Research Article

International Journal of Data Science and Applications (JOINDATA) 7(1), 1-12, 2024

Received: 30-Apr-2024 Accepted: 02-Jun-2024

homepage: https://dergipark.org.tr/tr/pub/joindata

1476136

SAKARYA UYGULAMALI BİLİMLER ÜNİVERSİTESİ

Effects of Discharge Cut-off Voltage Level on Available Battery Charge Capacity and Battery Life

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ABSTRACT

The capacity of lithium-ion batteries decreases after each cycle. This decrease varies depending on the chemical structure of the battery, the magnitude of the current drawn from the battery, and the depth of discharge. To prevent deep discharge damages, the discharge cut-off voltage level is provided by the manufacturer. Exceeding this critical voltage level will decrease the discharge capacity of the battery. Therefore, to prevent damage to the battery, the battery voltage is continuously monitored during discharge processes, and operation at a voltage below this critical discharge cut-off voltage level is prevented. Conversely, if desired, drawing current from the battery can be stopped at voltage levels greater than the discharge cut-off voltage level determined by the manufacturer. However, in this case, the battery's full charge capacity cannot be utilized. Consequently, the preferred discharge cut-off voltage level will either affect the battery's lifespan or result in less utilization of the battery capacity in each cycle. This article presents a study investigating how the discharge cut-off voltage level affects the battery charge capacity. The study examines the available charge capacity and the decrease in charge capacity according to the cut-off voltage.

Keywords: Battery management systems, Energy storage, Lithium-ion batteries, Product lifecycle management, State of charge.

1 Introduction

In recent years, increasing environmental awareness has led to a growing inclination towards the use of clean energy instead of fossil fuels. In many fields, the energy needs are met by burning fossil fuels. During the process of converting fossil fuel energy into thermal energy, harmful gases are released into the atmosphere as a byproduct of combustion. Today, the increasing concentration of these gases in the atmosphere has raised awareness and prompted a shift towards methods of obtaining the necessary energy without producing harmful gases. This trend has been particularly prominent in the automotive sector. Fuel cells and chemical batteries have emerged as alternatives to fossil fuels, with chemical batteries being more widely adopted due to challenges associated with hydrogen storage and

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transportation in fuel cells, as well as safety concerns [1]. Additionally, the infrastructure and technology required for hydrogen production, storage, and distribution make chemical batteries more advantageous in terms of cost [2].

Among chemical batteries, lithium-ion batteries (LIBs) have found widespread application due to their high energy density, low self-discharge rate, minimal memory effect, rapid charging and discharging capabilities, and longer cycle life [3]. This has particularly contributed to their increasing use in electric vehicles.

Currently, LIBs are produced and used with various chemical compositions, leading to differences in their cycle life. A cycle consists of one full charge and one full discharge, and the end of life occurs when the battery's nominal capacity drops to a certain level, typically around 80%. Manufacturers provide information on the cycle life of the LIBs they produce. However, this cycle count may vary depending on factors such as usage conditions, charge/discharge rate, battery temperature, ambient temperature, etc. [4]. The variation in battery lifespan under different usage conditions has necessitated the prediction of battery life to prevent unexpected failures and ensure uninterrupted operations in many applications. Therefore, in recent years, the number of studies on battery state of health estimation [5, 6] and battery life prediction [7, 8] has increased.

In laboratory settings, charging during a cycle is typically done using constant current-constant voltage charging, while discharging is usually done at a constant current. However, in practice, the currents drawn from batteries by electric vehicles vary during usage [9]. In fact, electric vehicles with regenerative braking feature charging during braking, deviating from the notion of discharging at a constant current for a cycle. To define a realistic battery discharge process, driving cycles have been introduced [10]. These driving cycles vary depending on geography, city traffic density, transportation infrastructure, etc. Different countries, and even different cities within the same country, have established different driving cycles tailored to their specific conditions [11]. The most common ones include:

- NEDC (New European Driving Cycle): Commonly used in Europe but replaced by WLTP (Worldwide Harmonized Light Vehicles Test Procedure) since 2017.

- WLTP (Worldwide Harmonized Light Vehicles Test Procedure): A global standard used in vehicle emission and fuel consumption tests.

- FTP-75 (Federal Test Procedure - 75): A driving cycle frequently used in the United States, representing urban driving conditions.

