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Development of an advanced current mode charging control strategy system for electric vehicle batteries

Liew Hui Fang[1], Muhammad Izuan Fahmi Romli[1], Rosemizi Abd Rahim[2], Muhammad Ezanuddin Abdul Aziz[3], Diyya Hidayah Abd Rahman[1], Habibah Haji Mokhtaruddin[1]
[1]Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia
[2]Faculty of Electronics Engineering and Technology, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia
[3]Faculty of Engineering and Built Environment, Lincoln Universiti College, Petaling Jaya, Malaysia

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ABSTRACT

Electric vehicles (EVs) face customer hesitancy due to challenges in locating fast charging stations, lengthy recharging times, and incompatible charging ports. This research addresses these issues by proposing a novel current mode control strategy for EV battery charging. Traditional charging methods often result in suboptimal rates, battery degradation, and safety risks. The primary objective is to enhance charging efficiency, safety, and battery lifespan by optimizing parameters such as voltage and current. Control mode charging offers significant advantages over plug-in charging by minimizing stress factors that contribute to degradation, such as high temperatures and excessive charging cycles. This approach aims to extend the lifespan of EV batteries while ensuring safe, efficient, and fast charging. The control system offers three charging modes: slow (0.49 A, 6.31 W, 264 mins), medium (2.74 A, 34.85 W, 50 mins), and fast (4.62 A, 50.80 W, 30 mins) using a 12 V single-phase supply. This advanced strategy significantly improves EV charging system efficiency, with fast charging achieving 80% higher efficiency than slow charging in both simulations and experimental testing. The key contribution of this research is the development of a tailored current mode charging strategy that optimizes charging efficiency while ensuring battery longevity and safety.

Corresponding Author:

Liew Hui Fang
Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis (UniMAP)
02600 Arau, Perlis, Malaysia
Email: hfliew@unimap.edu.my

1. INTRODUCTION

In the current scenario, the market trend for electric vehicles or EVs is on the rise. This growth can be attributed to a widespread belief that electric cars offer a solution to reducing carbon emissions and mitigating environmental degradation [1]. However, when considering the broader implications, it becomes apparent that the electricity required to charge EVs is primarily sourced from thermal power plants. This reliance on thermal power plants can lead to environmental pollution, potentially offsetting the environmental benefits typically associated with EVs when compared to gasoline-powered vehicles. Consequently, there is a growing realization that while EVs offer promise in reducing emissions at the vehicle level, the source of electricity generation must also be considered to comprehensively address environmental concerns associated with transportation [2], [3]. This highlights the importance of transitioning towards renewable energy sources to power EVs, thereby aligning with sustainability goals and effectively addressing environmental challenges posed by conventional power generation methods.

This research focuses on developing a battery charging system featuring three distinct charging modes. The prototype on-board charging system is designed to accommodate different charging needs: a slow charging mode intended for residential use, a medium charging mode suitable for office parking lots, and a fast-charging mode for on-road charging stations [4], [5]. Fast charging is particularly crucial in today's fast-paced world, where time is considered the most valuable currency. The development of a quick charging system through this study can be seen as a significant advancement in electric mobility solutions. The primary aim of this project is to create three charging modes for batteries, catering to the diverse needs of the public and enhancing the convenience of charging EVs [6]-[8].

The rapid growth of EVs has necessitated advancements in battery charging technologies to enhance efficiency, safety, and battery lifespan. Different battery chemistries, such as lithium-ion and nickel-metal hydride, have unique charging requirements, making effective charging control essential to prevent overcharging and overheating. Current mode control strategies offer real-time adjustment of the charging current, enhancing charge delivery precision and mitigating the risk of overcurrent conditions. Technological innovations, such as high-efficiency DC-DC converters and smart algorithms, further refine current control techniques. Regulatory efforts and international standards are evolving to ensure interoperability and safety across EV models and charging infrastructures. Efficient charging strategies reduce energy consumption and operational costs, improve battery longevity, and support the broader adoption of EVs, contributing to global efforts to reduce greenhouse gas emissions and dependence on fossil fuels. Therefore, developing an advanced current mode charging control strategy system for EV batteries is crucial for optimizing EV performance, safety, and sustainability.

The constant voltage (CV) charging method is widely utilized in commercial battery charging systems. This method involves maintaining a constant peak voltage during charging until the current drops to a predefined small value. In the proposed charging system, a microcontroller is employed to enable the relay between various voltage levels and currents [9]-[12]. A charging control system is a vital component of EVs responsible for managing and regulating the battery charging process. This system plays a pivotal role in ensuring the longevity and optimal performance of EV batteries [13]-[16]. By preventing overcharging, overheating, and other potential forms of damage during charging, the charging control system contributes to extending the battery's lifespan. Also, this research seeks to explore innovative methods for addressing battery degradation, a critical factor influencing the long-term performance and sustainability of EVs. The advanced control system developed in this study is designed to actively monitor and manage battery degradation, ensuring optimal charging efficiency and extending the lifespan of EV batteries [17]-[20]. Additionally, it provides users with valuable information regarding the charging process, including estimated charging times and other pertinent data [21], [22]. The integration of a microcontroller in the proposed charging system allows for dynamic adjustments of voltage and current levels, optimizing the charging process for various battery types and charging scenarios. This enhanced control capability enhances the efficiency and effectiveness of the charging system, contributing to improved battery health and overall performance of EVs [23].

