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Performance Evaluation of Lithium-Ion Batteries Considering State of Charge and State of Health for Electric Vehicle Applications

Bhupendra Deshmukh*, Mohite Utkarsha Laxman, Kadam Deepak Prakash

Abstract

This study aims to compare temperature-regulated and uncontrolled charging methodologies to determine the most effective approach for optimizing battery performance while minimizing charging duration. The study assesses both constant current (CC) and temperature-controlled pulse charging (TRPC) methods. The battery temperature increases in direct proportion to the applied current during CC charging and cannot be controlled in the absence of external cooling systems. Key performance measures, such as the effect on the State of Health (SOH) and the anticipated battery longevity, are the main focus of the investigation. Simulations using 12.8 V, 40 Ah Lithium-Ion ($LiFePO_4$) batteries show that improved temperature regulation significantly enhances charge acceptance without altering the charging rate. By maintaining optimal thermal conditions, battery efficiency and performance are increased, minimizing energy losses and potential thermal stress. This controlled environment ensures more stable electrochemical reactions, allowing the battery to accept higher charge levels within the same time frame. Such regulation plays a crucial role in prolonging battery lifespan, optimizing energy storage, and improving overall system reliability in real-world applications.

Keywords: SOC, SOH, Li-ion battery, TRPC, CC, CC-CV

INTRODUCTION

Many electronic devices rely solely on battery packs for power. Applications for them are numerous and include CD players, laptop computers, cars, and other electrical devices. The use of rechargeable batteries as a power source for electric vehicle applications is growing in popularity. Lithium-ion (Li-ion), lead-acid, nickel-cadmium (NiCd), and nickel-metal hydride (NiMH) batteries are among the several battery kinds that are utilized. However, because of their extended lifespan, high energy density, and environmental friendliness, lithium-ion batteries are recommended [1]. Furthermore, lithium-ion batteries have some economic advantages, such as being small and light, simple, having a wide operating temperature, being adaptable to fast charging, having a long battery life, a low self-discharge rate, and emitting little hydrogen gas [2]. Battery health indicators, such as State of Charge (SOC), State of Health (SOH), State of Function (SOF), as well as many others, were done by researchers to indicate the status of battery health [3].

SOC is a measure that reflects the state of the electric charge within the battery, whereas SOH is a measure that reflects the health of the battery [2]. The most commonly accepted definition of a

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battery's SOH is the ratio of its current fully charged/discharged capacity to its initial capacity; as a result, capacity is now the most accurate measure for estimating SOH [4]. When the battery is first used, it has the power to fully discharge its energy, and its SOH is expected to be 100%. The available charge stored inside a fully charged battery is expected to decrease with usage due to contamination, resulting in a significant decrease in SOH. When SOH falls below a certain level, it is assumed to be insufficient to meet usage requirements, and the battery is labeled as faulty [5].

Longer charging times are a major concern in the electric vehicle transition. This issue can be solved by employing the battery swapping concept or charging the batteries quickly to reduce charge time. Battery change comes at a high expense in terms of infrastructure. Therefore, the focus is on pricing strategies to cut down on wait times. Inserting current at a higher pace than the remainder of the charging process speeds up the process of charging batteries. Some charging procedures include pulse charging, multiple stage CCCV, constant current (CC), constant voltage (CV), and constant current constant voltage (CCCV) [6]. Because of the high-temperature rise, the strategies stated above are not used for the quick charging of lithium-ion batteries. Several clever techniques are employed to shorten battery charging times and enhance battery efficiency. These methods are as follows [7]: ant colony [8], fuzzy [9], neural fuzzy [10], trial-and-error method [11], and Taguchi method [12]. However, these methods necessitate a large amount of computational power, which raises the cost of the battery management system.

Temperature is not taken into account when charging the battery in any of the above-mentioned charging strategies. The temperature of the battery rises all through fast charging; if this temperature is not regulated, it will harm the battery's health over time [13]. A Matlab Simulink model has been proposed in this study for fast charging of a lithium-ion battery. To charge the lithium-ion battery in this model, the temperature-regulated pulse charging (TRPC) strategy is used; and TRPC and CC results are compared. In the next section, the battery cell structure and equivalent circuit of the battery are discussed; this is followed by the sections presenting the performance analysis of a battery and different charging strategies; then the section after that explains the working algorithm of simulations; and then in the last section, the results are reported.

BATTERY CELL STRUCTURE

The internal structure of the cylindrical Li-ion cell, as shown in Figure 1, is made up of multiple electrodes, dividers, as well as current collectors. The pore materials in the positive and negative electrodes allow lithium ions to be intercalated or de-intercalated. Graphite is popularly used as the active material in negative electrodes. The active substance for the positive electrode consists of one or more metal oxides. The chemical reactions that exist in such membranes could be simplified by a $LixC_6$/$LiyXO_2$ battery, where X is the metal part and x and y is the number of Li atoms from each reaction.

$$Li_xC_6 \overset{charge/discharge}{\Longleftrightarrow} Li_0C_6 + xLi^+ + xe^- \tag{1}$$

$$Li_0XO_2 + yLi^+ + ye^- \overset{charge/discharge}{\Longleftrightarrow} Li_yXO_2 \tag{2}$$

Equivalent Circuit

Equivalent circuit models play an important role besides studying the changes in battery performance throughout varied charging/discharging cycles. The far more popular equivalent circuits have been evaluated by Wehbe and Karami [14], and the Dual Polarization model has become an enhanced Thevenin's model that represents an additional RC branch, as shown in Figure 2. Equivalent capacitances, including electrochemical polarization capacitances, have been used to characterize the transient response during the cycles. The electrical behavior discovered by He *et al.* seems to be as follows [15]:

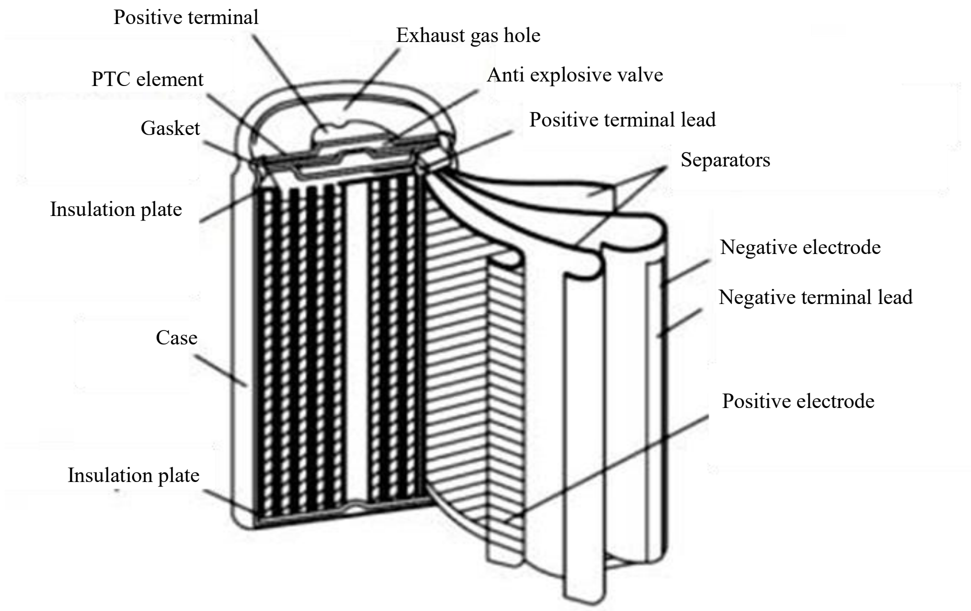

Figure 1. Lithium-ion cell internal structure.

