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Review

Overview of multi-stage charging strategies for Li-ion batteries

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ABSTRACT

To reduce the carbon footprint in the transportation sector and improve overall vehicle efficiency, a large number of electric vehicles are being manufactured. This is due to the fact that environmental concerns and the depletion of fossil fuels have become significant global problems. Lithium-ion batteries (LIBs) have been distinguished themselves from alternative energy storage technologies for electric vehicles (EVs) due to superior qualities like high energy and power density, extended cycle life, and low maintenance cost to a competitive price. However, there are still certain challenges to be solved, like EV fast charging, longer lifetime, and reduced weight. For fast charging, the multi-stage constant current (MSCC) charging technique is an emerging solution to improve charging efficiency, reduce temperature rise during charging, increase charging/discharging capacities, shorten charging time, and extend the cycle life. However, there are large variations in the implementation of the number of stages, stage transition criterion, and C-rate selection for each stage. This paper provides a review of these problems by compiling information from the literature. An overview of the impact of different design parameters (number of stages, stage transition, and C-rate) that the MSCC charging techniques have had on the LIB performance and cycle life is described in detail and analyzed. The impact of design parameters on lifetime, charging efficiency, charging and discharging capacity, charging speed, and rising temperature during charging is presented, and this review provides guidelines for designing advanced fast charging strategies and determining future research gaps.

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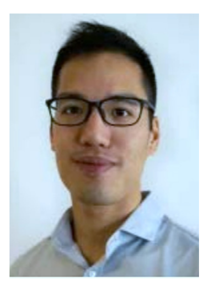

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1. Introduction

By the end of 2021, there were approximately 16.5 million electric vehicles (EVs) on the road worldwide, which was an enormous growth compared to 2020 (10 million EVs were on roads). By the first quarter of 2022, 2 million EVs had been sold, a 75% increase over the same period in 2021 [1]. EVs have grown in popularity in recent years due to their benefits in terms of energy efficiency and solution to the current environmental challenges, such as emissions, reducing reliance on fossil fuels, and air pollution in the cities. More than 20 countries have announced electrification goals or internal combustion engine (ICE) bans for vehicles. Eight countries, including the European Union (EU), have committed to net-zero emissions by 2050 [1,2]. The EVs must be mass-produced and sold in massive amounts to achieve this goal. The key components of EVs are power converters and lithium-ion batteries (LIBs). The LIBs stand out significantly compared to other energy storage technologies due to their high energy and power density, high efficiency, low maintenance cost, no memory effect, and low self-discharge rate [3–7]. From the user's perspective, the issues with EVs include their overall mileage, charging speed, range anxiety, and safe and reliable operations during driving. All these features depend strongly on the battery charging and discharging capacity, lifetime, charging time, and charging efficiency [8]. Traditionally, the current rate (C-rate) influences the performance-degradation behavior of LIBs. Thus, the charging method impacts the performance and lifetime parameters of the LIB [9]. On the other hand, the battery discharging is determined by the consumer's energy consumption behavior. To improve the lifetime and performance characteristics of LIBs, research on charging strategies is a crucial issue topic.

A suitable charging protocol is required for the optimal charging of LIBs. During the charging of LIBs, the battery charger controls the voltage, current, and/or power of LIBs [10]. Fast charging techniques for EV applications generally aim to achieve the optimal balance between the two contradictory objectives of reducing charging time and extending the lifetime [11,12]. However, lifetime must be carefully taken into account because high charge current rates are usually one of the main factors that cause degradation and low performance of LIBs [11–14]. The cause is attributed to several aging mechanisms, including solid electrolyte (SEI) growth [15–17], lithium plating [16,18–21], and mechanical degradation [17,22]. These aging mechanisms are highly dependent on different factors, including C-rate, temperature, state of charge (SOC), and state of health (SOH). The charging parameters vary depending on the operating conditions. The theoretical illustration of the charging process is shown in Fig. 1 [23,24]. During the charging process, electrons are extracted from the cathode and moved toward the anode through the external circuit by the charger. Meanwhile, Li^+ ions are deintercalated from the cathode electrode and moved to the anode electrode by passing through the electrolyte [25]. The charging process has three steps: (1) the diffuse-out of the Li^+ ions from the cathode, (2) the diffusion of solvated Li^+ ions into the electrolyte, and (3) the de-solvation of Li^+ ions by passing through the SEI and intercalation into the