Liu *et al.* [24] explained focus on battery charging, where the charger applies a constant current until the battery reaches a predefined voltage potential. Liu *et al*. [24] also found that the results for voltage and current are consistent, with values ranging from 50 A to 100 A for current and 300 V to 360 V for voltage. The difference among the three results lies in the charging time: the first charging time is 0 to 7 hours, the second result shows a charging time of 0 to 10 hours, and the last result indicates a charging time of 0 to 12 hours. Wang *et al.* [25] presented the charging protocol of lithium-ion batteries for EVs, employing the constant current-constant voltage (CC-CV) process. This method is a common approach to battery charging, where the charger applies a constant current until the battery reaches a predefined voltage potential. Wang *et al.* [25] found different results for power and charging time. The first result is for slow charging mode, with 7 kW for power and a charging time of four hours. The second result is for average charging mode, with 27 kW for power and a charging time of 1 hour and 30 minutes. The last result is for fast charging mode, with 83 kW for power and a charging time of 30 minutes. Additionally, the application for this method is in charging stations in public places. However, the advantage of this charging system is its ability to offer fast, medium, or slow charging options, while the disadvantage is an increase in cost and maintenance.

In a study by Collin *et al.* [26], it was noted that the CC-CV charging method is employed for fast charging an EV battery [18]. The study revealed different outcomes regarding power and charging time, specifically highlighting results for 50 kW of power and a charging time of 10 to 15 minutes. The second result is for 6.6 kW of power and a charging time of 3 hours. The last result is for 1.2 kW of power and a charging time of 15 hours to fully charge. Additionally, the application for this charging system is in charging stations in public places. Furthermore, the advantage of this method is its ability to provide power to designated appliances, while the disadvantage is a complex circuit design and an increase in maintenance. Tan *et al.* [27] described a CC-CV charging method used for fast charging an EV battery.

Tan *et al.* [27] found different results for voltage, power, and estimated charging time. The first result is for slow charging mode, which employs a 120 V single-phase power source with an approximate power of 1.4 kW and an estimated charging time of up to 17 hours. The second result is for medium charging mode, which utilizes a 240 V power source with an approximate power of 20 kW and an estimated charging time of up to 1.2 hours. The last result is for fast charging mode, which utilizes a 300 to 450 volt alternating current or VAC power source with an approximate power of 45 kW and an estimated charging time of up to 30 minutes. Additionally, the application used in this research is in a smart grid environment. The advantage of this research is a greater number of charge and discharge cycles operating at higher voltage, while the disadvantage is its extreme sensitivity to high temperatures. Battery chargers can also be classified into conductive and inductive types. Conductive battery chargers are defined as those charging systems that use direct physical contact between the connector and the charge inlet. On the contrary, inductive chargers are those that transfer power magnetically. Although some works deal with moving chargers, inductive chargers are mainly considered for stationary slow charging applications. Tan *et al.* [27] implemented the conductive charging system as part of the IEC 61851 adapter, which applies to on-board and off-board equipment for charging electric road vehicles at standard AC supply voltage up to 1000 V and at DC voltage up to 1500 V.

In addition, unlike the fueling cost which is a linear correlation between the cost and the fuel quantity, the EV charging process demonstrates a highly nonlinear characteristic with respect to the instant battery state of charge (SOC) as reported in the literature of Yang and Chen [28]. Yang and Chen [28] highlight the growing prominence of DC fast charging stations (DCFCs) for quick charging needs in situations where residential charging is unavailable. However, the authors also explained that the cost of using DCFCs can vary considerably due to the nonlinear charging power and higher charging fees compared to residential charging. Consequently, there's a growing need to optimize charging schedules to minimize costs, particularly with the rising adoption of EVs. To address this, the authors introduce two global optimization algorithms: a genetic algorithm (GA)-based approach and a dynamic programming (DP)-based approach. These algorithms aim to optimize EV charging schedules at DC fast charging stations, assuming predictable day-to-day EV data. The authors discovered that both the GA-based and DP-based approaches could substantially decrease charging costs when compared to non-optimal charging schedules. Specifically, they achieved reductions of 42.7% and 46.3%, respectively, over a 13-day period. These algorithms enable the global optimization of both EV charging time and the final SOC to minimize charging costs for individual charging events. Wu *et al.* [29] elucidated the significant challenge posed by the high operational costs of electric vehicle charging stations (EVCS), which hinder the widespread deployment of EVs due to the scarcity of EVCS. To address this issue, the authors proposed an approximate dynamic programming (ADP)-based energy management system (EMS) for EVCS with multiple types of chargers (EVCS-MTC). A fuzzy logic guiding system was developed to allocate appropriate charging spots to vehicles based on their charging urgency. Multiple EVs could utilize the charging service from a common charger in the EVCS-MTC. EMS, integrating ADP and evolutionary algorithms (EA), optimized charging start times for each EV, enhancing flexibility and reducing costs by over 50% compared to conventional schemes, considering dynamic electricity prices and uncertain future demand. This feature empowered the charging device to select the most favorable flexible charging pattern, thereby prolonging battery life and reducing communication requirements for the control system.