- HWFET (Highway Fuel Economy Test): Used by the Environmental Protection Agency (EPA) in the United States, representing highway driving conditions.

- JC08 (Japanese 10-15 Mode Cycle): Used in Japan, replacing NEDC.

- BJDC (Beijing Driving Cycle): Represents urban traffic conditions in Beijing, China.

- US06 (United States Federal Test Procedure - 06): Represents aggressive driving conditions in the US, designed to measure acceleration and deceleration capabilities at high speeds.

- DST (Durability Driving Cycle): Used to evaluate the durability and long-term performance of vehicles. It includes various driving conditions to test the durability of the engine, transmission, and other components. Understanding how vehicles will perform in long-term use is essential.

LIBs are discharged according to these driving cycles. When the critical voltage level, which is the charge cut-off voltage, is reached during discharge, the discharge process is terminated. Dropping below the charge cut-off voltage level permanently damages the chemical structure of the battery, significantly reducing its capacity. Moreover, if the discharge process continues, the chemical reactions of the electrolytes inside the battery can occur uncontrollably, leading to serious problems such as overheating and even explosion [12]. Therefore, terminating discharge at the charge cut-off voltage is crucial. Adherence to the values specified by the manufacturer becomes mandatory. However, this voltage value is determined through processors via analog-to-digital converters in Battery Management Systems (BMS). An error from either the sensor or the calculation can cause discharge to drop below the cut-off voltage. Therefore, rather than operating at the limit value, a slightly tolerant upper voltage level for discharge termination is preferred. This ensures that the battery operates within a safe range without exceeding the critical level. However, increasing the discharge cut-off voltage level will result in the full capacity of the battery not being fully utilized. Furthermore, the impact of this on the battery's lifespan is uncertain. In other words, the nominal capacity of the battery will decrease after the battery cycle processes, but how selecting a higher cut-off voltage level will affect this decrease is uncertain. This study presents an investigation into how the capacity of the battery is affected when the cut-off voltage level is set higher than the nominal charge cut-off voltage specified by the manufacturer, and how much of the available capacity is sacrificed. To achieve this, as in health condition detection and remaining useful life prediction studies, batteries are initially fully charged using the constant current-constant voltage procedure and then aged by full discharge in the DST driving cycle. The reason for selecting the DST driving cycle is that it is designed to push the limits of the tested motors. Adapting this driving cycle to the batteries of electric vehicles will also result in the batteries being discharged in a way that challenges their limits. Consequently, as the batteries undergo aging with the DST driving cycle, the adverse effects of each cycle on the battery will become more pronounced. Discharge termination was conducted at three different cut-off voltage levels, one of which is nominal. Three ASPILSAN INR18650A28 batteries were aged for 60 cycles, and values were recorded. The results obtained were used to investigate the effects of the cut-off voltage on battery capacity reduction.

2 Cycle Process and DST (Durability Driving Cycle)

A vehicle typically undergoes a design phase before being put into production. Testing the performance, fuel economy, and emissions of the produced vehicles by a driver over days or months would be cumbersome. Standardized evaluation of these tests in a controlled environment would facilitate trial processes. Therefore, test procedures designed to simulate driving conditions for vehicles have been developed. These procedures are referred to as "driving cycles." A driving cycle typically demonstrates how a vehicle behaves at different speeds, accelerations, and stop-and-go conditions within a certain period. These cycles can be designed for urban, highway, or mixed driving conditions, depending on the geographical characteristics, traffic density, or transportation infrastructure of the area where the vehicle will be used. These driving cycles ensure the comparability of different vehicle models. Vehicle manufacturers typically use driving cycles to optimize their vehicles' performance and ensure compliance with legal regulations. Additionally, driving cycles play an important role in the development of new technologies such as electric vehicles [13].

One of the most important parameters of electric vehicles is range, which is related to how efficiently batteries are used. To properly evaluate the behaviour and efficiency of batteries used in vehicles, it becomes important to discharge the batteries according to drivers' daily usage patterns. Therefore, driving cycles are adapted to electric vehicle batteries. For electric vehicles, driving cycles are often used to evaluate the battery's life and performance. These cycles simulate the vehicle's electricity consumption at different speeds and conditions, allowing estimations to be made about how far a vehicle can travel on a single charge or the lifespan of a battery pack [11, 14].

