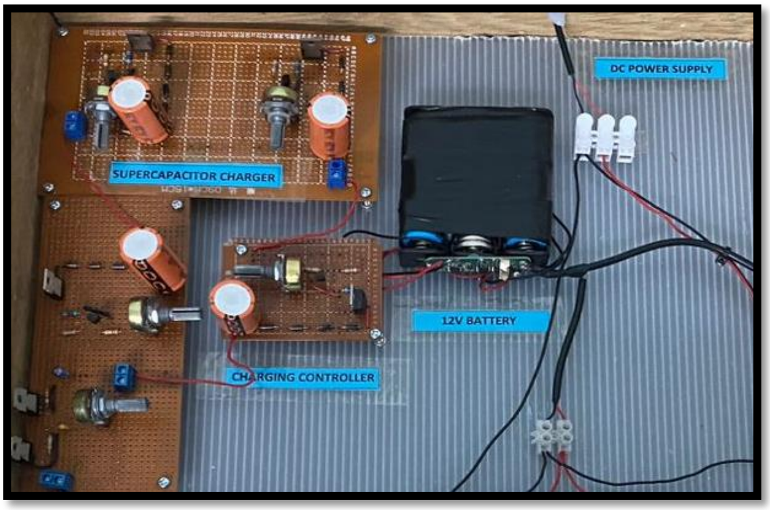


Figure 4. Experimental setup of battery charging system

2.5. Supercapacitor charging circuit with voltage regulator and current limitter

Figure 5 illustrates the voltage regulation and current limiter circuit designed for charging the supercapacitors. In this circuit, U7 represents the current limiter, and akin to the battery charging circuit, the current is restricted to 0.625 A. For voltage regulation, U8 maintains the voltage level at 12 V. This regulation is achieved using a 560 Ω resistor (R10) and a 10 kΩ potentiometer (RV4). These components work together to control the voltage output and ensure consistent charging of the supercapacitors.

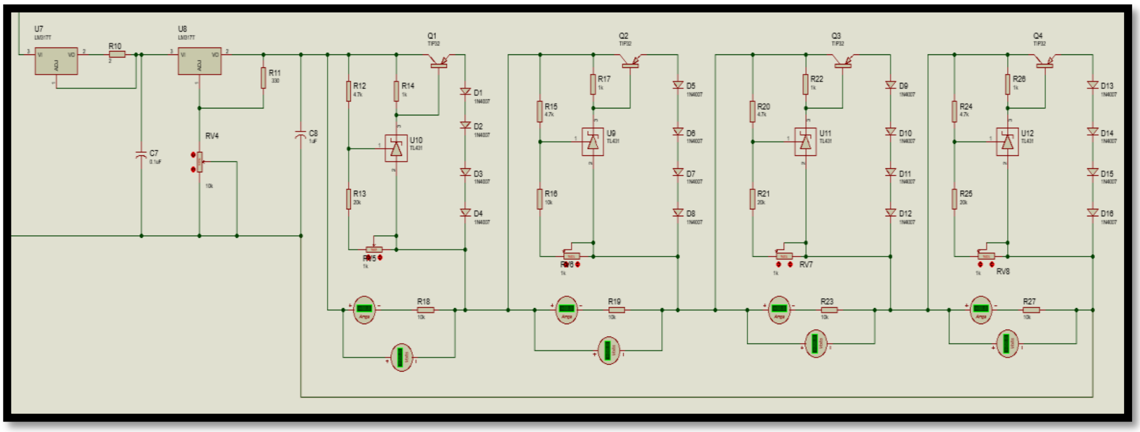


Figure 5. Supercapacitor charging circuit with voltage regulation and current limiter.

After the DC supply is regulated to a voltage level of 12 V and the current is limited to 0.625 A, the system is prepared to charge the supercapacitors using the following charging circuit. Ensuring the safe charging of the supercapacitors is crucial to avoid any damage. However, charging modules with protection circuits specifically designed for supercapacitors are rare and limited in the market. Therefore, the proposed design for the charging circuit utilizes a TL431 variable reference Zener diode and a TIP32 PNP transistor. Figure 6 illustrates one of the supercapacitor charging circuits incorporating the TL431 variable reference Zener diode and TIP32 PNP transistor. This design aims to provide effective and reliable charging while safeguarding the supercapacitors from potential damage.