The objective of this project is to develop an advanced charging control strategy system for electric vehicle batteries, aiming to streamline society's daily routines effortlessly. The primary goals of this study encompass modeling an advanced charging system tailored for the infrastructure of EV battery charging. Subsequently, the study seeks to design effective modes of charger control strategies specifically for EV batteries, based on the operation of the system. Finally, the project aims to analyze the impact of the advanced charging control strategy system on the performance of EV batteries in terms of voltage, current, charging time, and rated capacity. Battery chargers can be categorized into conductive and inductive types. Conductive battery chargers utilize direct physical contact between the connector and the charge inlet, whereas inductive chargers transfer power magnetically. While some research focuses on moving chargers, inductive chargers are predominantly considered for stationary slow charging applications. Various research efforts have explored charging technique methods, particularly the CV method. This method concentrates on battery charging, where the charger maintains a constant voltage until the battery reaches a predefined current potential. The project developed an advanced current mode charging control strategy for electric vehicle batteries. Therefore, it is found that main improved charging efficiency, extended battery lifespan, enhanced safety, and demonstrated scalability. Their work represents a significant step forward in optimizing EV charging technology for better performance and sustainability.

2. METHODOLOGY

This study aims to quantify the financial benefits of EVs offering charging services using advanced control strategies based on CV and constant current principles. Specifically, it explores a novel approach to address battery degradation. Here, an advanced control system actively manages battery degradation by applying differential current control modes. This section delineates the development and evaluation setup of the controller.

2.1. Block diagram for battery charger system into electrical vehicle applications

The block diagram depicted in Figure 1 illustrates the main power supply with a rated terminal voltage of 240 V. However, to meet the requirements for battery charging, this voltage is subsequently reduced to 12 V utilizing an AC-DC converter employing the CV method. The variable voltage of the control charging system, which fluctuates based on changes in operating current, serves as a key determinant influencing the development of the buck-boost converter. This study endeavors to design a control charging system for EV battery, specifically focusing on regulating the DC output current and voltage of the buck-boost converter using the CC-CV method. To realize the objectives of this research design, the initial step involves simulating the buck-boost converter. This simulation is conducted utilizing simulation tools such as Proteus software to analyze the output waveform of voltage and current. Subsequently, the prototype development is evaluated, considering factors such as load speed and the efficiency of different charging modes.

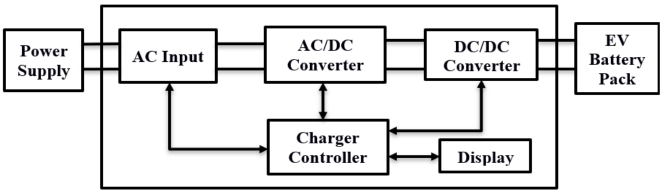

Figure 1. Block diagram for battery charger system into electrical vehicle applications

2.2. Design of charging control for EV battery simulation circuit

The advanced charging control system circuit utilizes the CV technique. The rectifier plays a crucial role in this circuit by converting AC to DC, effectively reducing the output voltage and current. However, the centerpiece of the circuit is the buck-boost converter, which functions to regulate the current and uphold the voltage within desired parameters. This critical component ensures precise control over the charging process. To control the buck-boost converter, the microcontroller Arduino Uno is employed, along with the TC4420 Driver and voltage and current sensors. These components work in tandem to monitor and adjust the charging parameters in real-time, ensuring optimal performance and battery health. Additionally, the output of the charging system is displayed on an LCD screen, showcasing different charging modes such as slow, medium, and fast charging. This visual feedback provides users with valuable information about the charging process, allowing for informed decision-making regarding their EV charging needs. Figure 2 depicts the completed battery charging circuit, showcasing the integration of various components working together seamlessly to achieve efficient and effective charging of EV. Changing the charging modes in an EV battery charging system involves using a sophisticated control system, typically part of the battery management system (BMS), to adjust voltage and current parameters according to predefined charging profiles. This process begins with selecting the appropriate mode based on battery state and charging strategy (e.g., slow, medium and fast). Voltage regulation is managed using DC-DC converters or similar power electronics to ensure the battery receives the correct voltage level for each mode. Current adjustment techniques like pulse-width modulation (PWM) or current limiting circuits are employed to deliver precise charging currents. Continuous monitoring of battery parameters such as voltage, current, temperature, and SOC via integrated sensors enables real-time feedback to optimize charging efficiency and battery health. Safety measures, including temperature sensors, and communication protocols, mitigate risks such as overcharging and overheating. Finally, a user interface provides operators or EV owners with control over mode selection, monitoring charging progress, and receiving alerts, ensuring safe and efficient charging operations.