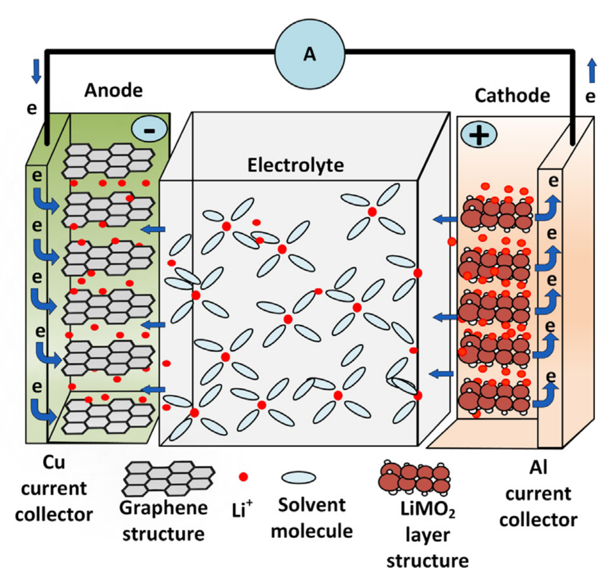

Fig. 1. The charging procedure for a standard Li-ion battery [24]. During the charging process, the solvated lithium ions (Li^+) are intercalated to the negative electrode (anode) after being de-intercalated from the positive electrode (cathode). The Li^+ is turning into Li after accepting the electrons from the electrode.

interlayer of graphite [18,26]. These are the ideal LIB working conditions. Nonetheless, LIBs are subjected to severe working conditions in real-world applications, which have a substantial impact on the side reactions during ion transport [19]. Therefore, the LIB performance and lifetime are substantially impacted by charging conditions [26]. Furthermore, the thermal behavior of the LIB is significantly reliant on the charging/discharging current. Therefore, the considerable heat generation raises safety concerns. Also, optimizing the charging strategy several times during battery operations can also extend the remaining useful battery lifetime [27]. Therefore, a suitable charging protocol is required for the optimal charging of LIB, which will positively impact the performance and lifetime of LIBs.

The constant current constant voltage (CCCV) is the standard charging method for LIBs [28–32]. This charging method consists of two stages, as depicted in Fig. 2 (a). In the first stage, the LIB is charged with constant current (CC), I_{ch}, until the maximum voltage V_{max} is reached. In the second stage, the LIB is charged with constant voltage (CV) until either the I_{ch} reaches the predefined cut-off current value I_{end} (typically, it is 5% of the nominal current) or a predefined maximum time t_{max} is reached. However, I_{ch} has the greatest impact on the charging rate, whereas V_{max} and I_{end} define the capacity of charged battery [11]. The manufacturer usually defines the I_{ch} rating, which is dependent on the chemistry of the LIB. Furthermore, higher C-rate charging has a negative effect on LIB health [33]. On the other hand, generally, CV mode takes a lot of the charging time and only has a limited contribution to the amount of charged capacity [34]. CV stage is very dependent on the C-rate employed, temperature, and the degradation level of the battery. Also, the diffusion limiting C-rate is an additional restriction that limits the diffusion process within the electrodes at higher C-rates, affecting the capacity and performance of LIB [35]. Fast Li^+ ion diffusivity in the active materials is recognized as one of the significant factors needed for fast charging [36]. Additionally, charging at high C-rates will lead to lithium plating in batteries, especially at low temperatures or at high SOC [19]. From the electrochemistry perspective, Li^+ builds up on the surface of the anode and transforms into lithium metal when the rate of diffusion of Li^+ ions to the anode material surface is faster than the rate of diffusion inside the material [37,38]. These conditions limit the charge transfer kinetics in the electrolyte and solid-state diffusion, causing the anode potential to drop below the lithium metal potential. This phenomenon, known as lithium plating, can negatively impact the LIB performance and cycle life. Therefore, various authors have proposed different charging techniques that restrain the lithium plating on the anode surface, prolonging the battery life, reducing charging time, decreasing temperature rise, and improving the charging efficiency [18,29,38–40].

Boost charging (BC) is one technique to improve the charging speed of the LIB compared to the CCCV method [11]. BC is a variant of CCCV charging that includes a higher CC or constant power (CP) period at the start of the charging period [41]. Because the LIBs are less sensitive to lithium plating at low SOC, this additional boost interval will minimize the charging time without compromising the cycle life. The BC charging strategy is shown in Fig. 2(b). The figure illustrates that the cell is first charged with a high current I_{boost} until enough charge is supplied into the cell (e.g., 40% SOC). The conventional CCCV procedure is then applied after the I_{boost} interval. The charging speed can be adjusted with the charging current level I_{boost}. Furthermore, the same conditions are applied to alter capacity utilization and charging rate as CCCV charging. When the boost interval is between 20%–60% SOC, the author in ref. [11] found that boost charging does not affect LIB capacity fade, thereby the aging, while minimizing the charging time [42,43]. This charging approach could be effective in EV applications for fast charging [28].