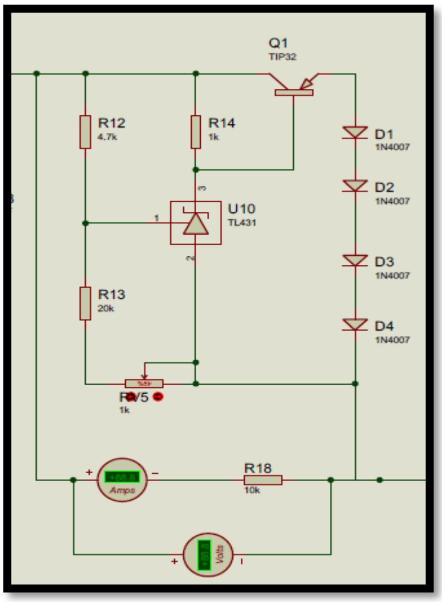


Figure 6. Supercapacitor charging circuit with TL431 variable reference Zener diode and TIP32 PNP transistor

When the supercapacitor is connected to the charging circuit with the supply, the charging process begins. Initially, when the voltage of the supercapacitor is below 3 V, the TL431 remains open, and the TIP32 transistor remains in the off state. As the supercapacitor charges and its voltage reaches 3 V, the TL431 closes and connects to the base of the TIP32 transistor. This action allows the supply to flow to the four 1N4007 diodes, which act as the load. The reference voltage of the TL431 can be fixed by adjusting the values of resistors R26 and R27, following (3) [30]–[31]. This adjustment allows for precise control over the charging process and ensures optimal performance of the circuit.

$$V_{ref}=2.5(1+\frac{R1}{R2}) \quad (3)$$

Referring to (3), V_{ref} represents the reference voltage that triggers the cutoff of the supercapacitor from the circuit when it is fully charged. R1 represents the value of resistor R26, and R2 represents the value of resistor R27. The 10k potentiometer RV4 is utilized to fine-tune the reference voltage of the TL431, allowing for precise control over the charging process. Since the four supercapacitors are charged in separate circuits, a charge balance can be maintained among them. The total voltage of the supercapacitors during the charging process will be recorded. Figure 7 depicts the connection of an experimental setup for the supercapacitors charging system, providing a visual representation of the circuit configuration and component placement.