2.3. Design of AC-DC converter model

The design of the AC-DC converter model, depicted in Figure 3, encompasses a comprehensive array of essential components meticulously integrated to facilitate efficient power conversion. The primary components featured in this design include input and output connectors, which serve as the interface between the AC power source and the DC output of the converter. Additionally, the design incorporates a voltage regulator, which plays a crucial role in stabilizing the DC output voltage of the converter. By ensuring that the output voltage remains within a specified range, despite fluctuations in the input voltage or variations in load conditions, the voltage regulator contributes to providing a consistent and reliable power supply to the connected load. The purpose of using a converter in the context of different voltage modes is to effectively regulate the charging process for electric vehicle batteries. In the slow charging mode, the converter boosts or adjusts the input voltage to deliver a high current, quickly replenishing the battery from a low state without exceeding safe voltage limits. During medium charging mode, the converter fine-tunes the voltage to gradually reduce the charging current as the battery approaches full capacity, preventing overcharging and maintaining optimal conditions for battery health. In fast charging mode, the converter maintains a stable, lower voltage to sustain the battery at full charge without causing damage from prolonged charging or self-discharge, ensuring the battery remains in optimal condition for extended periods of readiness and use. Overall, the converter's role across these modes is crucial in achieving efficient, safe, and reliable battery charging throughout the entire cycle.

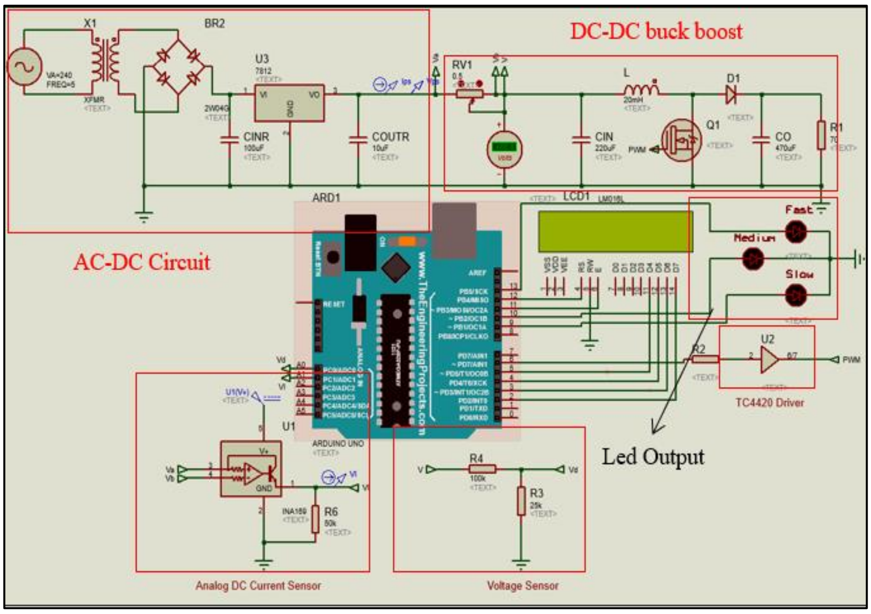

Figure 2. Advanced charging control battery circuit design using Proteus

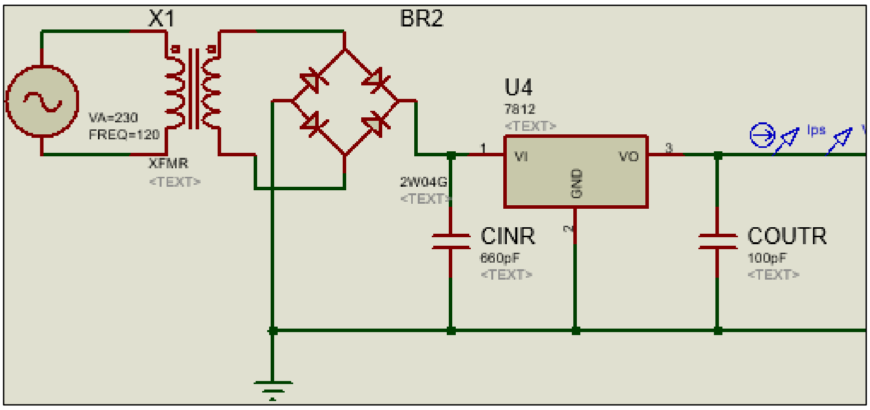

Figure 3. AC-DC converter circuit design using Proteus

2.4. Design of DC-DC converter model

The design of the DC-DC converter model, as illustrated in Figure 4, encompasses a carefully selected array of components essential for the operation of the buck-boost converter. The primary components featured in this design include input and output connectors, serving as the interface between the power source and the load. These connectors facilitate the transfer of power between the converter and the external devices, ensuring seamless connectivity and efficient power transmission. Another critical component of the DC-DC converter model is the metal-oxide-semiconductor field-effect transistor (MOSFET), which plays a pivotal role in controlling the flow of current through the converter. The MOSFET acts as a switch, enabling the converter to regulate the output voltage and current levels according to the requirements of the load. Additionally, the design incorporates a diode, which serves to prevent reverse current flow and ensure the efficient operation of the converter. The diode acts as a one-way valve, allowing current to flow in only one direction and preventing any backflow of current that could potentially damage the converter or the connected devices. Furthermore, the inclusion of an inductor, capacitor (100 µF), and resistor (10 kΩ) is essential for the proper functioning of the buck-boost converter. The inductor stores energy and helps to regulate the output voltage, while the capacitor and resistor work together to filter out any noise or ripple voltage present in the output signal, ensuring a smooth and stable DC output voltage for the connected load. In summary, the design of the DC-DC converter model involves the meticulous integration of various components, including input/output connectors, MOSFET, diode, inductor, capacitor, and resistor, to ensure efficient power conversion and the delivery of a stable and reliable DC output voltage suitable for powering a wide range of electronic devices and systems.