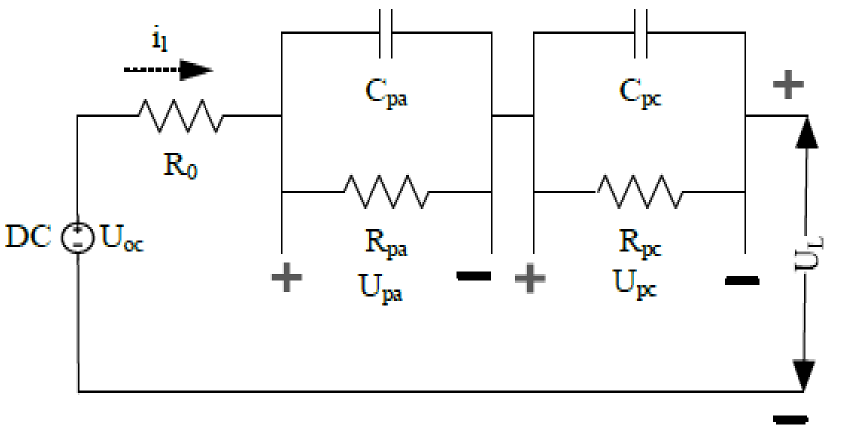

Figure 2. Dual polarization model.

Figure 2, when Upa and Upc are voltages across Cpa and Cpc. Cpa and Cpc are polarized capacitances. Rpa and Rpc are the resistances in the RC branch. R0 is the internal resistance of the battery, iL is loaded current and UL is load voltage.

PERFORMANCE ANALYSIS OF BATTERY

State of Charge

The SOC is calculated as the ratio of the available capacity Q (t) to the maximum possible charge that a battery can store, i.e. the nominal capacity Qn.

$$SOC(t) = \frac{Q(t)}{Qn} \tag{6}$$

Where SOC represents the battery's state of charge. The rated capacity, also known as a capability at the beginning of life (BOL), has been popularly used as a reference value. SOC is an essential factor for contributing to the success of an electrical vehicle and ensuring power responses in the context of the relevant operational conditions. Temperature and C-rate are two variables that have a serious influence on SOC in a short time. The SOC level is determined by the properties of the active electrode materials, and each active material acts differently. The depth of discharge (DOD) is indeed a term that describes how profoundly a battery has been discharged. Most of the time, it is associated with SOC. In real-world commercial vehicles, it is extremely difficult to accurately determine the lithium content of an electrode; conversely, the SOC must be approximated based on real-time voltage, current, as well as temperature assessments.

State of Health

SOH is not just a physical quantity, but it is significantly impacted by factors such as the number of charge-discharge cycles, capacity as well as power fade, and resistance value [16]. Different methods of SOH estimations are shown in Figure 3. The aging process is determined by the vehicle's utilization, the battery as well as cell design. Temperature, SOC range, electric energy conditions, and time are all critical parameters. When a battery's capability has declined by more than 20% from its initial capacity, it has reached the end of its life. Premised on such circumstances, and similarly to SOC, designers can describe a battery's state of charge as follows:

$$SOH(t) = SOH(0) - \frac{1}{2N\,Eo(0)} \int_0^t Pi(t)dt \tag{8}$$

SOH (0)=1 denotes an initial SOH and N refers to the total number of cycles before the end of life. Throughout the denominator, factor 2 makes up for both charging and discharging. A pack's life is terminated when SOH=0. In specific, N is not constant but is affected by battery operational conditions including DOD and C rate, among many others.

Lithium-Ion Battery Health Status Factors

The primary causes of battery aging and capacity loss have been assumed to have been lithium-ion deposition, solid electrolyte interface (SEI) membrane thickening, as well as active substance loss. Lithium-ion battery mistreatment enhances the battery aging process; normal battery charging does influence battery health as well as accelerates battery aging.

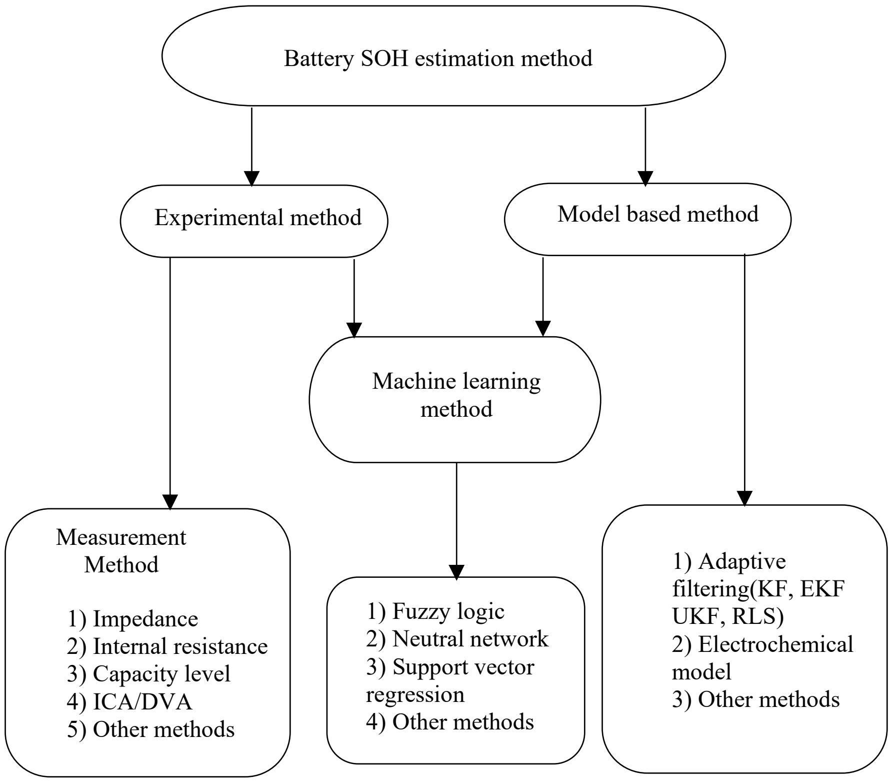

Figure 3. Battery SOH estimation method.