The duration of a driving cycle varies depending on the conditions under which it is prepared. Therefore, the duration from the beginning to the end of the driving cycles used worldwide differs from one another [15].

One driving cycle will not be sufficient to fully discharge a battery from a fully charged state to a fully discharged state. Therefore, the same driving cycle is applied until the battery is fully discharged [16]. In this study, the DST driving cycle was used. The current-time graph associated with the DST cycle is shown in Figure 1.

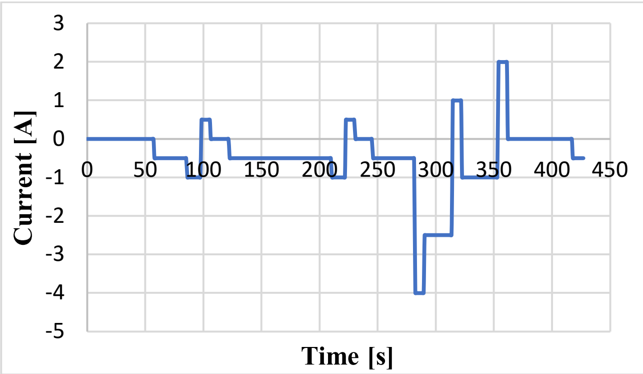

Figure 1: Current-time graph for the DST cycle.

One cycle of the DST driving cycle takes 426 seconds. Positive currents in the graph represent moments of regenerative braking, while negative currents indicate the currents drawn from the battery to generate power. This driving profile is applied after the battery is fully charged until the battery voltage drops to the discharge cut-off voltage. Thus, completing one cycle of the battery's operation. Figure 2 shows the current and voltage graph obtained during the full discharge process with the DST cycle.

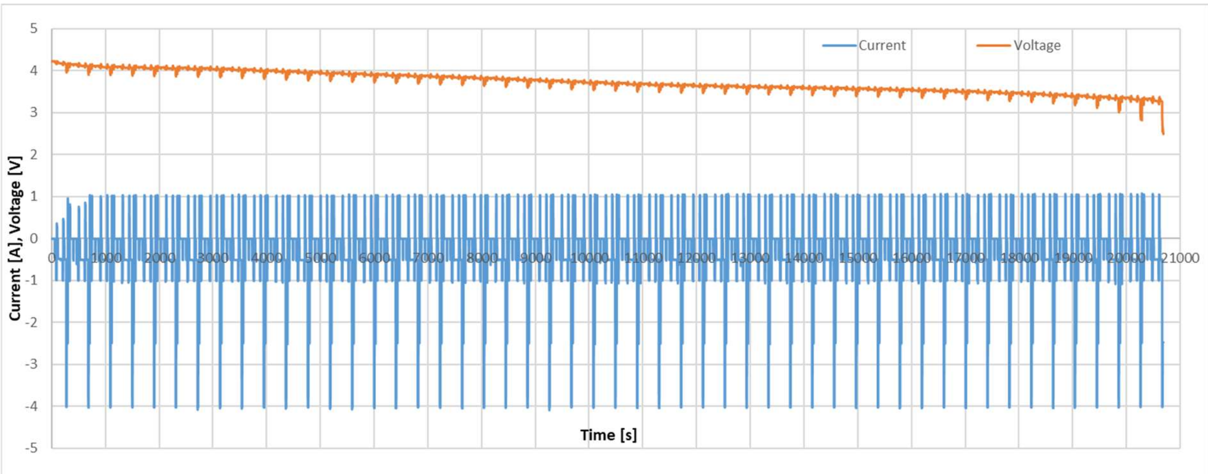

Figure 2: Current and voltage graphs obtained during full discharge process with the DST cycle.

The current and voltage curves in the graph illustrate the behavior of the battery during the full discharge process in detail. Initially, the voltage is at high levels as the battery is fully charged. However, as the discharge process begins, the voltage continuously decreases as current is drawn from the battery according to the DST driving cycle. The area under the curve in the graph represents the total energy delivered during the discharge process, while the area above represents the energy supplied to the battery. Analyzing this graph obtained with the DST cycle helps determine the storage capacity of the battery and its performance during the discharge process.