The pulse charging technique has been proposed by various authors to reduce the charging time, decrease temperature rise, and prolong the LIB lifespan [34,44,45]. Different types of current pulses exist based on the current frequency, amplitude, and duty cycle [4,44]. Several pulse charging patterns were proposed in the literature as a substitute for CCCV charging. The pulse charging is based on the periodic variation of different current pulses with variable current rates and directions. The charging current can be suspended, increased, decreased, or replaced by short discharging pulses for a specific period. As illustrated in Fig. 2(c), the most typical pulse charging approach is the positive pulse current (PPC) with some relaxation periods, where the design parameters are the peak charging current (I_p), the on-time of the pulse (t_p), the relaxation interval time (t_r), and the total period of the pulse (T), respectively. According to ref. [36], the PPC can extend the LIB lifetime by 60% at low frequency (0.05 Hz) and by 105% at high

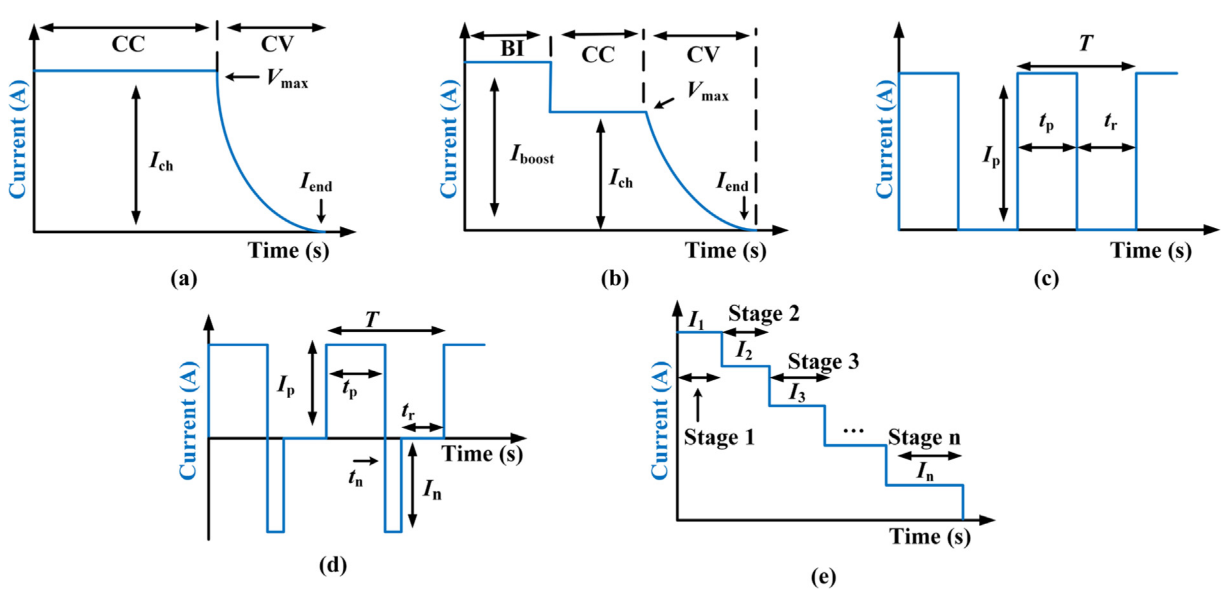

Fig. 2. Different charging methods for lithium-ion battery. (a) Standard CCCV method; (b) BC method; (c) PPC method; (d) NPC method followed by PCC; (e) MSCC charging strategy.

frequency (2 kHz) [46]. The Taguchi orthogonal arrays technique was used in ref. [47] to find the best pulse charging parameters that improve LIB charge and energy efficiency while reducing charging time. It was discovered that operating a PPC with ideal parameters reduced charging time by 47.6% and enhanced LIB charge and energy efficiency by 1.5% and 11.3%, respectively. The author in ref. [48] presented that the PPC reduces the charging time of 100 mA h and 45 mA h LIB by 37.35% and 15.56%, respectively. Another pulse charging strategy is negative pulse current (NPC), as shown in Fig. 2(d). In this case, the parameters I_p, I_n, t_p, t_r, t_n, and T are abbreviations for the peak charging current, peak discharging current during charging, the on-time of the pulse, the relaxation interval time, negative pulse time, and the total duration of the pulse, respectively. According to the authors in ref. [49], the NPC can increase active material utilization, resulting in higher discharge capacity and a longer lifetime. According to the authors in ref. [10], NPC with lower frequency and amplitude improves charging capacity by about 3.5% compared to NPC with higher amplitude and frequency. Therefore, it was established that pulse charging with a variety of modifications is slightly beneficial for LIB life cycles, charging time reduction, and increased discharge capacity [10,34,44–49].

