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RELIABILITY STUDY OF SWAP TYPE LIFEPO4 BATTERY BRACKET FOR ELECTRIC MOTORCYCLES

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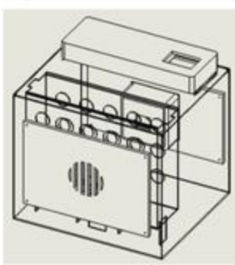
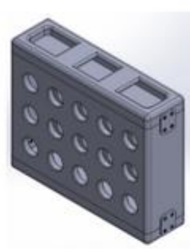
Graphical abstract

Design of Battery Charger



Design of Battery Case



Abstract

This research aims to conduct an in-depth study of the reliability of the swap-type LiFePO4 battery bracket on an electric motorbike. The main focus of this research is to evaluate the extent to which this battery bracket is reliable in everyday use, especially when facing various operational conditions. The methodological approach used in this study is very comprehensive. It includes a series of experiments and direct field tests on electric motorcycles equipped with LiFePO4 swap-type batteries. These tests were conducted to simulate various conditions encountered during daily use and evaluate the bracket's response. This study used three battery configurations: 24 Series 4 Parallel, 24 Series 5 Parallel, and 24 Series 6 Parallel. Reliability was calculated theoretically using an exponential reliability function, while experimental tests were conducted to measure the discharge duration and voltage stability under actual conditions. Theoretical calculation results show that the more cells are arranged in parallel, the higher the total reliability of the system. From the calculation results, 24 series 6 parallel configuration has the highest reliability compared to 24 series 4 parallel and 24 series 5 parallel. These results are supported by experimental testing, where 24 series 6 parallel shows a longer discharge duration and better voltage stability, indicating a more optimal system durability in long-term use. Thus, this study concludes that the 24 series 6 parallel configuration is the best option for improving the battery system's reliability on electric motorcycles. These findings provide important insights for developing more reliable battery pack designs for future electric vehicle applications.

Keywords: LiFePO4, Reliability, Series-Parallel Configuration, Electric Motorcycle, Optimization

Abstrak

Kajian ini bertujuan untuk menjalankan analisis mendalam terhadap kebolehpercayaan pendakap bateri LiFePO4 jenis tukar (swap-type) pada motosikal elektrik. Fokus utama kajian ini adalah untuk menilai tahap kebolehpercayaan pendakap bateri tersebut dalam penggunaan harian, khususnya apabila berhadapan dengan pelbagai keadaan operasi. Pendekatan metodologi yang digunakan adalah komprehensif, merangkumi satu siri eksperimen dan ujian lapangan secara langsung ke atas motosikal elektrik yang dilengkapi dengan bateri LiFePO4 jenis tukar. Ujian-ujian ini dijalankan bagi mensimulasikan keadaan sebenar penggunaan harian serta menilai tindak balas pendakap bateri terhadap beban operasi tersebut. Kajian ini menggunakan 3 konfigurasi bateri, iaitu 24 Siri 4 Selari, 24 Siri 5 Selari, dan 24 Siri 6 Selari. Analisis kebolehpercayaan dilakukan secara teori menggunakan fungsi kebolehpercayaan eksponen, manakala ujian eksperimen dijalankan bagi mengukur tempoh nyahcas dan kestabilan voltan dalam keadaan sebenar. Hasil pengiraan teori menunjukkan bahawa semakin banyak sel disusun secara selari, semakin tinggi kebolehpercayaan keseluruhan sistem. Berdasarkan keputusan tersebut, konfigurasi 24 Siri 6 Selari mencatatkan kebolehpercayaan tertinggi berbanding dua konfigurasi lain. Dapatan ini disokong oleh keputusan ujian eksperimen, di mana konfigurasi 24 Siri 6 Selari menunjukkan tempoh nyahcas yang lebih panjang serta kestabilan voltan yang lebih baik, menandakan ketahanan sistem yang lebih optimum untuk penggunaan jangka panjang. Oleh itu, kajian ini menyimpulkan bahawa konfigurasi 24 Siri 6 Selari merupakan pilihan terbaik bagi meningkatkan kebolehpercayaan sistem bateri pada motosikal elektrik.

Kata kunci: $LiFePO_4$, Kebolehpercayaan, Konfigurasi Siri-Selari, Motosikal Elektrik, Pengoptimuman

1.0 INTRODUCTION

Currently, electric vehicles utilizing renewable energy are being increasingly developed. Electric motorbikes are one of the vehicles being promoted because they are environmentally friendly; the exhaust emissions produced by electric motorbikes are zero [1], smoke-free, and do not cause noise, so they do not cause noise pollution [2]. Electric vehicles are also a short-term solution to reduce greenhouse gas emissions [3]. However, electric motorbikes have yet to be widely used because users tend to worry about the difficulty of setting charging patterns and finding battery charging stations closest by *fast charging/ battery swapping* if a *low battery* occurs [4]. The reliability of the distance traveled is also a significant factor influencing the spread of electric vehicles. Therefore, increasing the reliability of electric vehicle mileage by providing battery swap stations must be done [5].