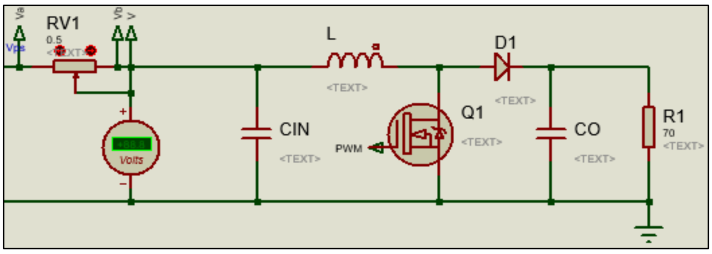

Figure 4. DC-DC buck boost converter circuit design using Proteus

2.5. Charging control circuit setup for batteries

The experimental design of the completed charging battery circuit, as depicted in Figure 5, incorporates an advanced charging control system utilizing CV techniques. The integration of the MOSFET connection within the DC-DC buck boost converter allows for precise control and data collection through the gate driver, ultimately facilitating communication with the Arduino Uno microcontroller. The Arduino Uno, in turn, orchestrates the charging process by leveraging data from the gate driver, voltage sensor, and current sensor to control the buck boost converter effectively. Additionally, the output from the DC-DC buck-boost converter is directed toward the battery, facilitating the charging process. The main functionality of this circuit lies within the DC-DC buck-boost converter, which effectively manages the current flow and voltage levels to ensure efficient charging. Furthermore, the Arduino Uno microcontroller is responsible for controlling the buck-boost converter, alongside the gate driver, voltage sensor, and current sensor. This control mechanism enables the microcontroller to adjust the charging parameters dynamically, catering to different charging modes such as slow, medium, and fast charging.

Moreover, Figure 6 presented various output designs, including voltage and current displays for the battery, a battery capacity indicator, input supply monitoring, a potentiometer for controlling charging modes, a load for discharging the battery, outputs for testing voltage and current, an LCD display for visual feedback, and a switch for activating the load. These output designs provide comprehensive monitoring and control capabilities, ensuring the efficient and effective operation of the charging battery circuit. The mode of charging is categories based on difference of current value that is, slow mode involves basic safety measures for slow charging from standard household sockets. The medium mode integrates added safety features like overcurrent protection when charging from domestic sockets. And the fast mode includes dedicated EV supply equipment (EVSE) with enhanced communication capabilities between the vehicle and supply point, ensuring safe and efficient charging. By controlling slow, medium, and fast charging for electric vehicles involves managing the charging current and voltage levels to achieve different rates of energy transfer. Slow charging typically uses lower currents, up to 0.49 A, and requires stable voltage from a charging station suitable for overnight or extended periods. Medium charging increases the current, ranging from 2.74 A, with similar voltage regulation as slow charging but reduces the overall charging time to a few hours. Fast charging utilizes high currents, often exceeding 4.62 A, and higher voltages, enabling rapid charging in under 30 minutes for quick stops or urgent needs. The control mechanisms include selecting appropriate charging stations or infrastructure, implementing charging profiles through the vehicle's BMS or charging station controls, and providing a user interface for easy mode selection and monitoring of the charging process, ensuring efficient and safe operation across different charging scenarios.