3 Experimental Study

In this study, the effect of discharge cut-off voltage level on battery capacity is examined. For this purpose, three identical batteries were subjected to 60-cycle aging tests using standard driving cycles. The batteries used are identical and are ASPILSAN's INR18650A28 lithium-ion batteries. The label values for the batteries are provided in Table 1.

Table 1: *Nominal values of batteries used in experiments.*

Parameter	Values
Discharge Capacity	2900mAh
Nominal Voltage	3.68V
Energy Density	244Wh/kg
Charging Cut-Off Voltage	4.25V
Standard Discharge Current	580mA
Max. Continuous Discharge Current	25000mA
Discharge Cut-Off Voltage	2.5V

Each battery was fully charged using the constant current constant voltage method before the discharge process began. The discharge process was conducted according to the DST driving cycle, and it was terminated based on the discharge cut-off voltage. Three different levels of cut-off voltage were determined for the study:

- For Battery 1: 2.5V

- For Battery 2: 2.7V

- For Battery 3: 2.9V

Each battery was fully charged at the same level, but the discharge process was terminated at its respective discharge cut-off voltage in each cycle.

Using the DST driving cycle during the discharge process necessitates both charging and discharging of the battery within the same period. Therefore, a system was designed to perform one cycle of aging during the battery aging process. This system includes three main components:

- A constant current - constant voltage source

- Programmable electronic load capable of maintaining a constant current

- Control board.

Based on the battery values given in Table 1, the battery voltage ranges between 2.8V and 4.2V. Additionally, the 1C value is 2.7A. Considering these values, a power supply was selected. The power supply used in the experiments can adjust the voltage between 0-35V and the current between 0-5A, providing a constant current and constant voltage output at the set values. This allows for the adjustment of the desired constant charge current and the maximum charge cutoff voltage to charge the batteries.

During the discharge processes, when the DST driving cycle given in Figure 1 is used, the maximum current drawn from the battery is 10.8A (4C). The programmable load unit is an electronic load that allows a constant current to be drawn from a source within the range of 0-12A. This enables the discharge of the battery using the DST cycle with this load unit.

The control board determines when the power source and the load will be activated at which level, referencing the DST driving cycle. In this activation process, the control board directs the flow of current between the battery, power source, and load through relays on the control board. Additionally, the designed control board reads the terminal current and terminal voltage and transfers this data to a computer via wireless data transmission. The data transferred to the computer is stored on the hard disk. In this context, the block diagram of the experimental setup is provided in Figure 3, and a photograph of the experimental setup is given in Figure 4.