In electric cars, the battery is the primary energy source that stores electrical energy and runs the engine so that the electric motor can move and become a source of electricity for electronic components and other systems. Good battery performance will support the devices it supports [6].

Batteries are vital components because they function as energy storage. [7]. *Lithium Iron Phosphate* (LiFePO4) batteries have been introduced as a material for the cathode in Li-ion batteries. LiFePO4 has a high energy capacity of 170 mAh/g and a *discharge* voltage of 3.4 V. LiFePO4 has various advantages compared to other cathode materials, such as affordable price, non-toxic, easy to obtain, high thermal and chemical stability, stable electrochemical performance in fully charged conditions, higher life cycle, high thermal and chemical stability, economic and environmentally friendly because it uses non-toxic materials. [8] However, LiFePO4 has disadvantages such as low conductivity, slow Li+ ion diffusion rate, and low energy density [9]. The following are the specifications of the 3.2 V 6 Ah LiFePO4 battery used in this study, shown in Table 1:

Table 1 LiFePO4 Battery Specifications

Item	Specification
Nominal Voltage	3.2 V
Nominal Capacity	6 Ah
Discharge Cut Off Voltage	2.0V
Charge Limited Voltage	3.65 +- 0.03 V
Standard Charge Current	0.2 C5 A
Standard Discharge Current	0.2 C5 A
Rapid Charge Current	0.5 C5 A
Rapid Discharge Current	3 C5 A
Max Discharge Current	3 C5 A
Max Pulse Discharge Current	5 C5 A
Weight	141 +-2g,
Diameter	16 mm
Height	70.5 mm

Battery quality and capacity also significantly affect the distance traveled, speed, and overall performance of an electric motorcycle. Charging the battery takes long enough to challenge electric vehicle users [10]. Swap type battery is a solution to overcome significant challenges electric motorcycles, namely the charging time tends to be slow [11]. With swap batteries, vehicle owners do not need to worry about battery degradation over time because the battery can be replaced with a new battery whenever required [12].

In the fast-charging system, there is a problem: the battery will heat up quickly, which results in the potential for burning/overheating and a significant decrease in battery life. To overcome this limitation, fast-charging technology with a cooling concept was developed. The battery pack design can be seen in Figure 1.

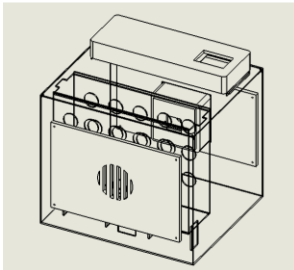


Figure 1 Battery Pack Casing Design

The battery pack casing design in Figure 1 was designed using the Solidworks 2021 application. The battery pack casing design has air-cooling ventilation holes. This innovation or novelty can improve the battery's thermal performance. These holes help circulate cool air through the battery, preventing overheating and increasing battery life. This design can also help maintain energy efficiency, especially in applications.

The body design of the swap battery recharging device is crucial because it affects the function, safety, efficiency, and user experience, as seen in Figure 2,

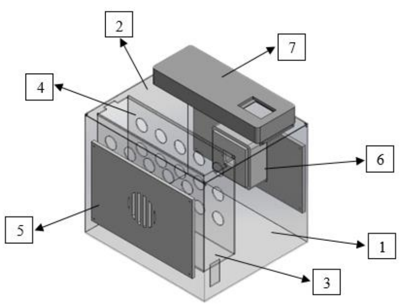


Figure 2 Battery Charging Tool Body Design

Where:

1. Body Charger 2. Charger Cover
3. Battery Holder 4. D.C. Fan Mount
5. Front Cover 6. Peltier Bracket
7. LCD Bracket

Next, the battery bracket is designed as follows, shown in Figure 3, which is also designed with Solidworks 2021.

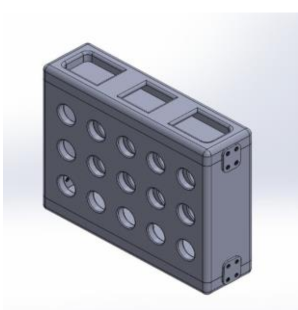


Figure 3 Battery Bracket Design

Reliability Study is a research or evaluation process conducted to measure the extent to which a product or component can function according to its purpose under various conditions and over a certain period without significant failure.

Reliability is defined as the probability of equipment or a system performing its function correctly, within a certain period, and under specific working conditions [13].

The reliability value consists of the failure value and the success value which when added together is one. The Weibull distribution is a distribution that is very important in the issues of reliability *and* maintainability analysis [14].