Battery performance is affected by temperature in two ways. High temperatures can accelerate internal chemical reactions, which can enhance battery performance and efficiency. However, they can also accelerate irreversible chemical reactions, which can lead to battery degradation. Figure 4 illustrates this. High temperatures cause the SEI membrane of a battery electrode to grow faster, making it more difficult for lithium-ion to penetrate the membrane and increasing intra-battery resistance.

High-multiplier discharge produces more heat inside the battery, accelerating battery aging. It was discovered that the layer SEI membrane of a high-rate battery discharge electrode seems to be bigger than that of the surface SEI membrane of a low-rate discharge electrode, which can be seen in Figure 5, similarly, it can be seen in Figure 6 that battery life degrades more rapidly when charged with 2C rate as compared to 1C.

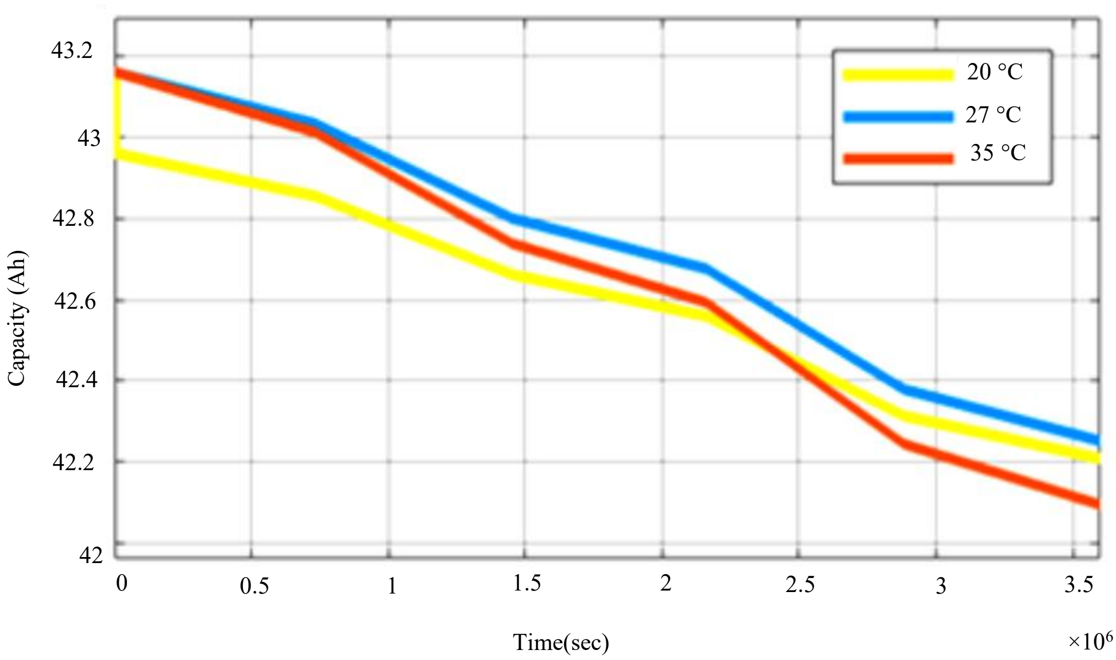

Figure 4. Capacity degradation at different temperature.

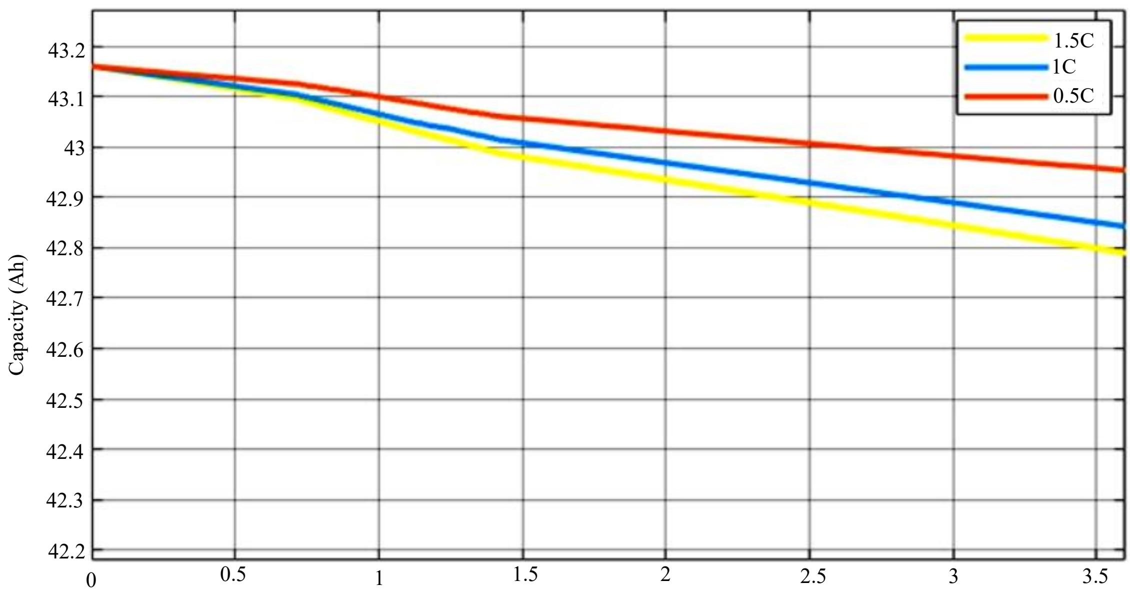

Figure 5. Effect of discharging current on battery capacity.

Battery aging and health are influenced by the depth of discharge and charge. Cycling at reduced DOD improves the life cycle of the battery, decreases its capacity fade. Figure 7 shows that at 80% DOD, capacity fading is less as compared to 90 and 100% DOD.

The health of batteries can be affected by overcharging and over releasing them, as well as by low voltage limits and improper voltage restrictions. An increase in side reactions, a decrease in active chemicals, the collapse of the graphite sheet layer, battery aging, and capacity decay are all caused by the battery's internal resistance, which increases as the discharge cut-off voltage decreases. Overcharging results in the negative pole producing the lithium phenomenon, excessive charging cut-off voltage raises the battery's internal temperature, and the associated side effects worsen, impacting the battery's aging and capacity.