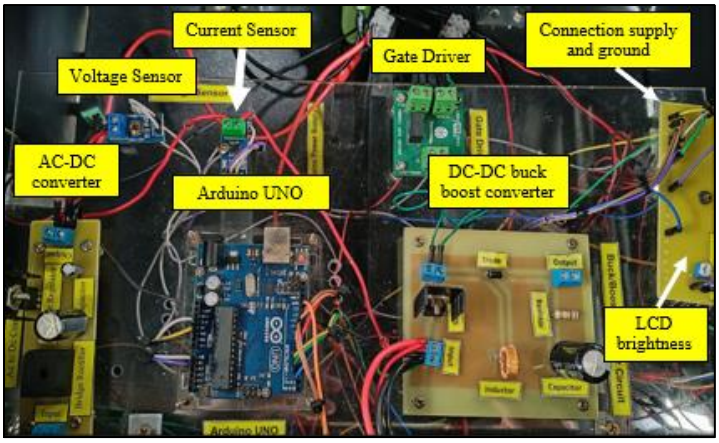

Figure 5. Charging control battery circuit in experimental setup

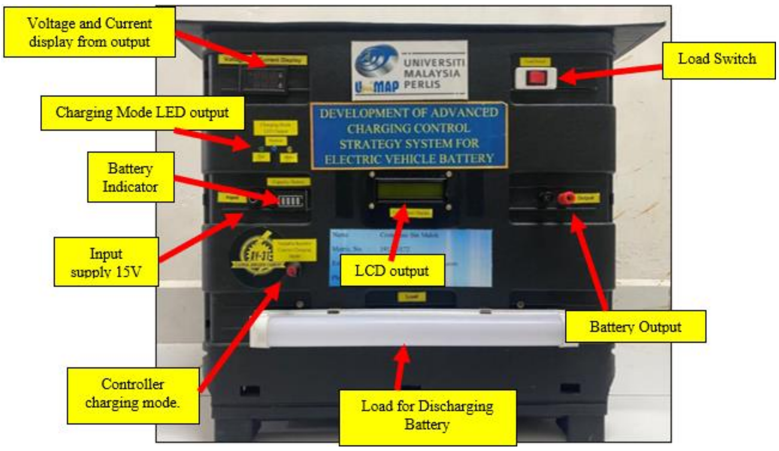

Figure 6. Overview of EV battery charging system

3. RESULTS AND DISCUSSION

In this section, during in slow charging mode selection, the potentiometer is on minimum value which consist of current is 0.49 A, and the charging time is 4 hours 40 minutes or 269 minutes. Secondly, when the potentiometer adjusted current to 2.74 A for medium charging mode the charging time is 0.8 hours or 48 minutes. Then, when the potentiometer increases to 4.62 A for fast charging mode selection and the charging time required is 0.48 hours or 28.6 minutes. In the charging modes, the power affects the charging to be fast and slow. Moreover, when the current is high the battery can be fully charged for 28.6 minutes at 12 volts while when the current is low the battery can be fully charged for 269 minutes with the same voltage of 12 volts. In this charging mode system, consist a lot of different result charging time when the voltage is not constant 12 volts. Table 1 show the result for theoretically calculation charging time with different charging mode. The (1) for charging time is [25]:

$$T = \frac{\text{Capacity Battery (mAh)}}{\text{Current (I)}} \tag{1}$$

While for power in (2) [26] is:

$$P = I \times V \tag{2}$$

Table 1. Calculation charging time based on charging mode selection

Charging mode	Voltage (V)	Current (A)	Charging time (minutes)
Slow	12	0.49	269
Medium	12	2.74	48
Fast	12	4.62	28.6

3.1. Simulation results of different charging modes performance

The selection of charging modes entails varying charging current values, primarily influenced by the potentiometer's pivotal role in regulating the resistor's value. This adjustment either increases or decreases the current flow. During the simulation, the waveform illustrates the characteristics of slow charging mode, showcasing a current of 0.45 A with a constant voltage of 11.83 V. Notably, the current experiences a reduction due to the potentiometer being set at its minimum value. Consequently, the voltage and frequency inputs are configured at 12 V and 50 Hz, respectively. The waveform analysis reveals a voltage peak to peak (Vpp) of 12 V, while the current peaks at 0.49 A. Figure 7 provides a visual representation of this waveform, showing voltage versus time, where the X-axis represents time and the Y-axis represents voltage and current values, depicting the current and voltage dynamics under slow charging mode conditions.

The simulation waveform analysis reveals intriguing insights into the medium charging mode dynamics. As observed, the voltage remains consistently at 11.44 V throughout the charging process. This stable voltage is accompanied by a notable increase in current, which escalates to 2.74 A. This surge in current is attributed to the potentiometer being adjusted to its medium value, effectively enhancing the flow of current. Furthermore, the voltage and frequency inputs are meticulously configured at 12 V and 50 Hz, respectively, to ensure optimal charging conditions. Despite the constant voltage input, the waveform display portrays a voltage peak to peak (Vpp) of 12 V, indicating the fluctuation of voltage within this range during the charging process. However, it's noteworthy that the peak current observed on the waveform remains consistent with the current readings, registering at 2.74 A. Figure 8 provides a visual representation of this waveform, showing voltage versus time, where the X-axis represents time and the Y-axis represents voltage and current values, depicting the current and voltage dynamics under medium charging mode conditions.

The simulation waveform analysis provides valuable insights into the dynamics of fast charging mode. Notably, the voltage remains constant at 11.39 V throughout the charging process. This stable voltage is coupled with a significant increase in current, which surges to 4.62 A. This notable rise in current is attributed to the potentiometer being adjusted to its maximum value, thus allowing for the maximum flow of current during the charging process. Moreover, it is important to note that despite the constant voltage input, the waveform display indicates a voltage peak-to-peak (Vpp) of 12 V, suggesting slight fluctuations within this range during the charging cycle. However, the current data reflects a maximum current of just 4.62 A, consistent with the readings obtained from the waveform analysis. Figure 9 provides a visual representation of this waveform, showing voltage versus time, where the X-axis represents time and the Y-axis represents voltage and current values, depicting the current and voltage dynamics under fast charging mode conditions.