The following presents the fundamental equation of the theory. Weibull distribution for reliability analysis [15]:

$$h = \frac{b}{T}\left(\frac{t}{T}\right)^{b-1} . e^{-\left(\frac{t}{T}\right)b} \quad (1)$$

Where:

h = The probability density for "moment" t
t = *Lifetime* variable
T = Scale parameter
b = Shape parameter

The series-parallel configuration of battery cells can significantly affect system reliability. When battery cells are connected in a series configuration, the system voltage is the sum of the voltages of each cell. This means that if one cell fails, the entire system can be affected. On the other hand, a parallel configuration divides the current load between different cells, so that if one cell fails, only a specific part of the system is affected.

The reliability of the battery bracket system depends on the series configuration, parallel configuration, or series-parallel combination configuration. Generally, the battery bracket system uses a series-parallel combination configuration to match the voltage and current specifications designed in the battery bracket system in Figure 4.

If each reliability component has a different value:

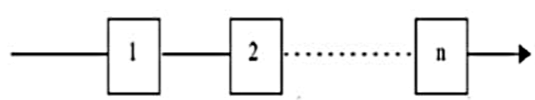


Figure 4 Series Configuration System

If each reliability component has a different value:

$$Rs = R1 \; X \; R2 \; X \ldots Rn \quad (2)$$

If each reliability component has the same value:

$$Rs = [Ri]^n \quad (3)$$

A parallel system is a configuration where not all components fail. If one part fails, then the system can still work. Conceptually, the parallel configuration system is not affected by the failure of one part, which causes the failure of the entire system (shutdown), so it still has the highest reliability value compared to other models. It can be seen in Figure 5, the system survives up to operating time T if one or both components remain functional (not failing).

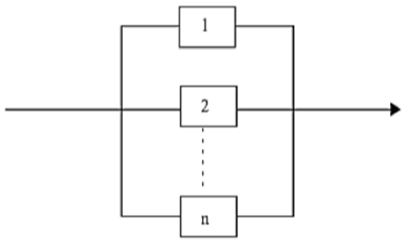


Figure 5 Parallel Configuration System

If each reliability component has a different value:

$$Rs = 1 - \prod(1 - R1) = 1 - (1 - R1)\ X\ (1 - R2)\ X\ (1 - Rn) \tag{4}$$

If each reliability component has a value the same one:

$$Rs = 1 - \prod(1 - R1) = 1 - [1 - R]^n \tag{5}$$

The combined series-parallel system will be further explained in the configuration shown in Figure 6. The

first subsystem consists of two blocks whose components are identically arranged in parallel and the second consists of five blocks arranged in parallel. Next, the two subsystems are combined into one system, and the overall system reliability is assessed {Formatting Citation}.

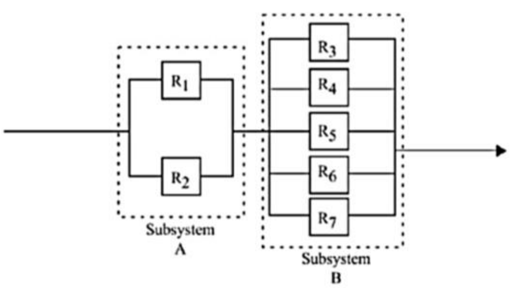


Figure 6 Combined series-parallel system configuration

Excessive temperature problems affect battery performance, which can cause mechanical damage to the battery and B.M.S. (Battery Management System) components [17], The BMS can be seen in Figure 7.

Figure 7 Battery Management System

When the temperature increases, it can cause effects such as overcharge, short circuit, or even explosion on the battery. The need for increased battery charging time with fast capacity.

This causes the battery's heat to increase, so the battery bracket needs to be equipped with cooling media [18].

A Peltier cooler is a tool used to convert electrical energy into heat with thermoelectric effects. The type of thermoelectric effect in thermoelectric coolers is the Peltier effect. Thermoelectric more excellent components consist only of heat absorbers and heat sinks. The heat sink part acts as a heat pump, while the heat sink part acts as a cooler.

2.0 METHODOLOGY

This research is based on the background written in the introduction. The research begins with a literature study on reliability, battery brackets, and electric motorcycles. Furthermore, specifications of tools and materials, testing methods, and data collection methods are found to determine reliability values. From the preparation - testing – and data collection series, an analysis process is carried out to reach conclusions that can answer the formulation of the problem. The battery swap charging circuit is shown in Figure 8

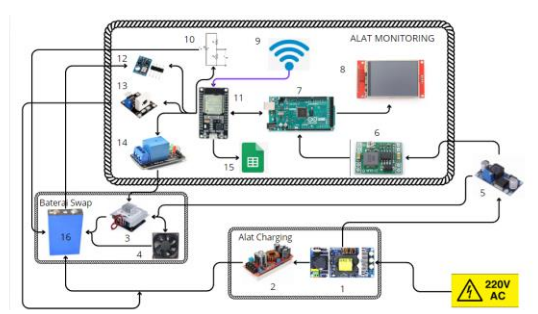


Figure 8 Battery Swap Charging Circuit

Infromation:

1. Transformator SMPS 36 Volt
2. Buck Converter Step Up 75 Volt
3. Peltier
4. Cooling Fan
5. Buck Converter Step Down 12 Volt