Multi-stage constant current (MSCC) charging is another charging strategy that has been proposed by various researchers to reduce the charging time, enhance the charging efficiency, and prolong the LIB lifetime [30,50–57]. Fig. 2(e) depicts the MSCC charging for LIBs. In the literature, various authors proposed a variable number of stages to charge a LIB. In refs. [30,50], the author conducted various experiments and discovered that the three-stage charging technique is more superior to the standard method (CCCV) in terms of reducing charging time and enhancing charging and discharging capacity. The authors of ref. [58] conducted experiments to determine the best C-rate for four-stage charging. Compared to the standard charging technique (CCCV), the authors determined that the optimal four-stage charging reduces charging time, extends LIB lifetime, and increases charge capacity without inducing temperature rise. In ref. [52], the author found the currents of the five-stage charging using the grey wolf optimization method, compared the results with the CCCV method, and discovered that utilizing MSCC charging reduced charging time by 5.33%, improved charging efficiency by 12.54%, and extended the life cycle by 79.6%. The authors of ref. [59] used a five-stage MSCC charging approach and identified the criteria to avoid lithium plating. The results indicate that the optimal MSCC has a lower effect on lithium plating and enables faster charging speeds as well as better capacity retention compared to the CCCV charging method. In ref. [60], the effects of MSCC charging at three different ambient temperatures were investigated. Compared to CCCV, MSCC decreases the charging time and increases the charging capacity at low and high temperatures. Many authors have proposed different numbers of charging stages to evaluate the charging time, charging efficiency, life cycles, and temperature rise. However, there is no consensus on the effect of MSCC on LIBs because studies have used different test goals, research objectives, and testing procedures. Therefore, it is necessary to conduct a comprehensive literature study, including comparison and drawing conclusions regarding the effect of MSCC strategies on LIBs, which is essential to be able to lead research into the optimal charging strategy.

Each charging technique has advantages and disadvantages of its own. Although CCCV charging is relatively simple to implement, it is unsuitable for fast charging. Similarly, PPC and NPC charging methods decrease charging time but are expensive and complicated. However, the MSCC charging approach is simple to use. The limitation of MSCC is the need to predict the SOC or voltage level for their utilization precisely. Several review publications and their contribution to the evaluation of the charging approach are presented in Table 1. The publications have focused on pulse charging, optimal charging strategies, and the dynamics of materials during fast charging. Therefore, this study aims to conduct a thorough analysis of the MSCC charging approach and its influence on the lifetime and performance characteristics of LIBs. This paper provides a comprehensive overview of the MSCC charging strategy. The existing MSCC charging modes are discussed in Section 2. The technique of transitioning into different stages is discussed in Section 3. The effects of MSCC charging on the charging time, charging efficiency, charging/discharging capacity, temperature rise, safety, and LIB lifetime are discussed in Section 4. Section 5 presents the analysis and discussion based on the findings. Section 6 provides the conclusions for the analysis done.

2. Multi-stage constant current charging for LIBs

Fast charging is one of the key solutions for overcoming the range anxiety issue that has limited the deployment of EVs [65,66]. The development of a charging strategy is critical for improving the EV user experience as well as increasing the charging efficiency, reducing charging time, extending the lifetime, and improving the safety of LIBs [67–69]. One of the primary charging strategies that can address the previously mentioned aspects is MSCC charging. According to the design requirements of battery charging, the CC during charging is divided into several currents with decreasing C-rates in the MSCC charging strategy. The decreasing CC rate considerably minimizes lithium precipitation from the negative electrode of the battery during continuous charging with a large current, as shown in Fig. 2(e) [55]. Moreover, as compared to the CCCV strategy, the MSCC charging approach eliminates the constant voltage charging stage. Thus, the electrolyte oxidation process produced by the high voltage is reduced [70]. As a result, the MSCC charging approach has attracted the large interest of many researchers.

Table 1
Summary of several research articles and their contribution to the evaluation of fast charging.

Ref.	Strategies	Contribution
[4]	Pulse charging	Comprehensive analysis of pulse charging and its effect on the performance and lifespan of LIBs.
[28]	Fast charging strategies	Review of fast-charging techniques and control limitations.
[31]	CCCV	Examining the influence of fast charging on the graphite anode as a result of Li-plating and the structural instability of layered lithium-metal oxide at the cathode.
[61]	Pulse charging	A summary and analysis of the impact of pulse charging on LIBs performance.
[39]	Charging optimization	Thorough overview of charge optimization strategies, including a general framework and a control protocol.
[62]	Charging and discharging strategies	Covering the systemic charging and discharging patterns of EVs at the level of the grid and providing recommendations.
[63]	Extreme fast charging	Overview of the fast-charging strategies and discussion on the limitations and challenges based on material perspectives.
[64]	Optimal charging strategy	Review and explanation of the charging approach based on the dynamics and control of the materials in the batteries.
This work	MSCC	A comprehensive review on the MSCC charging strategies and their impact on the performance and lifetime of LIBs.