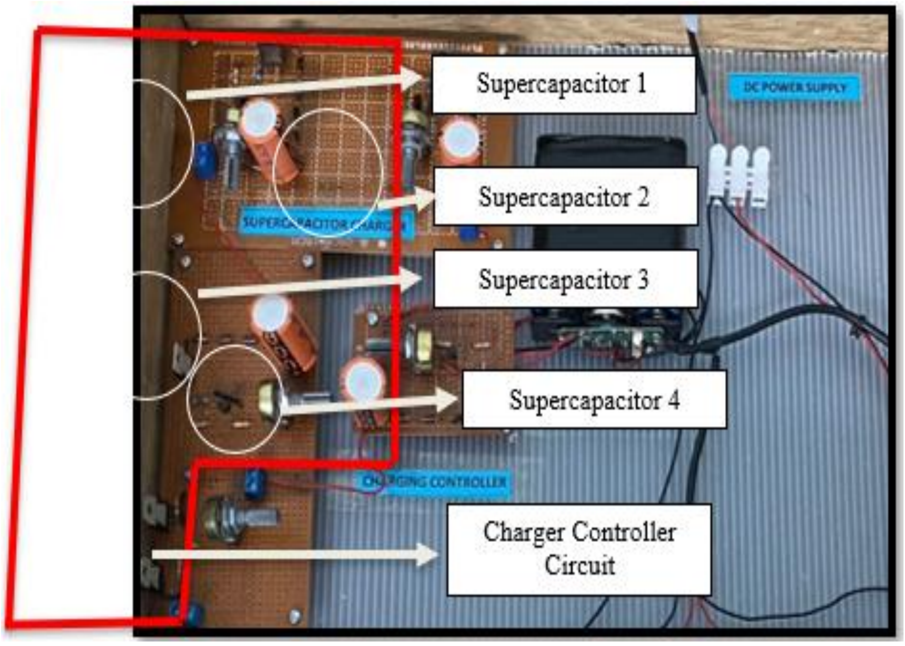


Figure 7. Supercapacitor charging system

2.6. Design of electric vechicle charging system

The charging system controller utilizes CC techniques, with a critical component being the buck-boost converter responsible for current control and voltage maintenance. Additionally, a PWM charge controller functionality has been integrated into the circuit to further optimize the charging process. This PWM charge controller enhances the precision of the charging mechanism by regulating the on-off cycles, effectively modulating the charging current. Furthermore, the microcontroller, an Arduino Uno, plays an instrumental role in this setup, providing a comprehensive display of voltage, current, and power delivered. These parameters are acquired through a voltage and current sensor, contributing to a more informed monitoring of the charging process. The culmination of these features is illustrated in Figure 8, showcasing the completed battery charging circuit designed for fast charging EVs. Figure 9 displays the setup of the complete battery charging circuit in the prototype, providing a visual representation of the assembled components and their arrangement.