6. Buck Converter Step Down 5 Volt
7. Arduino Mega 2560
8. LCD TFT
9. Wi-Fi
10. Voltage Devider
11. ESP32
12. AHT10
13. WCS1700
14. Rellay
15. Spreadsheet
16. Battery

From PLN power which has an A.C. with a voltage of 220V entering through the power supply then converted into D.C. In the power supply there is a voltage regulator that functions to ensure that the output voltage from the power supply is stable and meets the needs of the step-up converter (also known as a boost converter), which is 12V, then from 12V to the step-up converter there is an increase in DC voltage to a higher level according to the battery charging requirements, namely 72V. The circuit design in Figure 9 and Figure 10 uses the EasyEDA application to make it easier to organize the circuit and troubleshoot. Manufacturing via EasyEDA also makes it easier to create PCBs.

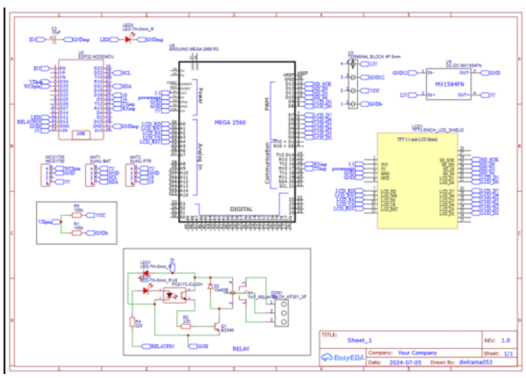


Figure 9 Monitoring System Circuit

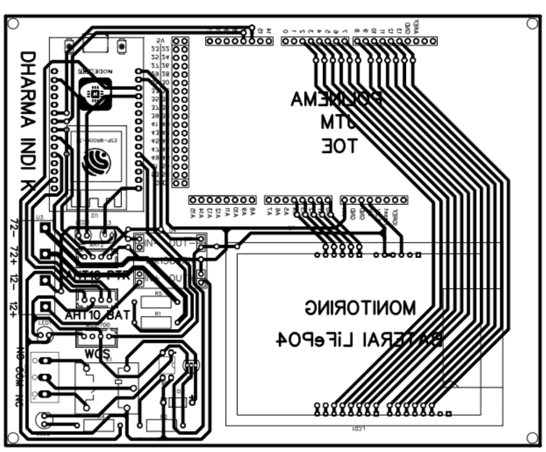


Figure 10 PCB Circuit

Next, Figure 11 is the prototype result of the battery pack casing design and charging tool in Figure 12.

Figure 11 Battery Casing

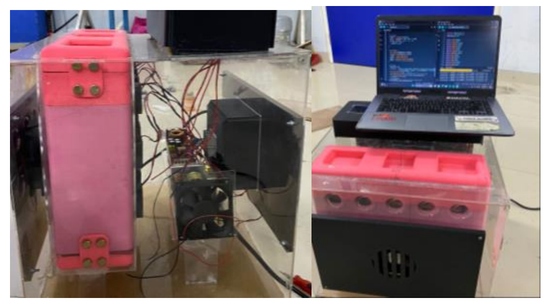


Figure 12 Prototype of Charging Device

Tool testing is done to prove whether the tool is working or not. Testing is done by charging the battery using and without coolant. This testing process can find problems with the tool and ensure that the tool is functioning correctly. When testing, the monitoring system and data-logger can monitor the charging that occurs in the battery so that the tool can function correctly. In addition, the accuracy of the measurement is also compared with a multi-meter as a standard for measuring voltage. The charging tool circuit also has a charging control system to ensure the correct current and voltage are applied to the battery, avoiding overcharging and battery damage. An LCD equipped with several sensors can display the battery percentage visually to avoid *overcharging* during the battery charging process.

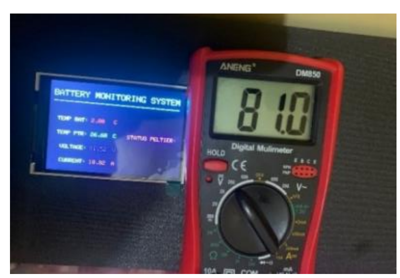


Figure 13 Measurement Results

The results obtained in Figure 13 show that the battery monitoring system produces a voltage of 81.52 V, while the multimeter is 81.0 V. Thus, the voltage difference is 0.52 volts. The charging device's output current is only capable of reaching 18 A.

3.0 RESULTS AND DISCUSSION

3.1 Optimization of Battery Series-Parallel Circuit Variations

Optimization of battery series-parallel circuit variations for reliability is the process of determining the best configuration of battery cells that maximizes the overall reliability of the battery pack system.

In a series circuit, adding battery cells increases the total voltage, but reliability decreases because the failure of one cell affects the entire circuit. A parallel circuit's total capacity and overall reliability increase because multiple parallel paths can support the load if one path fails.