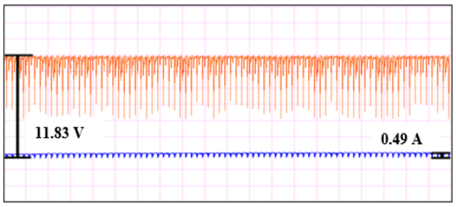

Figure 7. Simulation result for current and voltage in slow charging mode

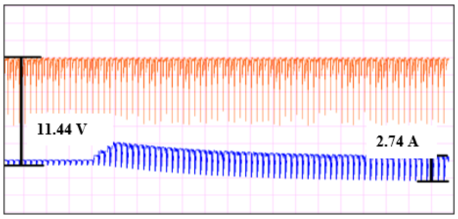

Figure 8. Simulation result for current and voltage in medium charging mode

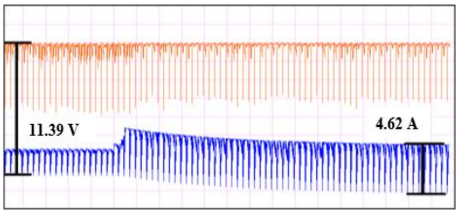

Figure 9. Simulation result for current and voltage in fast charging mode

3.2. Experimental results of charging time-based on charging mode selection

The results presented in the charging time table are based on the utilization of different potentiometer settings, each corresponding to a specific mode of charging: slow, medium, and fast. This Table 2 delineates the time taken for each mode of charging, both through simulation and experimental observation. Table 2 provides a comprehensive breakdown of the various charging modes alongside the corresponding currents and charging durations. To begin with, in the slow charging mode, a potentiometer with a resistance of 1 kΩ is employed to regulate the current flow. Upon reducing the potentiometer value to its minimum of 0.20 kΩ, the current diminishes to 0.49 A, consequently elongating the charging process to 264 minutes. Transitioning to the medium charging mode, an adjustment of the potentiometer to a value of 0.51 kΩ leads to an increase in current to 2.74 A. This augmentation results in a notably reduced charging duration of 50 minutes compared to the slow charging mode. Lastly, for fast charging, the potentiometer is set to its maximum value of 1.07 kΩ, elevating the current to 4.62 A. This substantial increase in current facilitates rapid charging, significantly reducing the charging time to just 30 minutes. Upon comparison between the simulated and experimental charging times for the EV battery, it is imperative to note any disparities or deviations. These variations provide valuable insights into the effectiveness and accuracy of the simulation model in predicting real-world charging behavior.

Table 2. Experimental charging time based on charging mode selection.

Charging mode	Ohm (kΩ)	Voltage (V)	Current (A)	Charging time (minutes)
Slow	0.20	12.90	0.49	264
Medium	0.51	12.73	2.74	50
Fast	1.07	12.95	4.62	30

3.3. Comparison of charging mode results between simulation and experimental studies

Table 3 displays a comprehensive comparison between the charging modes as per both simulated and experimental results. This table is instrumental in assessing the accuracy and reliability of the simulation model in predicting charging times. Subsequently, the percentage accuracy is computed to quantify the disparity between the simulated and experimental results. In the slow charging mode, the percentage accuracy in charging time between simulation and experimental results is calculated at 1.9%. Moving on to the medium charging mode, the percentage accuracy is slightly higher at 4%, indicating a marginally larger deviation between the simulated and experimental charging times. Finally, in the fast-charging mode, the percentage accuracy in charging time rises to 7%, suggesting a relatively larger discrepancy between the simulated and experimental results in this mode. Overall, the charging mode system has been successfully developed, with the simulation demonstrating a commendable level of agreement with the experimental results. The minimal percentage accuracy observed across the different charging modes underscore the effectiveness and reliability of the simulation model in accurately predicting the charging behavior of the system.

Table 3. Comparison of charging mode result between simulation and experimental

Charging mode	Simulation	Experimental	Differences in accuracy between simulation and experimental data
Slow	Current: 0.49 A	Current: 0.49 A	0%
	Voltage: 12 V	Voltage: 12.90 V	7%
	Charging time: 269 minutes	Charging time: 264 minutes	1.9%
Medium	Current: 2.74 A	Current: 2.74 A	0%
	Voltage: 12 V	Voltage: 12.73 V	5.7%
	Charging time: 48 minutes	Charging time: 50 minutes	4%
Fast	Current: 4.62 A	Current: 4.62 A	0%
	Voltage: 12 V	Voltage: 12.95 V	7%
	Charging time: 28.6 minutes	Charging time: 30 minutes	4.7%

3.4. Experimental result of battery capacity and charging time for three difference charging mode

The battery capacity performance exhibits distinct characteristics across three different charging modes. In the slow charging mode, where a current of 0.49 A, voltage of 12.90 V, and power of 6.31 W are applied, the battery requires 264 minutes to reach full charge. Conversely, in the medium charging mode, with a current of 2.74 A, voltage of 12.73 V, and power of 34.85 W, the charging time is reduced significantly to just 50 minutes for full battery charge. Finally, in the fast-charging mode, employing a current of 4.62 A, voltage of 12.95 V, and power of 50.80 W, the battery achieves full charge in a mere 30 minutes. Figure 10 visually represents the experimental results depicting the relationship between battery capacity and charging time across the three distinct charging modes. Figure 10 representation offers valuable insights into the performance of the battery under varying charging conditions, highlighting the impact of charging mode selection on charging time and overall battery capacity.