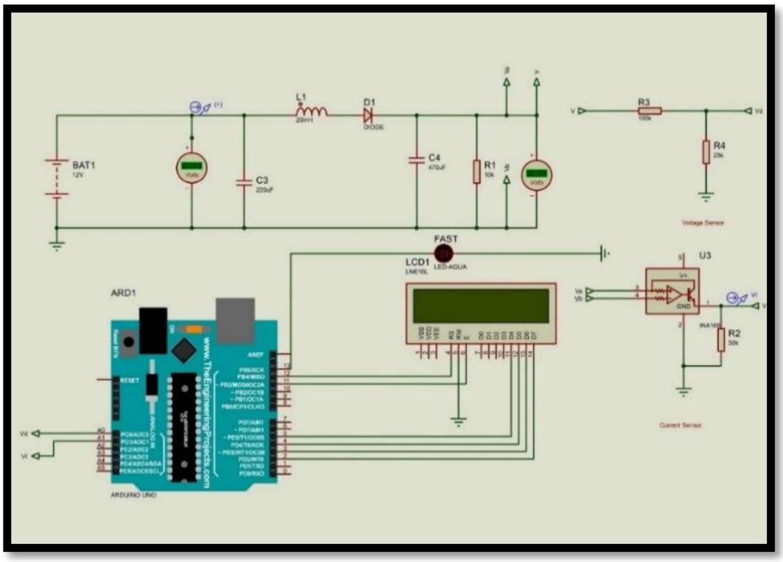


Figure 8. Charging control battery circuit design by Proteus

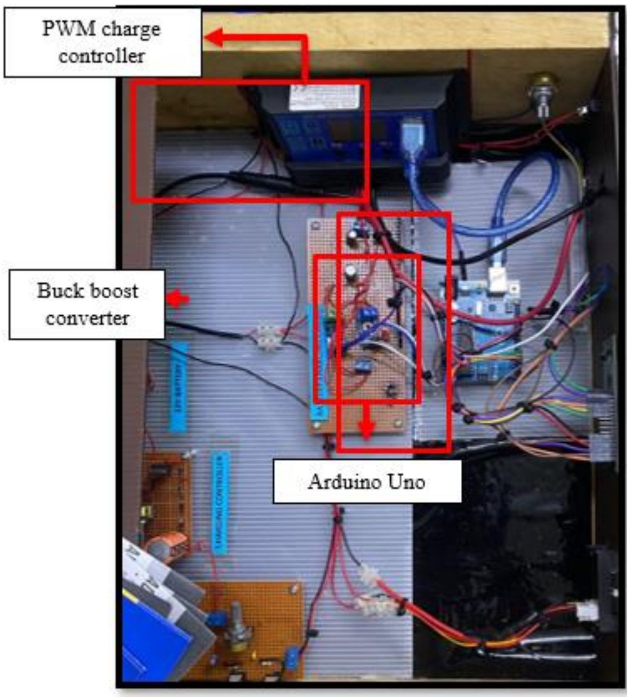


Figure 9. Charging control battery circuit

3. RESULTS AND DISCUSSION

In this section, the results and performance analysis obtained from the designed circuits are simulated and analyzed using Proteus software. The results are divided into two parts: the HESS and the electric vehicle charging circuit. Each circuit will be designed, measured, and analyzed in Proteus software, and the results will be compared to experimental data. During the charging process, the LCD will display the status performance, providing real-time feedback on parameters such as voltage, current, and power delivered. This allows for a comprehensive understanding of the charging process and facilitates comparison between simulated and experimental results. By conducting simulations and analyses in Proteus software, the performance of the designed circuits can be evaluated under various conditions and scenarios. This enables optimization and refinement of the circuits to ensure efficient and reliable operation in practical applications.

3.1. Performance of hybrid energy storage circuit

The experiment utilized a direct current (DC) power source to provide voltage to the charging circuit in the storage system. The input voltage was set at 12.6 V, with a current of 5 A. Once the DC supply is activated, it will provide power to the charging controller circuit. This circuit is responsible for managing a 12 V battery with a capacity of 2.2 Ah, as well as a BMS. Additionally, it supplies power to a parallel configuration of supercapacitors with a capacitance of 10 F, also operating at 12 V.

Subsequently, the data depicted in Table 3 illustrates the comparison result between simulation and experimental results at the point where it reaches 100% SOC. Additionally, there are some significant differences in terms of charging time and output current stated in the comparison between simulation data and experimental data. This is due to the charging time showing a 76% percentage error, as the simulation charging time requires 1800 seconds or 30 minutes to reach 100% SOC, while in the experiment, it requires 3168 seconds or 52.8 minutes to reach 100% SOC. The significant difference in charging time, with a 76% disparity between simulated and experimental outcomes, can be attributed to a noticeable decrease in the charging current from 5 A to 2.52 A.

The decrease in electrical current observed during the charging process may result from various factors that impact the charging system. One possible reason is that the charging algorithm used in the simulation or experimental setup is programmed to gradually reduce the charging current as the battery approaches its maximum capacity. The decrease in current may serve as the actual battery used in the experiment might have characteristics (e.g., internal resistance, capacity, age, temperature effects) that are not perfectly represented in the simulation model. Real batteries may experience degradation or other performance variations not accounted for in the simulation. On the other hand, several factors such as temperature fluctuations, resistance in the cable and connectors, or constraints in the charging infrastructure can affect the decrease in current, thereby affecting the total time required for charging. Therefore, the study underscores the importance reasons behind the differences in charging times and currents can lead to the development of optimized charging protocols that are both efficient and safe. This can improve battery life, reduce charging times, and enhance overall performance.

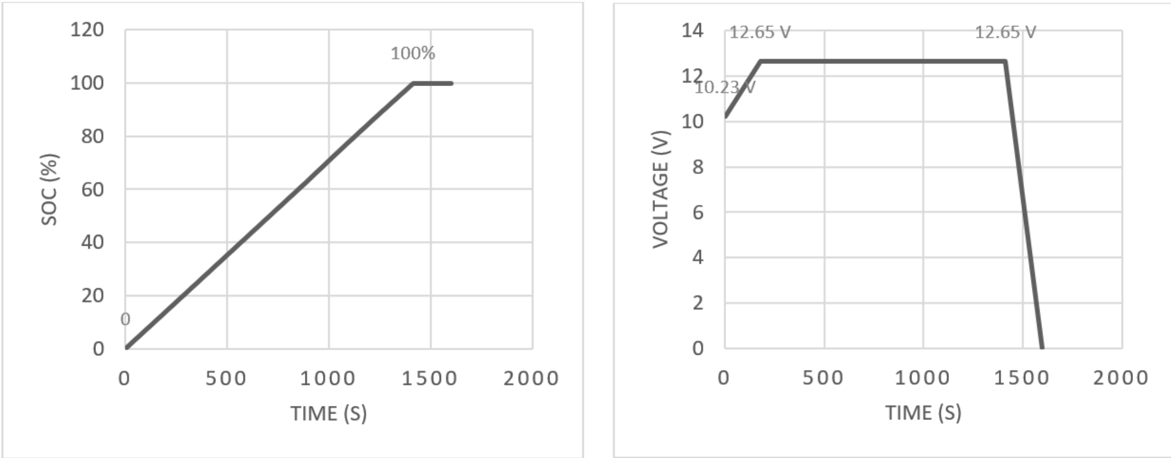
Table 3. Comparison result between simulation and experimental for HESS circuit