In this study, LiFePO4 batteries were arranged in variations in battery configurations of 24 series and 4 parallel, 24 series and 5 parallel, and 24 series and 6 parallel. To determine the reliability of battery packs from 3 different configurations, the total voltage, total capacity, and overall reliability for each battery pack will be calculated.

1. Individual Battery Reliability

The following formula is a reliability function for an individual battery that follows an exponential distribution:

$$R(t) = e^{-\left(\frac{t}{T}\right)} \quad (6)$$

$R(t)$ is the probability that the battery is still functioning correctly at t.

t = 4440 (Battery usage time in cycles).

T = 22485 (Mean Time Between Failures or MTBF, the average time before the battery fails).

The ratio between t and T is calculated as:

$$\frac{t}{T} = \frac{4440}{22485} \approx 0.1974 \quad (7)$$

$$R(t) = e^{-0.1974}$$

$$R(t)e \approx {}^{-0.1974} \approx 0.82077 \quad (8)$$

The individual reliability of the LiFePO4 battery is 0.82077. This means there is about an 82.08% probability that the battery is still functioning properly after that period.

2. Battery Series Reliability (24 Series)

$$Rseries = Rn \quad (9)$$

$R = 0.82$ (1 Cell Reliability)

$n = 24$ (Number of cells in the series)

$$Rseries = 0.82^{24} \quad (10)$$

$$Rseries \approx 0.0413 \quad (11)$$

The reliability of the LiFePO4 battery series is 0.0413

3. Parallel Battery Reliability

$$Rparallel = 1 - (1 - R)^m \quad (12)$$

$R = 0.82$ (1 Cell Reliability)

m = Number of cells in parallel (4,5, or 6)

4. Reliability of Series Parallel Battery Combination

- 24 Series 4 Parallel Configuration

$$Rparallel = 1 - (1 - 0.82)^4 \quad (13)$$

$$Rparallel = 1 - 0.00105 \quad (14)$$

$$Rparallel = 0.9671 \quad (15)$$

Total Reliability 24 Series 4 Parallel Configuration

$$Rtotal = Rseries \times Rparallel \quad (16)$$

$$Rtotal = 0.0413 \times 0.9671 \quad (17)$$

$$Rtotal \approx 0.0399 \quad (18)$$

- 24 Series 5 Parallel Configuration

$$Rparallel = 1 - (1 - 0.82)^5 \quad (19)$$

$$Rparallel = 1 - 0.00019 \quad (20)$$

$$Rparallel = 0.9911 \quad (21)$$

Total Reliability 24 Series 5 Parallel Configuration

$$Rtotal = Rseries \times Rparallel \quad (22)$$

$$Rtotal = 0.0413 \times 0.9911 \quad (23)$$

$$Rtotal \approx 0.409 \quad (24)$$

- 24 Series 6 Parallel Configuration

$$Rparallel = 1 - (1 - 0.82)^6 \quad (25)$$

$$Rparallel = 1 - 0.00003 \quad (26)$$

$$Rparallel = 0.9976 \quad (27)$$

Total Reliability 24 Series 6 Parallel Configuration

$$Rtotal = Rseries \times Rparallel \quad (28)$$

$$Rtotal = 0.0413 \times 0.9976 \quad (29)$$

$$Rtotal \approx 0.412 \quad (30)$$

The 24 series 6 parallel configuration is the most reliable, providing a lower probability of system failure than other configurations.

3.2 Charging Test with Cooler and Without Cooler

The charging voltage tends to be stable from 81.36 V to 81.28 V for 120 minutes. In Figure 14 shows good stability and little voltage difference ranging from 81.14 to 81.37. There is a slight decrease in the 30-50 minutes data point, but the voltage value stabilizes afterwards. The reason is that when it reaches the 30th to 50th minute, there is a slight increase in battery temperature, so the BMS slightly lowers its voltage. However, when the battery temperature decreases, the voltage is monitored to return to normal and even increases. This proves that the cooling system affects voltage.

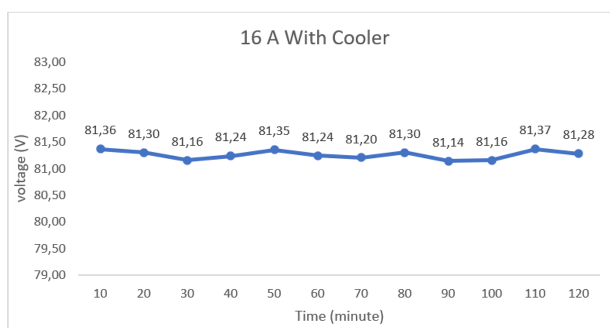


Figure 14 Input Voltage when Current is 16 A With Cooler

In Figure 15, the incoming voltage during charging is 16 A without cooling. Where when charging takes place, the charging voltage tends to last for 140 minutes. The graph shows a more significant voltage difference than 14 A with the cooler. Some sudden drops and increases indicate instability in charging without a coolant. The voltage values show more significant variation, with peaks at data points 20 and 60 reaching 80.92 and 81.08, respectively. This shows a more significant voltage difference than the graph with coolant. The difference in voltage stability in graphs 4.5 and 4.6 shows that voltage instability does occur at a current of 16 A without coolant. This is due to the higher temperature conditions compared to when using a coolant.