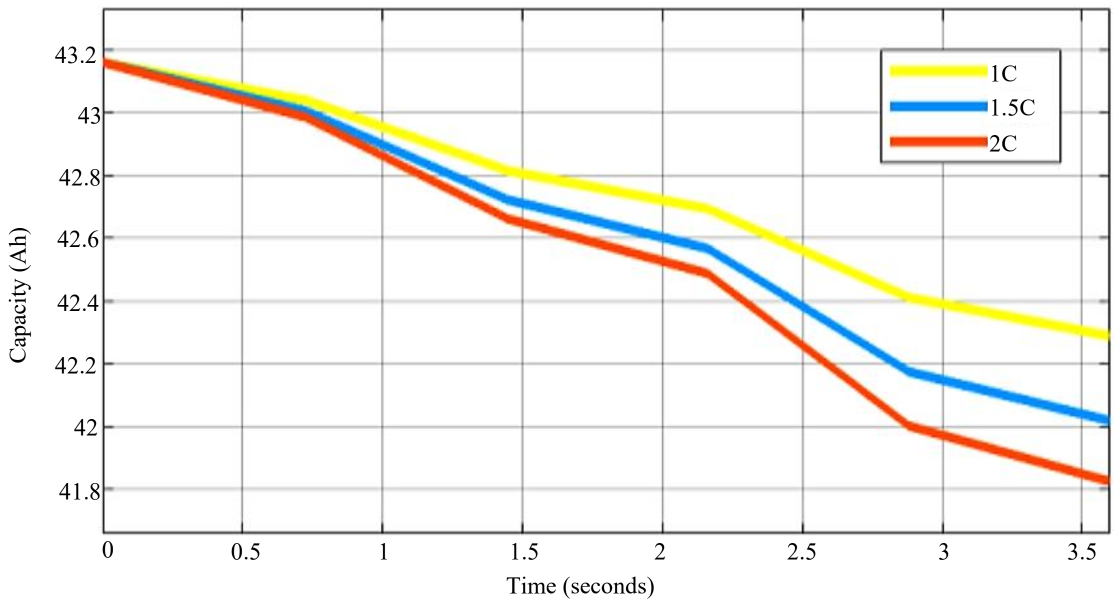

Figure 6. Effect of charging current on battery capacity.

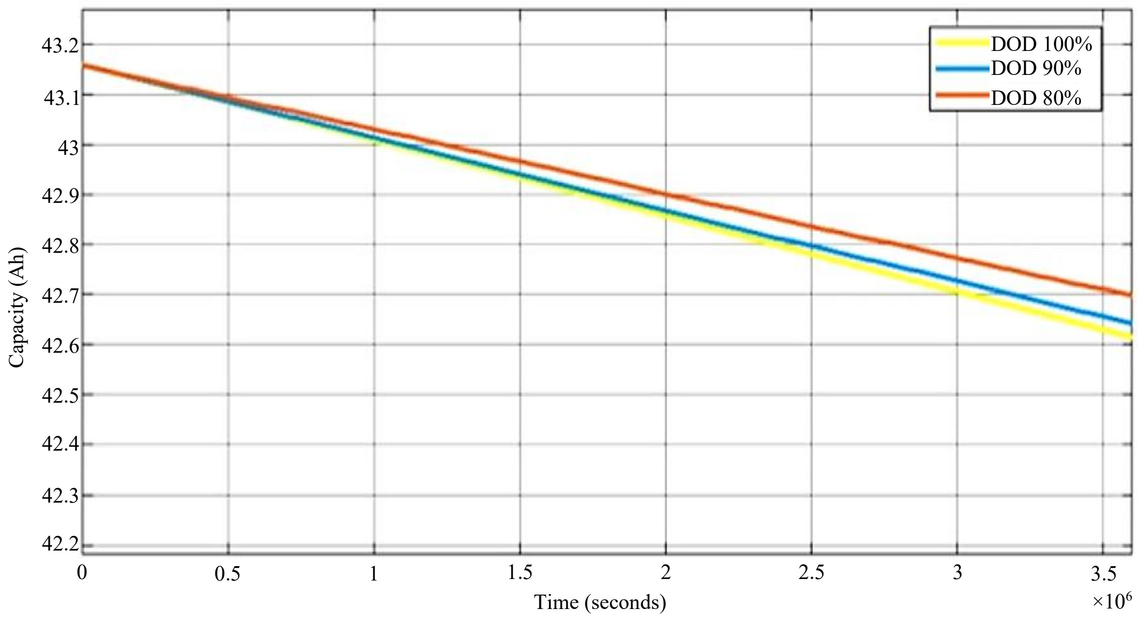

Figure 7. Depth of discharge on battery.

VARIOUS CHARGING STRATEGIES FOR BATTERY

Constant Voltage Method

It is an older method of charging that is still being used. Figure 8 represents a constant voltage approach. The battery is charged using this procedure by keeping a voltage constant from across terminals of the battery throughout the charging process as part of a variable resistor connected in series with the battery. Whenever the battery is discharged [17], the initial charging current is quite high, with a very low back emf, and it decreases rapidly as the battery charges, leading to an increased back emf. The said technique is much more widely used only for lead-acid batteries, but can also be used for lithium-ion batteries with additional circuitry to protect the battery.

Constant Current Method

Figure 9 represents the constant current approach to battery charging. A current flow is kept constant across the charging process with the help of a variable resistor connected in series with the battery or by attempting to control the source voltage in that same technique of charging. When compared to the constant voltage technique, the constant current method takes a bit longer. Even so, if the current is supplied above the C-rating of the battery, the temperature of the battery rises, which would be undesirable in this technique. As a result, this technique is not recommended for fast battery charging [18]. To reduce the charging time, two or more constant current rates can be applied.

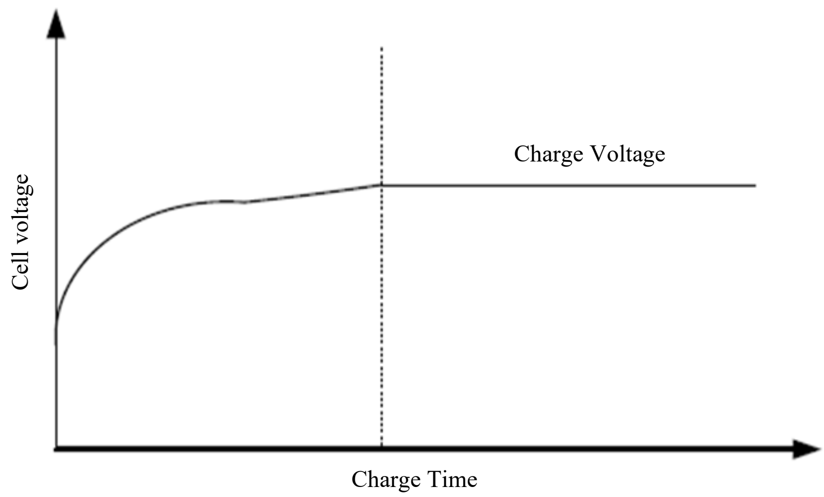

Figure 8. Constant voltage method.