	Simulation	Experimental
Input Voltage (V)	12.65	12.60
Input Current (A)	5.00	5.00
Charging Time (s)	1800	3168
Output Voltage (V)	12.40	12.40
Output Current (A)	5.00	2.52

3.2. Simulation performance of charging Li-Ion batteries

Figure 10 shows the simulation result of charging the lithium-ion battery's performance. The lithium-ion battery used in this simulation has a cumulative voltage of 11.1 V and a capacity of 2000 mAh. It comprises three separate lithium-ion cells, each rated at 3.7 V and 2000 mAh, connected in series. Initially, Figure 10(a) demonstrates that the lithium-ion battery requires approximately 23.33 minutes to reach full SOC, transitioning from 0% to 100%. This observation highlights the efficiency and charging capabilities of lithium-ion batteries in this configuration.

Figure 10(b) offers a comprehensive depiction of the voltage progression during the charging cycle of a lithium-ion battery. In the initial 23.33 minutes, equivalent to 1413.55 seconds, the battery's voltage ascends from 10.23 V to its zenith at 12.65 V, signifying the attainment of a full charge. Concurrently, the SOC attains a range of 90% to 100%. It is imperative to highlight that the battery is on the verge of reaching its maximum capacity, and any further charging could potentially lead to adverse consequences. Moreover, as a preventive measure against overcharging, the recommended strategy involves the incorporation of a battery protection system. This system operates in a continuous monitoring capacity throughout the charging process, automatically terminating the charging procedure upon the battery's achievement of full capacity. The integration of a battery management system serves a dual purpose: safeguarding the battery's integrity and promoting an extended operational lifespan while ensuring consistent and efficient performance. This proactive approach assumes paramount importance in the context of preserving the overall health of lithium-ion batteries, particularly in scenarios where precise control of voltage and charge levels holds critical significance. These emphasize that precise control of voltage and charge levels is critical for maintaining the overall SOC of lithium-ion batteries, especially in scenarios demanding high accuracy.



(a) (b)

Figure 10. Performance of Lithium-ion battery (a) SOC changes against charging time and (b) the voltage of lithium-ion battery increases proportionally with time in charging state

The simulation results indicate that the optimal current input for the CC charging method is 5 A. This choice is based on several factors, including the desired charging time and the resulting output voltage. The simulation shows that using a current input of 5 A leads to a charging time of 23.33 minutes or 1413.55 seconds, with an output voltage of 12.65 V. The summary of the simulation results presented in Table 4 involved testing various CC inputs, namely 2 A, 3 A, 4 A, 5 A, and 6 A. After considering multiple factors, it was determined that a current input of 5 A was the most favorable choice. Firstly, considering the charging time, the simulation showed that a current input of 5 A resulted in a charging time of 23.33 minutes or 1413.55 seconds. In comparison to the other tested current inputs, it was observed that this led to longer charging times. The use of a 5 A current input resulted in a shorter charging time, which is advantageous for efficient fast charging and aligns with the research objective. Furthermore, analyzing the output voltage, the simulation indicated that a current input of 5 A produced an output voltage of 12.65 V. This output voltage falls within the desired range for efficient charging. Although other current inputs may have yielded slightly higher or lower voltages, the output voltage of 12.65 V achieved with 5 A was considered optimal for the charging process.