Based on the multi-stage concept, a variety of charging stages ranging from three to ten were proposed in the literature, and the results are quite diverse. In addition, the criteria for transitioning from one stage to another varies, and the current rating varies from stage to stage based on the method used to determine the C-rate. There are four parameters that are usually used to analyze the performance of LIBs: (1) charging time, (2) charging efficiency, (3) charge/discharging capacity, and (4) temperature rise during charging.

2.1. Charging time

The charging time is determined by the charging C-rate; the higher the C-rate, the shorter the charging time. However, increasing the C-rate during the charging process has a detrimental effect on charging efficiency and cycle life. Higher charging current, within the manufacturer's specified limit, in the low SOC level has a less detrimental impact on LIB life cycles and performance parameters [71]. When the SOC exceeds a particular threshold (usually it is 40%–50% of SOC), a higher charging current has a negative impact owing to polarization. Polarization occurs when Li^+ is intercalated on the anode, and as a result, the capacity fade occurs. In the MSCC charging strategy, the charging current reduces from a higher C-rate to a lower C-rate to reduce the charging time and create a less polarization effect on LIBs [71].

2.2. Charging efficiency

Charging efficiency is one of the key performance indicators for the LIB charging procedure. Charging efficiency is defined as the ratio of discharging capacity extracted from the charged LIB to the charging capacity of LIB during charging. The charging efficiency is computed using the following Eq. (1).

$$\eta(\%) = \frac{I_d \times t_d}{\sum_{i=1}^{n} I_c \times t_c} \times 100 \quad (1)$$

In Eq. (1), n, I_d, t_d, I_c, and t_c show the number of stages, discharging current, discharging time, charging current, and charging time, respectively. In the CCCV method, the capacity loss during the charging procedure increases as the C-rate increases. The same concept is applied to the MSCC charging strategy for higher C-rates. However, the energy loss is reduced due to the varied number of charging stages in comparison to the CCCV method. It is essential to reduce energy loss to improve charging efficiency. In some cases, the charging time and energy loss conflict with each other [72,73]. In ref. [74], it is shown that the charging time is reduced by 34% compared to CCCV using the SOC-based four-stage charging strategy, but the energy efficiency is reduced by 0.6% as well. In another case, the MSCC charging strategy with voltage cut-off transition criteria has a positive impact on energy efficiency with optimal charge pattern [51,75,76].

2.3. Charge/discharge capacity

Another performance parameter is the charge/discharge capacity. The entire amount of charge that is stored in the LIB during charging is known as the charging capacity. Due to operational conditions such as ambient temperature, last-stage charging current, and end-of-charge criteria, the charge capacity will vary. The LIBs are not fully charged at 0 °C or negative temperature [60]. Similarly, the discharging capacity is the total amount of energy that is drawn during discharging of LIBs. Thus, the normalized charge and discharge capacity can be evaluated using Eqs. (2) and (3) [51].

$$\text{NCC} = \frac{C_{c-\text{MSCC}}}{C_{c-\text{cccv}}} \quad (2)$$

$$\text{NDC} = \frac{C_{d-\text{MSCC}}}{C_{d-\text{cccv}}} \quad (3)$$

Here NCC, NDC, $C_{c\text{-MSCC}}$, $C_{c\text{-cccv}}$, $C_{d\text{-MSCC}}$, and $C_{d\text{-cccv}}$ are the abbreviations of normalized charge capacity, normalized discharge capacity, charge capacity during MSCC charging, charge capacity during CCCV charging, the discharge capacity of charged LIB (charged with MSCC charging strategy), and discharge capacity of charged LIB (charged with CCCV method), respectively. The charge and discharge capacity are compared with those of the standard charging method (CCCV). MSCC charging strategy has a positive impact on the charge and discharge capacity of LIB compared to the CCCV method [51,55,60].

2.4. Temperature rise

The rise in temperature during charging has a negative impact on the performance and lifetime of LIB. During fast charging, significant heat is generated [40,77]. The heat produced by ohmic loss is proportional to the square of the root mean square (RMS) current. As the current increases, the temperature of LIB rises. In addition, LIBs are occasionally subject to thermal runaway due to their tremendous heat generation [78,79]. Therefore, the temperature rise during charging has a negative impact on the overall performance and lifetime of LIBs.

2.5. Cycle life

Numerous techniques can be used to determine the cycle life of LIB. Generally, the aging test is conducted at various charging profiles of the MSCC charging strategy and compared with the CCCV or CC method. The cycle life depends upon the chemistry and constituents (electrolyte, electrodes, and separator materials) of the LIB. Depending on the operating conditions (temperature, current, and voltage), the active components of LIB degrade with time, and cycle life degrades.

Various works in the literature focus on particular performance parameters (charging time, charging efficiency, charge/discharge rate, and temperature rise) instead of all of them. Also, the findings of each article are different from the others based on the chemistry of the cell and the method used to find the C-rate, and the number of multiple charging stages.