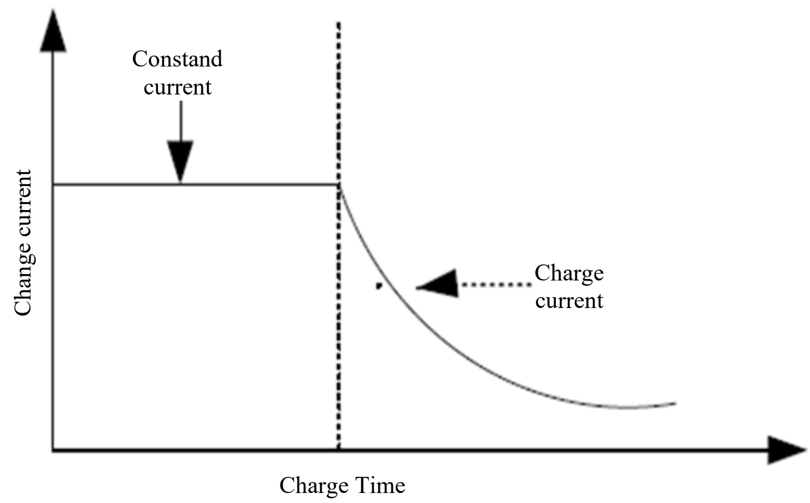

Figure 9. Constant current methods.

Constant Current Constant Voltage Method

This has been the most commonly used type of charge in Lithium-ion battery chargers [19]. It is primarily divided into the following stages: (a) Trickle charge, (b) Constant current charge, (c) Constant voltage charge, and (d) Charge termination. Figure 10 depicts a constant current, constant voltage strategy.

Trickle Charge

Such batteries are charged at a reduced constant current rate, typically around 0.1 of the full rate, whenever their charge state is extremely low. A battery's voltage increases during this period, but it does not achieve the full charged rate until it reaches a specific threshold.

Constant Current Charge

The constant current rate stage begins when the battery voltage surpasses the trickle charge threshold. At this point, the steady current should be between 0.5 and 1C [20].

Constant Voltage Charge

A constant voltage charge step is triggered after the battery voltage reaches its maximum charge voltage. At this point, a charging voltage remains constant. It is crucial for lithium-ion batteries because if they are charged at a voltage higher than their maximum, they would fail catastrophically. Its voltage regulation tolerance should be more than ±1% in order to maximize performance.

Charge Termination

Whenever the charging current falls below a certain level, the charger has to be separated from the battery; usually at 0.1 or 0.05 of the current full-rate charges. For lithium-ion batteries, the lowest possible charge current or timer technique is being used to terminate the charge. The lowest possible charge current method monitors the charge current during the CV stage and shuts down when it falls between 0.02 and 0.07C. The Timer method controls whenever the constant voltage method begins. Charging continues for 2 h before being terminated.

Temperature Regulated Pulse Charging

This method is the modification in the pulse charging method. This technique was created as a quick charging technique for lithium-ion batteries [21]. A pulse used in, Temperature Regulated Pulse charging strategy is shown in Figure 11. In this technique, a current pulse of particular pulse width is applied continuously. The width of the pulse can be changed by changing the duty cycle. For fast charging, it is necessary to increase the C-rate which causes overheating and overcharging of the battery.

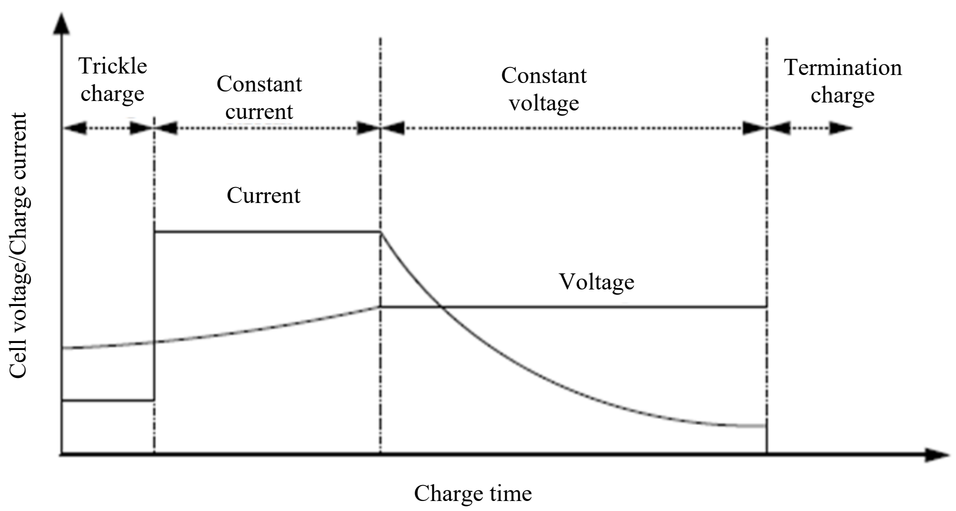

Figure 10. Constant current constant voltage method.

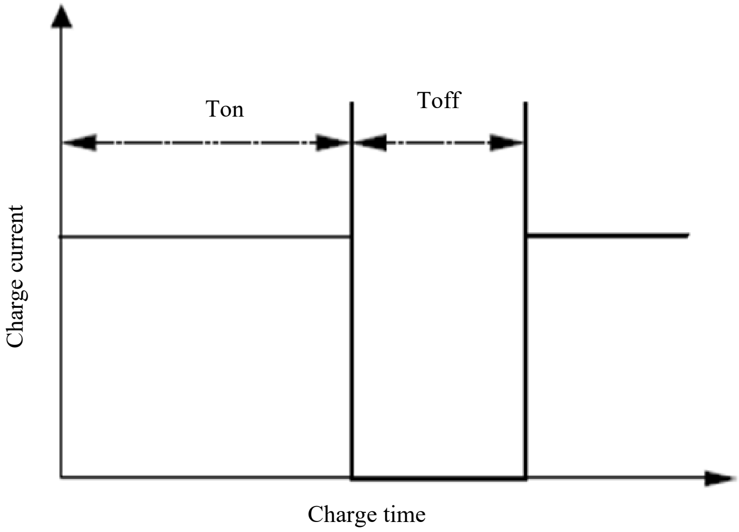

Figure 11. Temperature regulated pulse charging.