Table 4. Summary results of charging time on lithium-ion battery

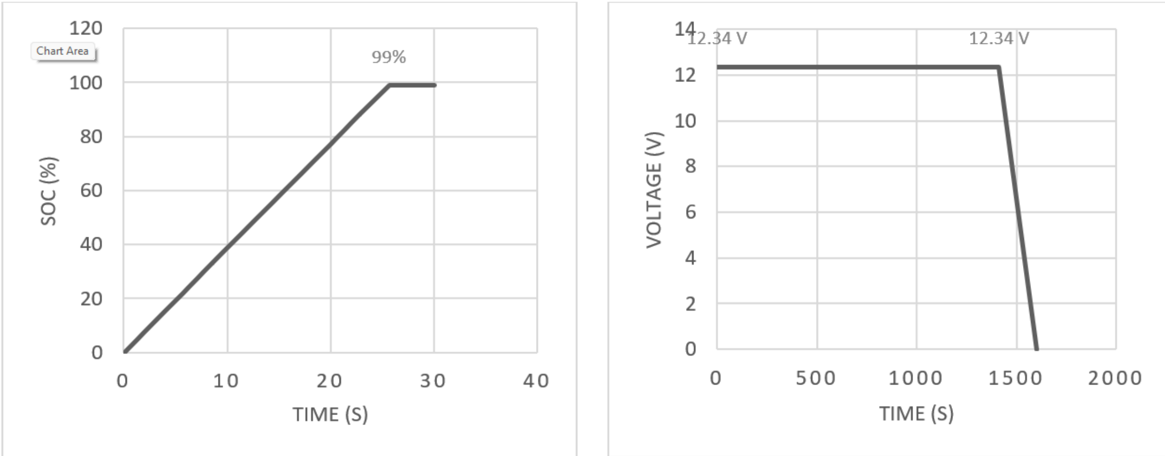
Current Input (A)	Charging Time (s)		Voltages (V)	
	Theoretical	Simulation	Simulation	Experimental
2	3960.00	3416.00	10.87	11.09
3	2700.00	2215.23	11.05	12.90
4	2100.00	1757.25	11.48	10.50
5	1800.00	1413.55	12.65	12.00
6	1500.00	1162.30	13.54	12.60

3.3. Simulation performance of supercapacitor charging

Four supercapacitors, each with a rating of 3 V and 40 F, are connected in series to create a supercapacitor unit. The combined voltage of these supercapacitors is 12 V, and their total capacitance is 10 F. The charging current used in the simulation is 5 A. Figure 11 is the performance of the supercapacitor during charging. Figure 11(a) shows the variations in supercapacitor SOC during the charging procedure. In 30 seconds, the SOC of the supercapacitors increased from 0% to 99%. Internal resistance in supercapacitors can cause voltage fluctuations and affect the charging process. As a supercapacitor charges, the voltage across its terminals can rise, resulting in greater voltage fluctuations across its internal resistance. This can hinder the charging efficacy and prevent the battery from reaching 100% capacity within the specific time frame. Thus, it is highlighting the importance of considering internal resistance and voltage fluctuations when designing and simulating charging processes for supercapacitors, as these factors can significantly influence charging efficiency and capacity attainment.

Figure 11(b) illustrates that the voltage of a supercapacitor varies as time passes during the charging process. The voltage rose dramatically from its initial reading of 0.08 V to its final reading of 12.34 V in just

25.50 seconds. It is important to note that when supercapacitors are very near to having their capacity entirely utilized, their voltage hits 12.34 V rather than the standard 12 V. This is because supercapacitors have a tolerance built into them. It is crucial to prevent any damage to the supercapacitor by strictly adhering to the recommended voltage limit. If the simulation keeps going above that limit, it might result in catastrophic repercussions, such as irreparable damage to the supercapacitor. This damage can cause the capacitance to decrease, the voltage to be less steady, put undue stress on the internal elements like electrodes, and even lead to the component heating up too much.



(a) (b)

Figure 11. Performance of Supercapacitor during charging (a) SOC versus time during charging (b) voltage with charging time

The results of the simulation indicate that selecting a current input of 5 A for the CC charging procedure yields optimal results. This decision is influenced by a number of significant factors, including the intended charging time and output voltage. In particular, using a current input of 5 A results in a remarkably efficient charging process, completing in just 25.50 seconds while achieving the desired output voltage of 12.34 V. The primary objective of the study is to improve the charging process, specifically by decreasing charging times and total energy consumption.