Different methods are used to assess the lifetime and performance. The optimal C-rate is found using a variety of techniques, including empirical approaches, analytical techniques, and optimization methods. Various methods of transitioning from one charging stage to the next stage are also proposed and validated. The conceptual diagram for the MSCC charging strategy is shown in Fig. 3, along with the methods and strategies used to do a transition from one stage to the next one and the parameters used to evaluate the performance. From the literature, the MSCC charging strategy improves performance metrics and lifetime. For example, in ref. [50], the authors conducted numerous experiments and discovered that the three-stage charging reduced the charging time and increased the charging capacity when compared to the CCCV method. The authors of ref. [58] concluded that using a four-stage charging technique results in a shorter charging time, less charge capacity loss, and longer cycle life for LIBs. The four-stage charging strategy was also used to study the impact of weighting parameters on the Taguchi method [30]. The equal weighting factor technique, according to the authors, increased the charging efficiency and decreased charging time. The five-stage charging increased the charging efficiency by 2.8% and decreased the temperature rise by 9.3 °C compared to the CCCV method [76]. Using a five-stage charging method, the authors of ref. [52] concluded that a multi-stage charging strategy reduces charging time while

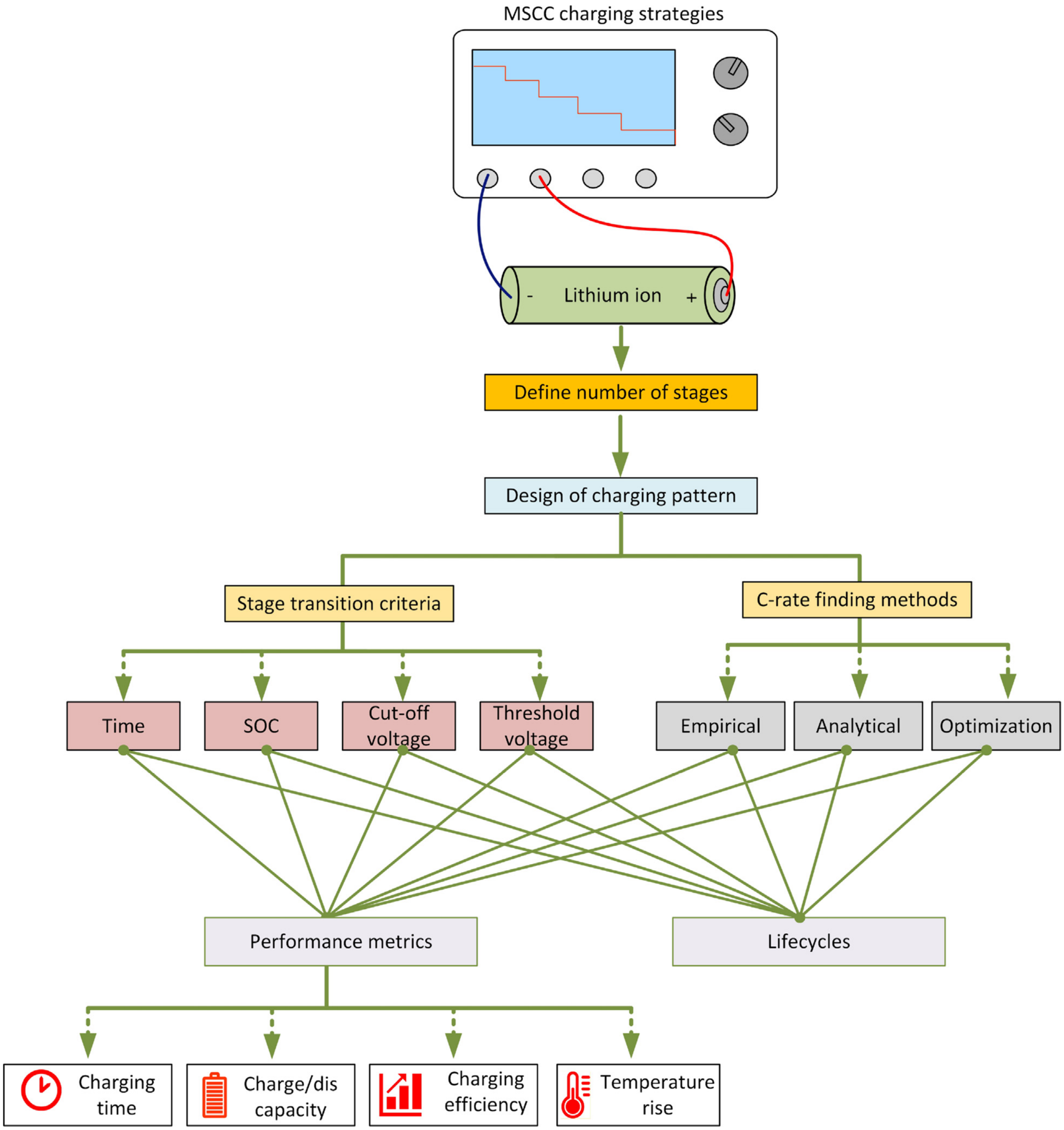

Fig. 3. Conceptual design for the MSCC charging strategies, along with mentioned techniques for determining the C-rate for each stage and criteria for transitioning of stages from one to the next one.