So, it can be concluded that this cooling system affects voltage.

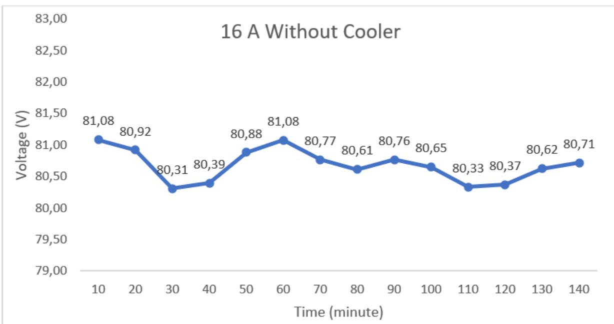


Figure 15 Input Voltage when Current is16 A Without a Cooler

3.3 Comparison of Using Cooler and Without Cooler

Figure 16 and Figure 17 show that the cooling system affects the voltage during the charging process. At currents of 12A, 14A, and 16A that do not use a cooling system, there is a larger voltage difference, and the charging time tends to be longer than when using a cooler with the same current variation. The cooling system can stabilize the voltage, so it can contribute to improving the performance and longevity of battery components.

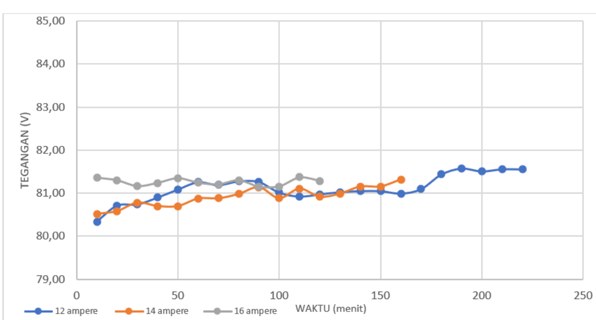


Figure 16 Voltage Stability Using a Cooler

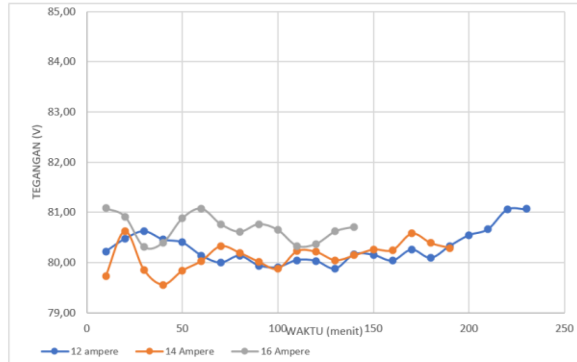


Figure 17 Voltage Stability Without Using a Cooler

3.4 Process Capability Test

Cp and Cpk tests are statistical methods used in quality control to measure the capability of the manufacturing process. This study uses the Cp and Cpk tests to determine the process capability of the fast charging type swap charging device with this cooling feature. Minitab 19 software was used for this processing, and the results are displayed in Figure 18.

Based on Figure 18, the LSL value is 80.34 V, and the USL is 81.56. The fast charging device with a cooling feature shows a *mean* value of charging around 81.0865. The standard deviation shows the variability in the process, with the deviation within (0.115208) lower than the overall (0.273465), indicating better control under optimal conditions.

With the cooling feature, the fast charging device can reduce the risk of overheating, keeping the charging process stable and safe. Cpk values (1.37) and Cp (1.76) indicate that the value is ÿ 1.33, which means the tool has a good and proper process.

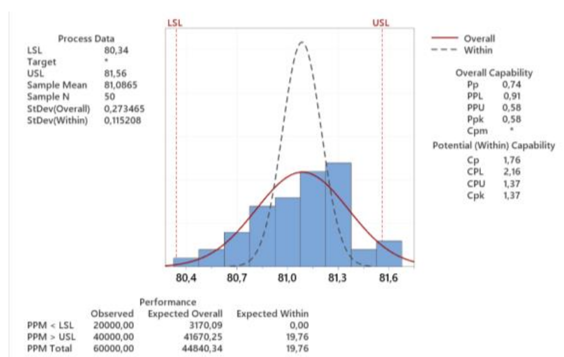


Figure 18 Process Capability Testing Results

3.5 Experimental Testing

The graph shown in Figure 19 is a Distribution Overview Plot for 24 series 4 parallel configuration lifetime using a Weibull distribution with ML (Maximum Likelihood) Estimates. The distribution peaks around 193.8–193.9, indicating that the lifetime values are most often found in this range. The shape of the curve shows a Weibull distribution that is positively skewed. The curve gradually decreases, indicating that the higher the lifetime value, the lower the probability that the battery will stay at that value.