Table 5 presents a comparison of charging times and voltages for supercapacitors at various current inputs, detailing theoretical values, simulation results, and experimental measurements. For each current input, the table shows that charging times predicted by the simulation are slightly longer than theoretical values. For example, at a 2 A current input, the theoretical charging time is 59.60 seconds, whereas the simulation time is 61.05 seconds. This pattern of simulations predicting slightly longer charging times continues across all current inputs. In terms of voltage, there are significant differences between simulation and experimental results. For instance, at 5 A, the simulation predicts a voltage of 12.34 V, while the experimental measurement is lower at 10.44 V. This discrepancy indicates that real-world factors, such as internal resistance, cause the experimental voltages to be lower than those predicted by simulations. Overall, the table highlights that while simulations provide a close approximation of charging times, real-world conditions lead to notable differences in voltage performance. The results suggest that simulations may not fully capture all practical factors affecting supercapacitor behavior.

Table 5. Summary results of charging time on supercapacitor

Current input (A)	Charging time (s)		Voltages (V)	
	Theoretical	Simulation	Simulation	Experimental
2	59.60	61.05	10.30	9.30
3	39.73	41.55	10.75	11.55
4	29.80	30.45	11.33	13.33
5	23.84	25.50	12.34	10.44
6	19.87	22.25	13.54	12.14

3.4. Experimental result of energy storage system

Table 6 provides experimental data for a hybrid storage system composed of a battery and a supercapacitor. Both components in the system operate at similar voltages, with the battery at 12.4 V and the supercapacitor at 12.2 V. This close voltage range indicates effective voltage matching, which is crucial for efficient integration and energy transfer in the hybrid system. Additionally, both the battery and the supercapacitor have the same current value of 2.5 A. This balanced current distribution suggests that the load is equally shared between the two components, optimizing the system's performance and potentially extending its operational lifespan. Overall, the data in Table 6 highlights the compatibility of the battery and supercapacitor in a hybrid storage system, emphasizing efficient energy transfer and balanced load distribution, which are essential for achieving a reliable and efficient energy storage solution.

Table 6. Experimental data for both hybrid storage system (battery and supercapacitor)

Hybrid storage system	Voltage (V)	Current (A)
Battery	12.4	2.5
Supercapacitor	12.2	2.5

Table 7 compares the results of simulations and experiments for a storage system, focusing on various parameters. The input voltage is nearly the same for both simulation (12.65 V) and experimental conditions (12.60 V), and the input current is consistent at 5.00 A, indicating that the initial conditions were well-matched. However, there is a notable discrepancy in the charging time: the simulation predicts a charging duration of 1800 seconds (30 minutes), while the experiment shows a much longer time of 3168 seconds (52.8 minutes). This difference suggests that the simulation may not account for all real-world factors affecting the charging process. Both simulation and experimental results achieve the same output voltage of 12.40 V, showing consistency in the final voltage. However, the output current differs significantly, with the simulation showing 5.00 A and the experiment showing only 2.52 A. This variation indicates that real-world inefficiencies, such as internal resistance, may be affecting the output current, which is not fully captured in the simulation. Overall, the table highlights that while some parameters match well between simulation and experiment, significant differences in charging time and output current suggest that additional real-world factors need to be considered for more accurate simulations.

Table 7. Comparison results between simulation and experiment in storage system

Parameter	Simulation	Experimental
Input voltage (V)	12.65	12.60
Input current (A)	5.00	5.00
Charging time (s)	1800	3168
Output voltage (V)	12.40	12.40
Output current (A)	5.00	`2.52
Input voltage (V)	12.65	12.60

Table 8 summarizes the key parameters of an electric vehicle (EV) battery charging system. The battery has a large capacity of 12,000 Ah, indicating its ability to store a significant amount of energy. It operates at a voltage of 14.4 V. During charging, the system provides a current of 2.52 A. This results in a power output of 36.25 W, which is calculated by multiplying the voltage and current. Table 8 provides a clear overview of the battery's capacity, operational voltage, and charging power, essential for evaluating the performance and efficiency of the EV battery charging system. The study is important because it helps in assessing the efficiency and effectiveness of EV battery charging systems. By analyzing key parameters such as battery capacity, charging current, and power output, the study provides valuable insights into the performance of the charging system, which is essential for improving battery life, charging speed, and overall vehicle performance.