To overcome this problem a temperature-regulated pulse charging strategy is used. In this method, two temperature limits are set, upper (Tmax) and lower limit (Tmin). To achieve the temperature limit information, battery temperature is required and can be obtained by the datasheet of the battery. Charging starts at ambient temperature; as time passes, battery temperature rises and when it touches the set upper limit (Tmax), the battery supply gets disconnected and battery temperature starts reducing to its lower limit (Tmin). When battery temperature reaches its lower limit (Tmin) then voltage source gets connected to the battery and battery temperature starts increasing and this cycle repeats until the battery is charged.

PROPOSED WORK

In this study two simulation models are developed: i) fast charging of Li-ion battery using TRPC method; and ii) Model for studying the aging effect of Li-ion battery for different charging strategies. The working of these two models is explained below. The battery used in these simulations is $LiFeMgPO_4$, which has a capacity of 40 Ah and a rated output voltage is 12.8 V.

Fast charging of Li-ion battery using TRPC method

Figure 12 depicts the TRPC technique's procedure. Figure 13 depicts a block diagram of the temperature-regulated pulse charging control strategy. The switching circuit receives two inputs: battery temperature (Tbat) and percentage of SOC. Battery charging has been divided into two modes for a temperature-regulated pulse charging strategy. Tbat has existed between the highest and lowest temperatures in the first mode (Tmax and Tmin).

Throughout that mode, a constant current is applied to the battery. In the second mode, if Tbat $\geqslant$ Tmax, the current is set to zero until Tbat falls below Tmin. The procedure was repeated for each cycle. These cycles are repeated until the battery is charged to 95% capacity. Temperature-regulated pulse charging for Li-ion cells was proposed in this study to reduce recharge time (Figure 14).

The comparative analysis has been implemented to identify a suitable charging strategy besides fast charging of EVs. Figure 15 depicts the operational waveform of the temperature-regulated pulse charging strategy. Whenever a current significantly higher than the normal charging current (xC/10) has been injected into the battery (x>1), the temperature goes up from ambient (Tamb) to steady-state temperature (TSS). If a large level of 'x' is injected into the battery, the battery temperature (Tbat) rises above the upper limit allowed and it may even cause thermal runaway.

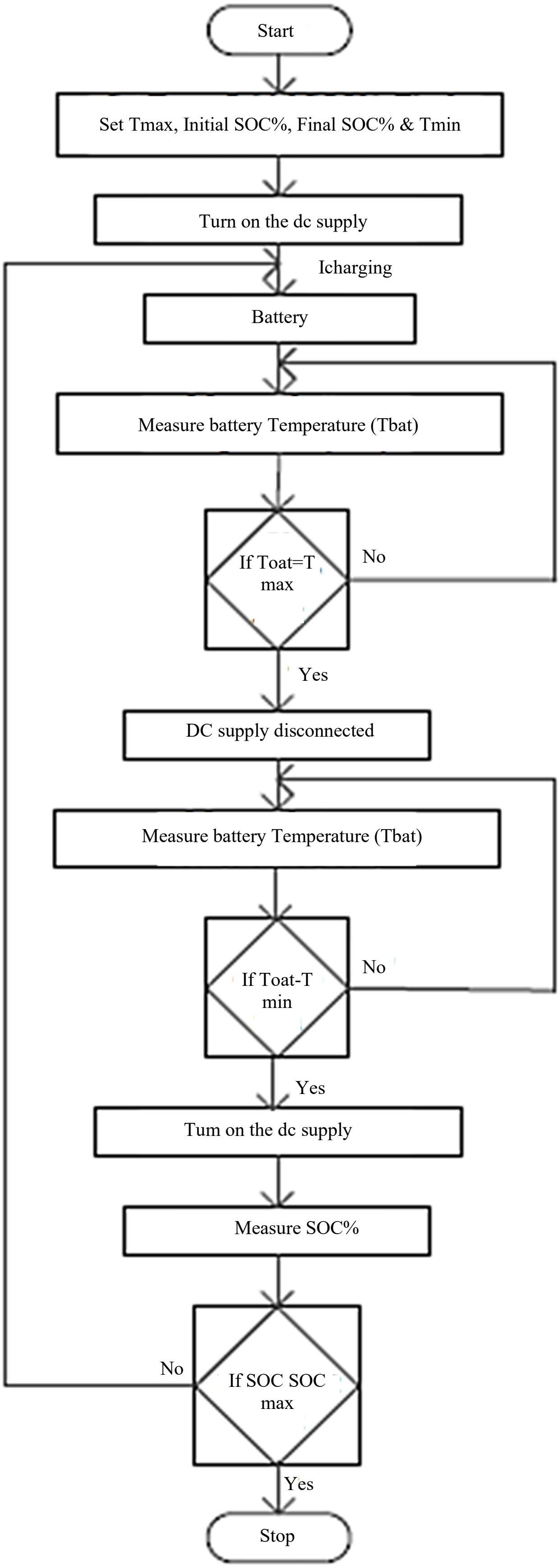

Figure 12. TRPC method flowchart.

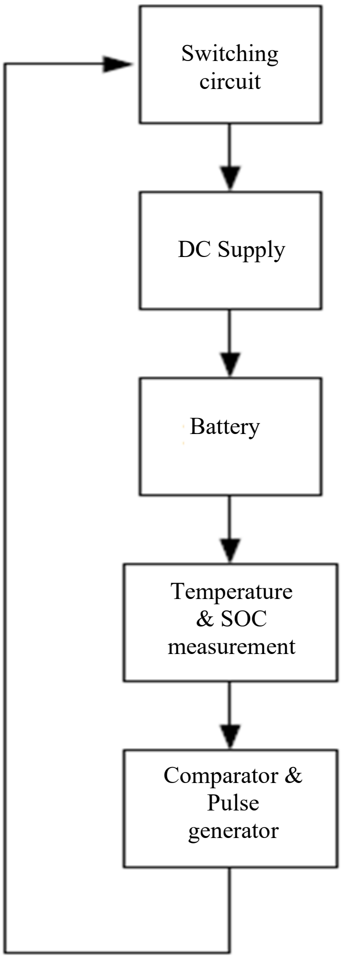

Figure 13. Functional diagram of TRPC.

To sustain temperature regulation, two operating temperatures were set: maximum (Tmax) and minimum (Tmin), and also an adjusted temperature band T=8°C. So, if Tbat exceeds the final limit Tmax, the MOSFET turns off and Tbat starts to decline to the lowest possible set limit. When Tbat=Tmin then the MOSFET turns on, the current is supplied to the battery, and the cycle is repeated until the batteries are fully charged to 95% SOC. For this charging, three control operation levels are set: Tmax, Tmin, and maximum SOC.