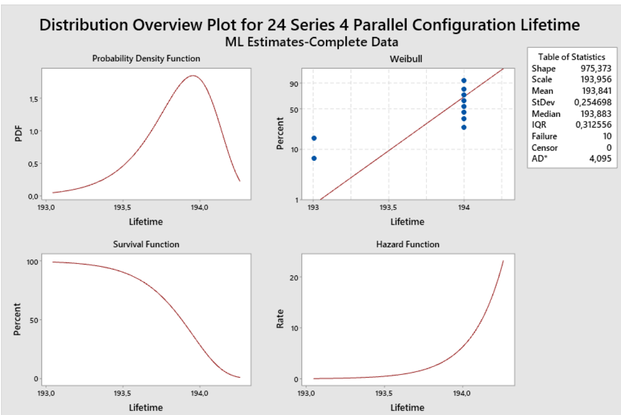


Figure 19 Distribution Overview Plot for Configuration of 24 Series 4 Parallel Combinations

In Figure 20, the X-axis shows the 24 series 4 parallel configuration lifetime, while the Y-axis shows the cumulative failure percentage. The blue dots are the actual data from the test results, and the main red line is the Weibull distribution estimated from the data. In this graph, most data points are located around the Weibull distribution line, but there is a slight deviation at the lower lifetime values (around 192.5–193). The Weibull distribution fits fairly well, but some deviations exist.

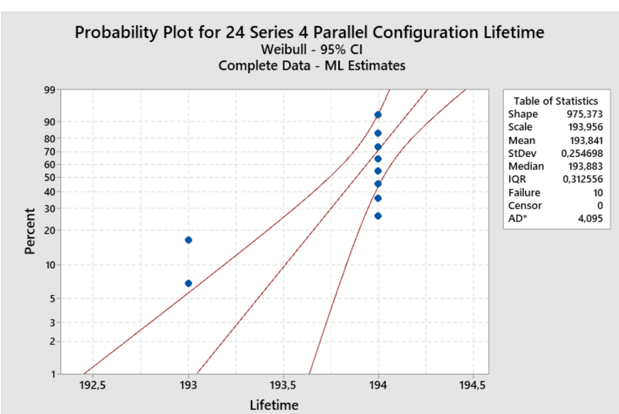


Figure 20 Probability Plot for Configuration of 24 Series 4 Parallel Combinations

2. Configuration of 24 Series 5 Parallel Combination

Figure 21, the Distribution Overview Plot for 24 series 5 parallel configuration lifetime, uses the Weibull distribution with ML (Maximum Likelihood) Estimates. This graph provides a more comprehensive picture than the Probability Plot of the 24 series 4 parallel battery pack configuration. The graph is skewed, with a peak of around 180. This means the lifetime most often occurs around 180, while events outside this range are rarer. The data distribution is relatively narrow, indicating the consistency of the lifetime. The blue dots on the graph represent the actual data, and the red line shows the estimated Weibull distribution. Most dots are close to the red line, indicating that the data is based on the Weibull distribution.

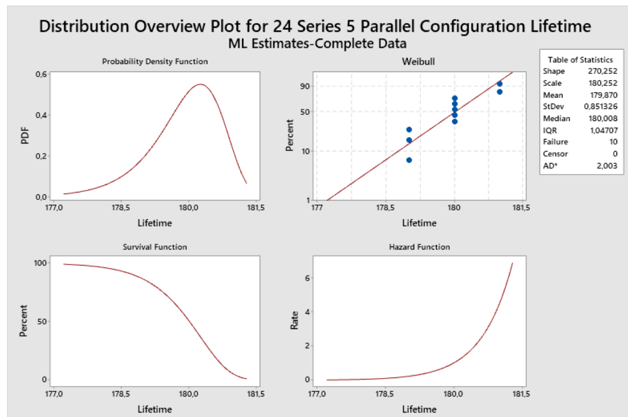


Figure 21 Distribution Overview Plot for Configuration of 24 Series 5 Parallel Combinations

In Figure 22, the X-axis shows the 24 series 5 parallel configuration lifetime, while the Y-axis shows the cumulative failure percentage.

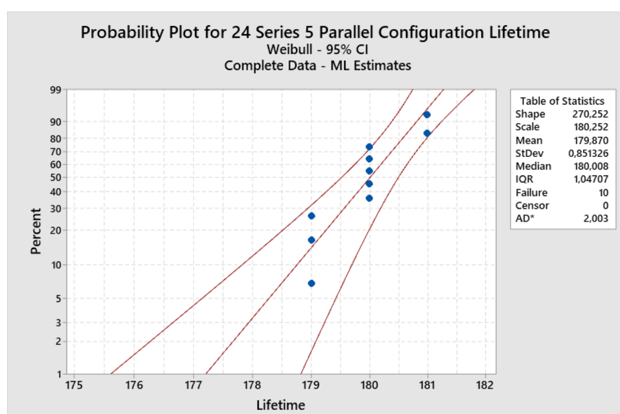


Figure 22 Probability Plot for Configuration of 24 Series 5 Parallel Combinations

The blue dots are the actual data from the test results, and the main red line is the Weibull distribution estimated based on the data. In this graph, Most of the blue dots are close to the straight red line, indicating that the data fit the Weibull distribution. The points that deviate slightly are still within the 95% CI limits, indicating that the model is valid. The dots align with the straight line in the middle, indicating that the Weibull distribution is accurate for this data.