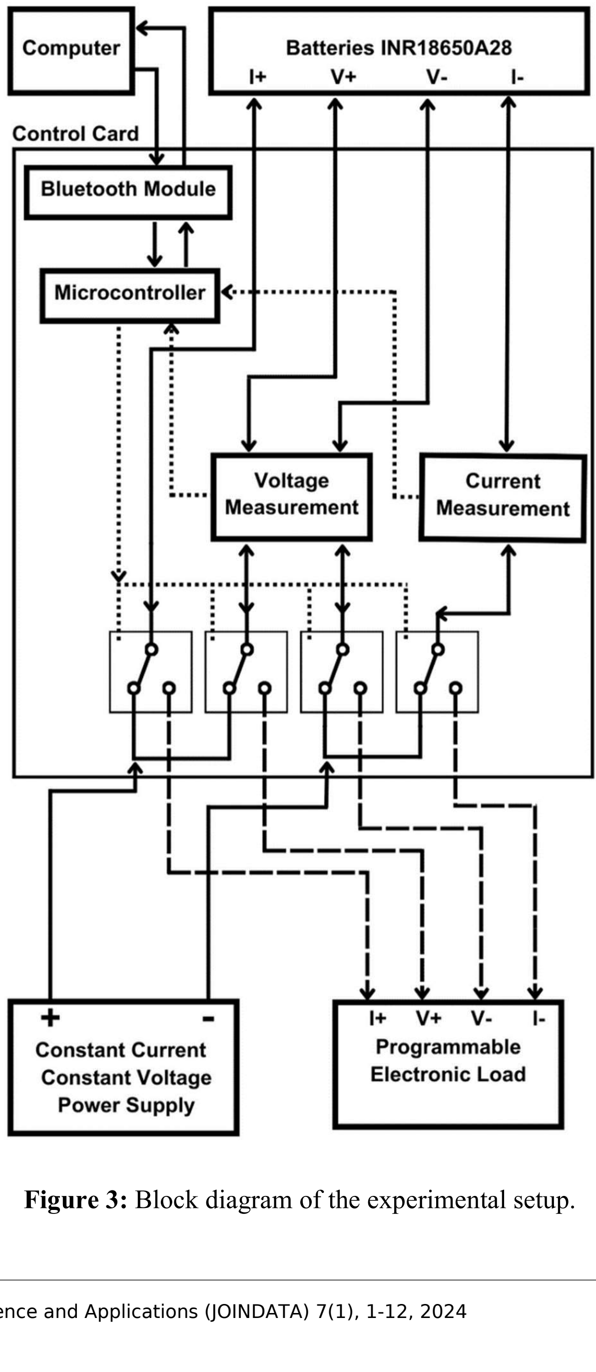

Figure 3: Block diagram of the experimental setup.

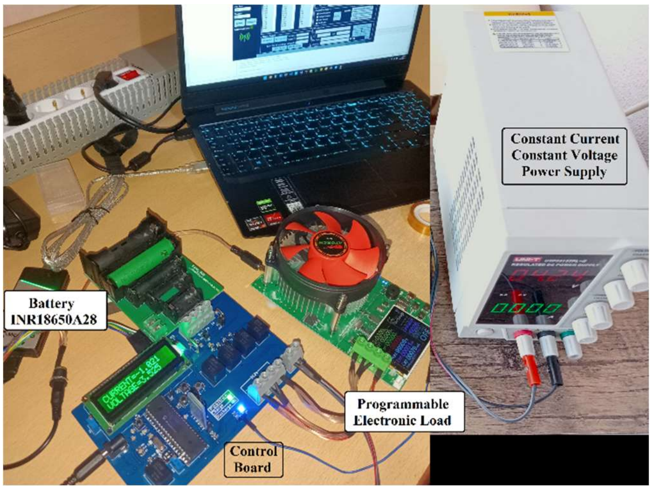

Figure 4: Photo of the experimental setup.

In each aging cycle, the charging and discharging processes were carried out sequentially, starting with Battery 1, followed by Battery 2, and then Battery 3. The same sequence of charging and discharging was repeated when moving to the 2nd cycle. Each cycle was completed in approximately 6 hours. Initially, before any usage, the batteries were fully charged using the constant current - constant voltage method, and then fully discharged at a constant current, and their capacities were recorded in the table. After the tests began, the battery capacities were recorded in the table every 10 cycles. The capacities obtained after each cycle were compared to the total load amount indicated on the programmable electronic load and the calculated battery capacity value obtained through the current integration method using the designed control board, ensuring the accuracy of the measured capacities.

This procedure was followed to document how the capacity was affected during the aging process. Due to the pronounced adverse effects of the cycles on the battery observed during the experimental study, the study was concluded after the 60th cycle. Thus, a total of 60 cycles of charge-discharge operations were completed for the three batteries. The flow chart of the testing process is given in Figure 5. All experiments were conducted in the same environment and at room temperature.