Model for Studying the Aging Effect of Li-ion Battery

The Li-ion battery in this model undergoes numerous cycles of charging and discharging. During this aging process, the maximum capacity of the battery is monitored. The flow chart of this model is shown in Figure 14. Initially, SOC max, SOC min and SOC int, and Tamb are set. According to the logic of the flow chart if a battery SOC is less than SOC min, then the battery is charged and then batteries SOC has monitored; if battery's SOC is greater than or equal to SOC max then the battery is discharged. Again, battery's SOC is monitored and if the batteries' SOC is less than or equal to SOC min then again the battery is charged.

This process repeated many times. This causes the aging of the battery and as the battery ages, its maximum capacity decreases; the result of this capacity fade is discussed in the next section. Here we have taken two cases: in the first case, CC strategy is used for charging and the battery is discharged at 1C. In the second case, the TRPC strategy is used for charging and the battery is discharged at 1C. The result of these two cases is discussed in the next section.

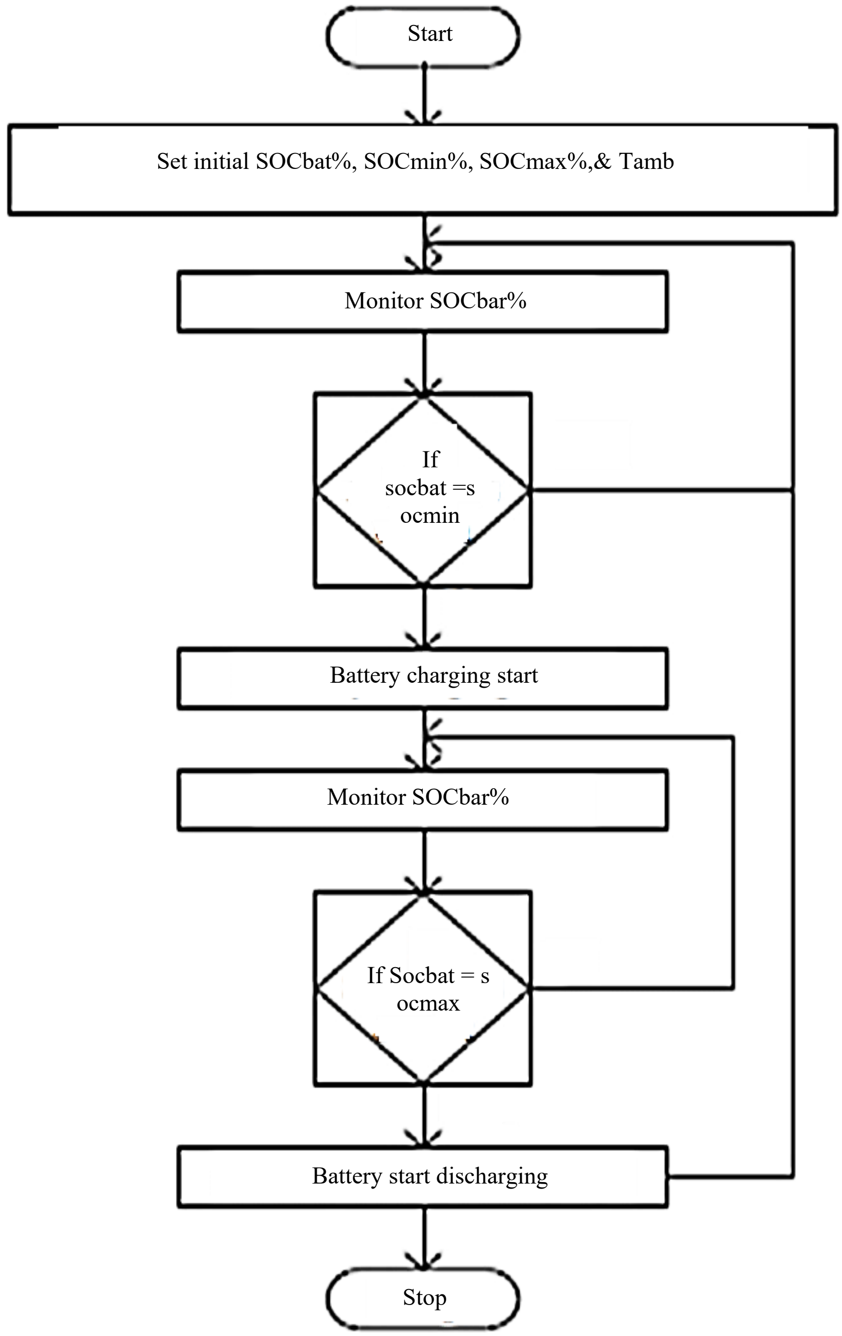

Figure 14. Aging of battery flowchart.

SIMULATION RESULT AND DISCUSSION

The result for the above two simulation models is discussed below:

1. In the TRPC charging simulation model, the Tmax and Tmin are 27 and 35°C, corresponding to the switching pulse shown in Figure 15, which is given to the MOSFET. The charging current pulse is shown in Figure 16, and the variation in cell temperature is shown in Figure 17. If the lithium-ion battery is charged using the CC method in which the charging current rate is 2C and the same battery is charged at 2C rate using the TRPC method then the battery charges faster in the CC method as compared to the TRPC method. But it is practically not possible to use the CC method at a 2C rate because the battery temperature rises critically. This can damage the battery. Whereas in TRPC method, temperature lies in the band of 27 and 35°C. This comes under the operating range of a Lithium-ion battery.

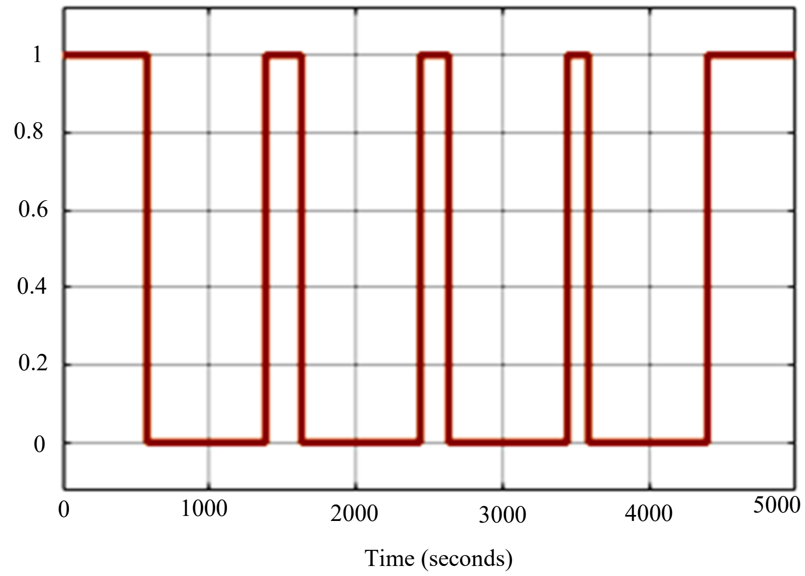

Figure 15. Switching pulse of MOSFET.