Table 8. Summary result of EV battery charging system

Battery Capacity	12 000 Ah
Voltage	14.4 V
Current	2.52 A
Power	36.25 W
Charging Time	4.74 hours

4. CONCLUSION

The highlighted research on combining batteries and supercapacitors in a HESS leverages the high energy density of batteries and the rapid charge-discharge capabilities of supercapacitors. The innovative control strategy developed for this system ensures optimal power flow management, effectively addressing the inefficiencies and long charging times prevalent in conventional EV charging infrastructure. The integration of supercapacitors with batteries significantly reduces the overall charging time. Supercapacitors can handle rapid charge and discharge cycles, thereby absorbing high power spikes during charging and reducing the burden on batteries, which leads to faster charging rates. This integrated system significantly reduces the charging time of a 12 Ah battery to just 4.74 hours while maintaining desired output parameters. The experimental results predicted that the HESS can reduce charging time by up to 40% compared to conventional systems, demonstrating its potential to revolutionize EV charging technology. Additionally, the HESS optimizes power quality, reduces battery size, extends the lifespan of energy storage devices, and minimizes charging costs, ultimately enhancing vehicle performance. Combining batteries and supercapacitors leverages their complementary characteristic, high energy density of batteries and high-power density of supercapacitors resulting in more efficient energy storage and delivery compared to stand-alone battery systems. Future work will focus on optimizing control algorithms to adapt to varying grid conditions and exploring the integration of renewable energy sources into the HESS framework. These efforts will further enhance the sustainability and efficiency of EV charging, ultimately supporting the community's goals for cleaner and more reliable energy solutions.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Liew Hui Fang	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Muhammad Izuan Fahmi Romli		✓				✓	✓	✓	✓	✓	✓	✓		
Rosemizi bin Abd Rahim	✓		✓	✓			✓	✓		✓	✓		✓	✓

C : Conceptualization
M : Methodology
So : Software
Va : Validation
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I : Investigation
R : Resources
D : Data Curation
O : Writing - Original Draft
E : Writing - Review & Editing
Vi : Visualization
Su : Supervision
P : Project administration
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CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. Due to privacy and confidentiality considerations involving research participants, the data are not publicly available and are subject to institutional or ethical restrictions.

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BIOGRAPHIES OF AUTHORS

Dr. Liew Hui Fang currently is a senior lecturer at Faculty of Electrical Engineering Technology from Universiti Malaysia Perlis. In 2012, she holds her degree, in Electrical Systems Engineering at University Malaysia Perlis (UniMAP), Malaysia. In 2015. M.Sc. degree in Microelectronics Engineering from University Malaysia Perlis (UniMAP), in 2018, she received the Ph.D. degree in Electrical Systems Engineering at University Malaysia Perlis (UniMAP). Her research interest includes the analysis and development of new sources of energy harvesting system and techniques, renewable energy, Power Energy, Microwave Communication and RF MEMS. She can be contacted at email: hfliew@unimap.edu.my

Associate Professor Dr. Muhammad Izuan Fahmi Romli obtained his PhD degree and Master of Science from University of Nottingham Malaysia Campus. In 2010, he received the Bachelor of Electrical Engineering Technology from Universiti Kuala Lumpur. Being active as an Associate Professor in the University Malaysia Perlis, his current interest lies on renewable energy, supercapacitor, optimisation and energy storage for electric vehicle. He can be contacted at email: izfahmi@gmail.com.

Associate Professor Madya Ir. Dr. Rosemizi bin Abd Rahim was born in Kedah, Malaysia in 1976. He received the B.Eng. degree in Electrical Engineering from Universiti Teknologi Mara, Malaysia, in 2000 and the M.Sc. degree in Electronic System Design Engineering from Universiti Sains Malaysia, in 2004. In 2013, he received the Ph.D. degree in Communication Engineering from Universiti Malaysia Perlis. From 2000 to 2004, he was a failure analysis engineer at a multinational electronic manufacturing company in Penang, Malaysia. His task was to resolve any failure that occur during the production process of electronic products. Then, since 2005 he has been moved to Universiti Malaysia Perlis as an academician. His research interest includes the analysis and development of new sources of energy harvesting system and techniques, antenna design and microwave engineering. Currently he is a senior lecturer at Faculty of Electronics Engineering Technology at University Malaysia Perlis (UniMAP). He can be contacted at email: rosemizi@unimap.edu.my.