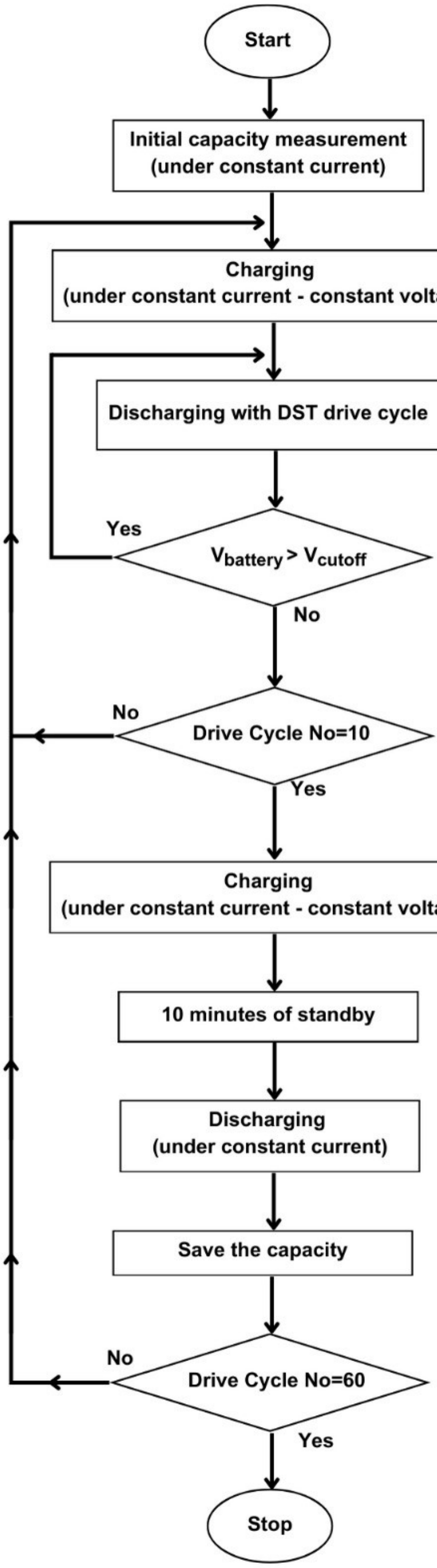

Figure 5: The flow chart of the testing process.

4 Experimental Results

The initial capacity values and the capacity values obtained after every 10 cycles of the 60-cycle tests conducted for Li-ion batteries are provided in Table 2.

Table 1: *The capacity values were obtained after 60 cycles of testing.*

Cycles	Battery1 Vcut-off 2,5V	Battery2 Vcut-off 2,7V	Battery3 Vcut-off 2,9V
0	2880	2850	2800
10	2770	2806	2780
20	2813	2790	2758
30	2793	2787	2771
40	2791	2758	2765
50	2796	2778	2779
60	2753	2760	2743

When examining the aging process of all batteries, a noticeable decrease in capacity is observed. This decrease becomes more pronounced as the number of cycles increases. To determine the relationship between the values in Table 2 and to make clearer conclusions, the values were plotted on a graph, and a linear trend line was obtained from the plotted points. The obtained linear trend graphs are shown in Figure 6, and the mathematical expressions for these trend lines are provided in Table 3.

Table3: *Mathematical expressions of linear trend lines.*

Battery Number [$V_{cut\text{-}off}$]	**Mathematical expressions**
1 [2.5V]	$y = -1.2536x + 2837$
2 [2.7V]	$y = -1.2786x + 2828$
3 [2.9V]	$y = -0.5929x + 2788$

This section may each be divided by subheadings or may be combined. This should explore the significance of the results of the work, don’t repeat them. Avoid extensive citations and discussion of published literature only, instead discuss recent literature for comparing your work to highlight novelty of the work in view of recent development and challenges in the field.

In the discussion section, the conclusions of the current study are compared with the conclusions of similar studies in the literature while interpreting the possible reasons for the conclusions.

5 Discussion

When examining the aging process of all batteries, a noticeable decrease in capacity is observed. This decrease becomes more pronounced as the number of cycles increases. When inspecting the values in Table 2, it can be seen that after the 1st cycle, the capacity of Battery 1 decreases more rapidly compared to the others. This situation can be considered as an indication of the tendency of the battery's chemical structure to deteriorate due to the low discharge cutoff voltage.

As the number of cycles increases, capacity values decrease for each battery. However, sometimes the values can be higher than in the previous cycle. This discrepancy may arise from measurement errors due to the current integration method or the inability to reach the full charge voltage during charging, resulting in incomplete charging. These errors are negligible proportionally. Therefore, instead of analysing the results of each cycle individually, analyses were conducted based on the linear trend lines shown in Figure 6.

Upon examining Figure 6, it is evident that as the number of cycles increases, the capacities of all three batteries decrease at a certain rate. While the decrease rates are similar for Battery 1 and Battery 2, Battery 3 exhibits a slower decrease in capacity. The exact decrease rates can be observed from the slopes of the trend lines provided in Table 3, where it is found that the decrease rate for Battery 1 is -1.2536, for Battery 2 is -1.2786, and for Battery 3 is -0.5929. Although the capacity decreases for Battery 1 and Battery 2 may appear similar in the graph in Figure 6, it is apparent from the slopes of the trend lines that Battery 2's capacity decreases more rapidly compared to Battery 1 as the cycles progress. The capacity decrease for Battery 3 is slower than both Battery 1 and Battery 2. Consequently, it can be inferred that a discharge cutoff voltage of 2.9V is the optimal value for this battery model.