simultaneously increasing cycle life and charging efficiency. The authors of ref. [80] used an eight-stage charging technique and determined that multi-stage charging minimizes temperature rise and charging time. The author in ref. [51] utilized the ten-stage charging strategy, and the result demonstrated that the multi-stage charging strategy increases charging capacity at lower temperature while reducing charging capacity compared to the CCCV method. Various authors suggested varying numbers of stages for charging the LIBs. Additionally, different authors used different criteria to transition between stages, and different C-rates are proposed. These topics are covered in further details in Section 3.

3. Design of charging pattern

The optimal design of the charging pattern is critical. To identify the optimal charging pattern, several authors have employed a variety of techniques. Researchers employed different charging techniques to find the C-rates for the MSCC charging, i.e., analytical methods, optimization techniques, and empirical approaches. Below is a thorough review of various techniques to find the C-rate for charging the LIBs. In addition, the transition from one stage to the next stage is another significant variation across the literature. Various authors proposed different ways of transitioning from one stage to another one. The stage transition criteria are discussed below.

3.1. Stage transition criteria

The transition from one stage to the next one is determined by meeting one of the following four criteria, found in the relevant studies.

3.1.1. Time-based transition

Time is one parameter to switch from one stage to the next stage, as illustrated in Fig. 4(a). Time-based transitions are simple to implement, but there is no standard method for determining when stages are shifted from one to the next one. The three-stage charging strategy was chosen to charge the LIB up to 80% of SOC in less than 40 min [71]. The time interval is chosen based on the SOC intervals. The best-chosen group has time lengths of 10, 12, and 14 min for three stages with SOCs of 0%–30%, 30%–60%, and 60%–80%. The C-rates were selected randomly, and several experiments were conducted to identify the optimal pattern (1.8 C, 1.5 C, and 0.9 C). The findings revealed that MSCC charging improves cycle life and significantly shortens the charging time compared to the CC method. Also, the MSCC charging strategy has a lower polarization and lithium plating effect compared to the CC method. However, no standard procedure is proposed to find the optimal C-rate for each stage.

3.1.2. SOC-based transition

To transition from one stage to another one, different studies proposed distinct numbers of SOC stages. The accurate estimation of SOC is a challenging task. The SOC-based transition was used to shift from one stage to another one [50,74,80–83], as shown in Fig. 4(b). The specific number of stages used in various papers is summarized in Table 2. The number of stages was selected randomly and applied to the LIB to determine the charging time, charging efficiency, charge and discharge capacity, and temperature rise during charging. The results revealed that the proposed MSCC strategy with SOC-based transition can reduce the charging time [50,80–83], improve charging efficiency [82], enhance the charge/discharge capacity [50], reduce the temperature rise [82], and extend the LIB lifetime [83] in comparison to the standard method (CCCV). In ref. [50], the authors performed experiments on different SOC intervals. As higher the first-stage SOC interval as much lower the charging time and the higher the temperature rise. Furthermore, the authors of ref. [74] concluded that the four-stage SOC-based MSCC charging approach reduced charging time (roughly 15.3%), slightly decreased charging efficiency (0.4%), and slightly reduced the temperature rise when compared to the equivalent CCCV method. In addition, authors used post-mortem analyses to investigate the impact of MSCC on graphite exfoliation and crystallization damage [83]. The results demonstrated that the MSCC reduced the SEI layer growth of anode, lowered internal resistance, and extended the LIB lifetime.

SOC estimation is challenging due to significant variations in the battery parameters (voltage, current, and operating temperature during its lifespan owing to aging and nonlinear behavior). In addition, the SOC-based stage transition is expensive due to its computational cost and burden [84] and a little bit complex to implement due to various parameters in the LIB operations. There are various methods in the literature for calculating the SOC; however, each strategy has certain advantages and drawbacks [85]. Therefore, it can be challenging to apply the SOC-based transition in practical application due to the need for relying on a parameter, which is not accurately measurable and needs to be estimated.