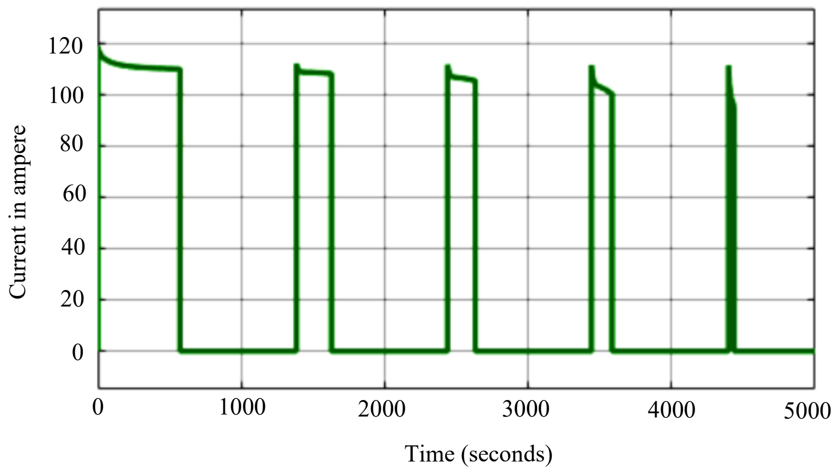

Figure 16. Current vs. time graph.

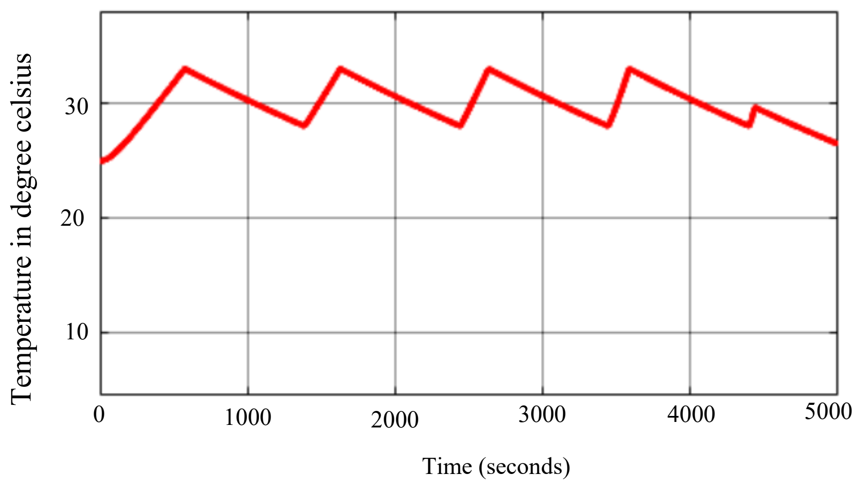

Figure 17. Temperature vs. time graph.

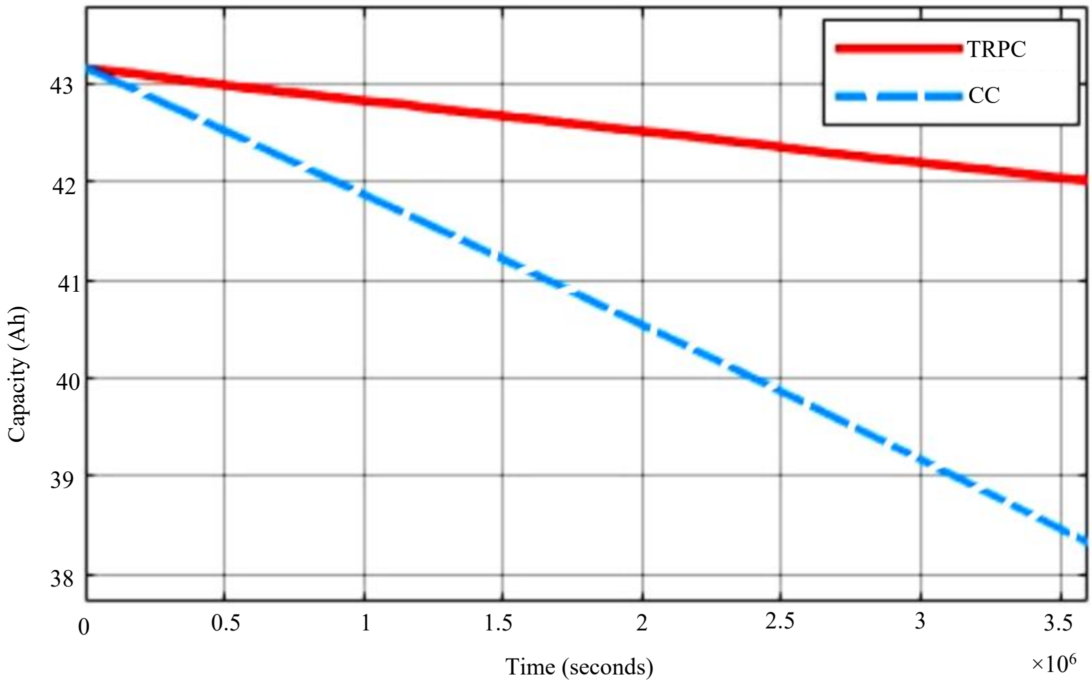

Figure 18. Battery capacities fade.

2. In the aging model, charging current for the TRPC method is 2C and the same charging current is given in the CC method. The output of the aging model is shown in Figure 18. From Figure 18 it is clear that the maximum capacity of the battery decreases rapidly in the CC method because the temperature is not regulated in this method.

CONCLUSION

The current work includes the development of two Matlab/Simulink designs: one for temperature-regulated pulse charging of a lithium-ion battery and another one for determining the aging effect of a lithium-ion battery. The second simulation model reveals that when the battery is fast charged using the constant current strategy, the maximum capacity of the battery fades rapidly in comparison to when the battery has been fast charged using the TRPC method. This is because the temperature of a battery is not controlled inside the CC technique. In the case of TRPC, the temperature is regulated, so the battery capacity does not fade as quickly. Furthermore, for the same temperature variation, this same TRPC method is faster than the CC method. As a result, the CC strategy cannot be used for fast charging in EVs, while the TRPC method can be used for EV fast charging. By implementing this strategy, the charging time of the battery can be reduced without compromising its health.

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