However, due to variations in the electrolyte, anode, and cathode production processes, as well as the final assembly stages of the battery and the initial charging (conditioning) process after production, complete uniformity may not be achieved in the batteries produced. Additionally, Battery 3 may have a different uniformity from the others, leading to such a difference. Moreover, the cutoff of the discharge current from the battery at a higher discharge cutoff voltage may result in better preservation of the battery chemistry, leading to a more efficient cycle process and capacity preservation.

To examine the effects of discharge cutoff voltages on the capacities obtained from the battery, the arithmetic mean of the values in Table 2 was calculated. The average capacities were found to be 2799 mAh for Battery 1, 2789 mAh for Battery 2, and 2770 mAh for Battery 3. This calculation demonstrates that reducing the discharge cutoff voltage reduces the usable capacity of the battery. However, when this decrease is compared to the battery capacity, it remains very small. The decrease rates are 2.8% for Battery 1, 2.1% for Battery 2, and 1.04% for Battery 3. The capacity decrease for Battery 3 is lower than the others. Considering that the highest cutoff voltage (2.9V) was applied in the tests for Battery 3, it can be concluded that discontinuing the current draw from the battery at higher discharge cutoff voltage levels may lead to healthier battery usage, thereby extending its lifespan.

6 Conclusions

This study presents an investigation into how the discharge cutoff voltage level affects the charging capacity of LIP batteries. Three batteries underwent 60-cycle aging tests. During the tests, discharge processes were operated in DST standard driving mode. In these aging processes, full discharge was performed with the battery cycle being stopped at three different discharge cutoff voltages. The current capacities were recorded every 10 cycles. The results obtained from the examination of these values are presented below:

- As the discharge cutoff voltage increases, the usable capacity from the battery decreases. However, when this decrease is compared to the battery capacity, it remains quite small (approximately 2%).

- The rate of capacity decrease during the aging process decreases as the discharge cutoff voltage level increases. In this study, batteries with a nominal discharge cutoff voltage of 2.5V were used, and the highest rate was observed at the highest value of 2.9V.

In addition, this study demonstrates the design of a system capable of performing LIP aging cycles with standard driving cycles by designing a control card that can organize a power supply capable of providing constant current and constant voltage and a programmable load device.

The battery cycles in this study were conducted indoors (within a room). There is no precise temperature control, but the temperature variation is not significant. To ensure consistency and eliminate the effects of temperature changes, Battery 1, Battery 2, and Battery 3 were consecutively subjected to the same processes. Conducting these experiments in a thermal chamber would provide a more accurate assessment of temperature effects. Furthermore, using a larger number of samples in the tests would yield more precise results.

The results of this study have shown that maintaining a high discharge cutoff voltage reduces the decrease in battery capacity during its usage. Conversely, increasing the discharge voltage level at that moment reduces the capacity obtained from the battery. However, this reduction remains at low levels. Future studies can focus on finding an optimal solution for these two opposing conditions. Specifically, research can be conducted to determine the most optimal voltage level that minimizes capacity reduction while maximizing capacity usage when the discharge cutoff voltage is increased.

7 Declarations

7.1 Study Limitations

None.

7.2 Acknowledgements

None.

7.3 Funding source

This study was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK) within the scope of the 2209-A Research Fellowship Program, under project number 1919B012215575 titled 'Implementation of a Charge-Discharge System to Enhance the Cycle Life of Lithium-Ion Batteries'.

7.4 Competing Interests

There is no conflict of interest in this study.

7.5 Authors' Contributions

Corresponding Author Hayri ARABACI: Developing ideas or hypotheses for the research and/or article, planning the materials and methods to reach the results, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review during the research, taking responsibility for the creation of the entire manuscript or the main part, reworking not only in terms of spelling and grammar.

2. Ahmet Hakan MADEN: Planning the materials and methods to reach the results, taking responsibility for the experiments, organizing and reporting the data, taking responsibility for the explanation and presentation of the results.

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