3. Configuration of 24 Series 6 Parallel Combination

The graph shown in Figure 23 is the Distribution Overview Plot for 24 series 6 parallel configuration lifetimes, using Weibull distribution with ML (Maximum Likelihood) Estimates.

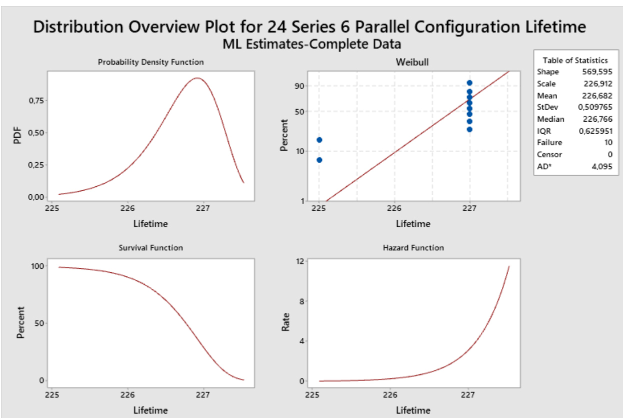


Figure 23 Distribution Overview Plot for Configuration of 24 Series 6 Parallel Combinations

This graph shows the relative probability of various lifetimes in the 24 Series 6 Parallel combination battery pack. The peak of the Probability Density Function curve is around 226.8, indicating that the lifetime is most often around this value. The asymmetrical curve indicates a Weibull distribution that tends towards a higher lifetime. The data points are spread close to a straight line, indicating that the Weibull model fits the data. This graph shows that the 24 Series 6 Parallel Combination battery pack shows the highest reliability among the other configurations, with an average lifetime value of 226.682. This system is suitable for applications that require long-lasting power. The stable survival function and low hazard function in the early phase indicate optimal performance over a longer period of time.

Figure 24 shows the test data following a Weibull distribution with a 95% Confidence Interval (CI). A large shape value indicates a low failure rate early in operation (high reliability). The median or middle value of duration shows that half of the batteries in the test had a lifetime above this value, indicating fairly consistent performance. The data points (blue) are relatively close to the distribution line, indicating that the test data fits the Weibull model. The confidence interval (red dashed line) provides a reasonable range of prediction for the variability in the data. The range of discharge times is relatively narrow (around 224 to 228), indicating stable performance for this configuration. The graph shows high reliability for the 24 Series 6 Parallel Combination configuration, with the risk of failure increasing gradually as the operating time increases. The average lifetime is close to the median and scale values, indicating a uniform or consistent distribution of battery performance across the test.

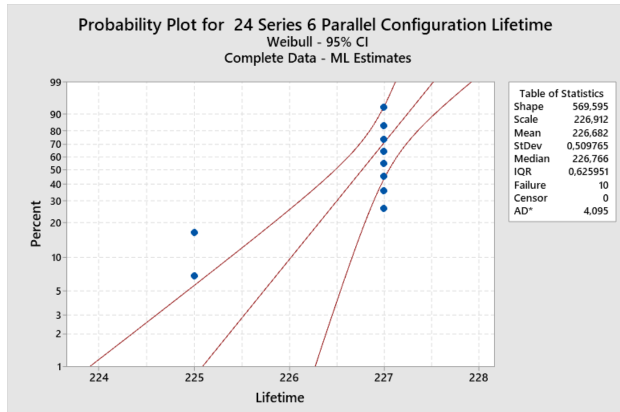


Figure 24 Probability Plot for Configuration of 24 Series 6 Parallel Combinations

4.0 CONCLUSION

The optimized LiFePO4 battery bracket design, using 3D Printing, acrylic, and a variety of air-cooling media, provides a high level of reliability. This bracket is designed to support batteries with an optimal series-parallel configuration so that it can withstand vibrations and impacts in various operating conditions of electric motorcycles.

Based on the results of theoretical calculations and experimental tests, the 24 series 6 parallel battery pack configuration is proven to have the highest reliability compared to other configurations, such as 24 series 4 parallel and 24 series 5 parallel.

Theoretically, system reliability is calculated by considering two main factors: series circuit reliability (24 series) and parallel circuit reliability (4 parallel, 5 parallel, and 6 parallel).

In a series configuration, the failure of one cell causes the failure of the entire system, while in a parallel configuration, the remaining cells can support the system even if some individual cells fail. The calculation results show that the system's total reliability increases with the number of cells in the parallel arrangement.

The experimental test results also show that the 24 series 6 parallel configuration can last longer with a lower failure rate than other configurations. This indicates that increasing the number of parallel cells can optimize the battery pack's reliability in actual use.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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