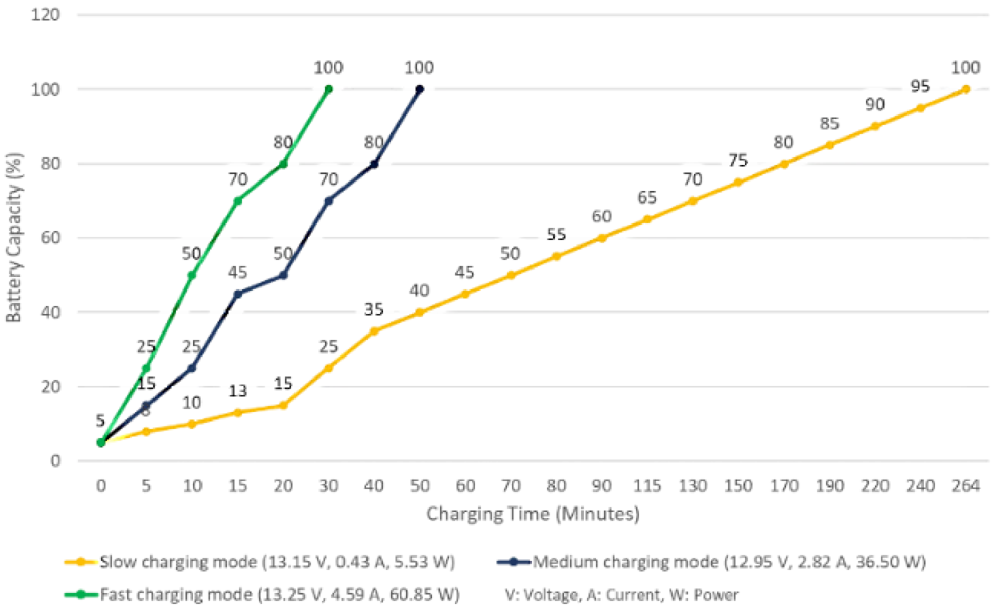

Figure 10. Comparison battery capacity and charging time for three differences charging mode

4. CONCLUSION

In conclusion, the analysis comprises three distinct charging modes for the battery, each simulated and examined thoroughly. These modes include slow charging, medium charging, and fast charging, with the circuit encompassing both AC-DC and DC-DC components. The regulation of current for charging mode selection is achieved through the utilization of a potentiometer, which adjusts the resistance value to render the current adjustable across the three charging modes. The charging technique employed in this system is CV. The results obtained for the slow charging mode indicate a current of 0.49 A, a power of 6.31 W, and a charging time of 264 minutes. Similarly, the medium charging mode yields a current of 2.74 A, a power of 34.85 W, and a charging time of 50 minutes. Finally, the fast-charging mode demonstrates a current of 4.62 A, a power of 50.80 W, and a charging time of 30 minutes. Comparing these results, it is evident that fast charging outperforms both slow charging and medium charging. This is primarily due to the highest current value of 4.62 A achieved in fast charging mode, leading to a significantly reduced charging time of just 30 minutes, in contrast to 264 minutes for slow charging and 50 minutes for medium charging. Moreover, the charging control system implemented can optimize the charging process, ensuring efficient charging of EVs while minimizing strain on the electrical grid. This system also contributes to balancing the demand for electricity on the power grid, thereby reducing the risk of blackouts or other disruptions.

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BIOGRAPHIES OF AUTHORS

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.

Muhammad Izuan Fahmi Bin Romli obtained his Ph.D. 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, optimization, and energy storage for electric vehicle. He can be contacted at email: izfahmi@gmail.com.

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.

Muhammad Ezanuddin bin Abdul Aziz currently serves as an assistant professor at Lincoln University College, Malaysia. He has also served as a dean in the Faculty of Architecture and Engineering at LUCT, Cyberjaya, Malaysia (2021-2023), Spectrum College of Technology, Subang, Malaysia (2021), and previously at Lincoln University College (2019-2020). With over 10 years of experience in the education sector, he holds a Ph.D. in Communication Engineering. Additionally, he has coordinated and spearheaded UniMAP's Institute of Electric and Electronic Engineers student branch for several years. He has also worked as a field engineer maintaining communication, server workability, and ICT hardware at a state hospital. He can be contacted at email: ezanuddin@lincoln.edu.my.

Diyya Hidayah Binti Abd Rahman obtained her master of engineering from Universiti Tun Hussein Onn Malaysia (UTHM). In 2008, she received the bachelor of electrical engineering (Hons) from Universiti Malaysia Perlis (UniMAP). Being active as vocational training officer in Universiti Malaysia Perlis, her current interest lies on renewable energy, control system, and power electronics. She can be contacted at email: dhidayah@unimap.edu.my.

Habibah Binti Haji Mokhtaruddin obtained her master of electrical engineering from Universiti Tun Hussein Onn Malaysia (UTHM). In 2008, she received the bachelor of industrial electronic engineering (Hons) from Universiti Malaysia Perlis (UniMAP). Being active as vocational training officer in Universiti Malaysia Perlis, her current interest lies on electrical installation, power electronics, and computer drafting. She can be contacted at email: habibah@unimap.edu.my.