3.1.3. Voltage threshold-based criteria

The voltage threshold-based transition is another criterion for designing charging transitioning between two consecutive stages. In this case, a different voltage threshold is selected to modify the stage and charging current value, as shown in Fig. 4(c). The authors employed the voltage threshold-based stage transition [20,21,29]. The voltage thresholds ranged from 3.6 to 4.2 V since the author selected to use gradually decreasing voltage increments between each stage. The finding revealed that using a five- and ten-stage voltage threshold-based technique reduced the charging

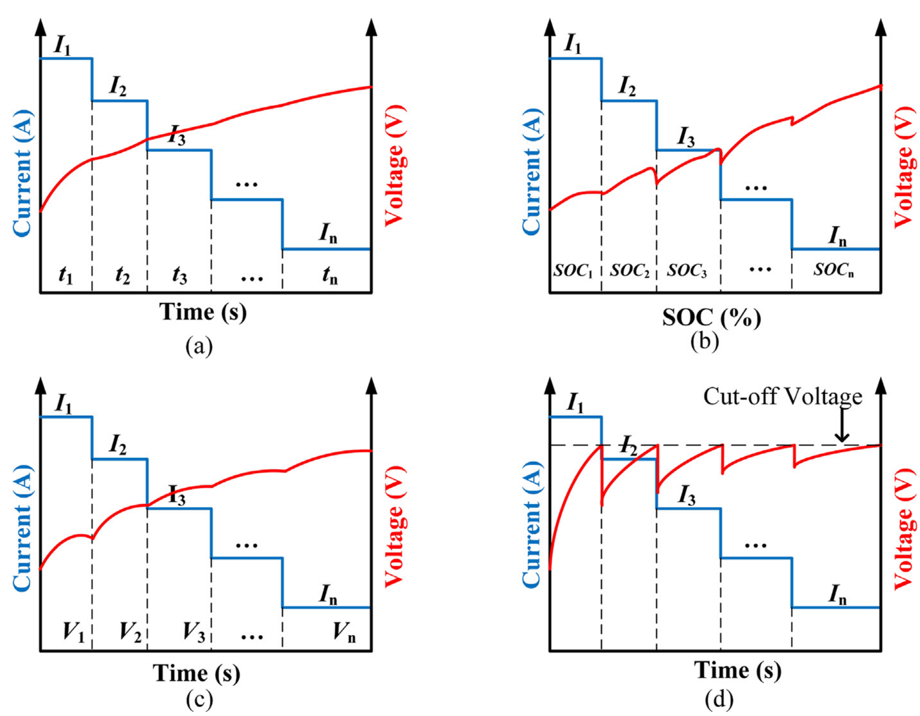

Fig. 4. Theoretical illustration of current (blue) and voltage (red) profiles verses time during MSCC charging strategies for transition criteria from one stage to the next stage. (a) Time-based transition between stages; (b) SOC-based transition; (c) threshold Voltage based transition; (d) cut-off voltage-based transition.

Table 2
Different numbers of charging stages used for charging transitions proposed by various authors.

Ref.	Cell chemistry	Multi-stage SOC-based charging (SOC in %)							
		S1	S2	S3	S4	S5	S6	S7	S8
[50]	NCM	0%–70%	70%–80%	80%–100%					
[74]	Li-ion	0%–25%	25%–50%	50%–75%	75%–100%				
[83]	NMC	0%–20%	20%–40%	20%–60%	60%–80%	80%–100%			
[80]	$LiFePO_4$	10%–20%	20%–30%	30%–40%	40%–50%	50%–60%	60%–70%	70%–80%	80%–90%

time while the lifetime was unaffected [21,29]. Similarly, the authors employed four- and five-stage MSCC charging strategies to check its effect on the lithium plating [20]. The findings revealed that high C-rate charging strategies have more lithium plating during charging than low C-rate charging strategies. The author selected voltage-threshold values randomly. No particular method is used to determine the threshold voltage at each stage. Nevertheless, the threshold-based stage transition technique is easier to implement than the SOC-based transition criteria.

3.1.4. Cut-off voltage-based criteria

Cut-off voltage-based criteria are the most utilized criterion in the literature for transitioning from one stage to the next one. An illustration of this strategy is shown in Fig. 4(d). The manufacturer predetermines the cut-off voltage value. Usually, it is 4.2 V for cobalt-based LIBs. In this method, once the cut-off voltage is achieved while charging, the current is reduced (stage transitioning), and charging continues until the cut-off voltage is reached again. This procedure is repeated until the predefined number of stages is reached. Therefore, it is simple and easy to implement. In literature, various authors implemented different stages, like four stages [30,58,73,86], five stages [51,52,75,76,87–90], and ten stages [60] to check the LIB lifetime and performance. The result shows that the MSCC charging strategy can improve the charging efficiency [30,51,52,76,88–90], reduce the charging time [30,52,58,60,73,76,86–90], enhance the charge and discharge capacity [51,58,60], reduce the temperature rise [89], and prolong the lifetime [58,87–90] of LIBs in comparison to the equivalent CCCV method. At the same time, charging the battery above the manufacturer's cut-off voltage has a negative impact on the battery lifetime [51,72,91]. In addition, the cut-off voltage-based criteria are simple and easily implementable compared to other criteria.

3.2. C-rate finding methods

The charging current is one of the most significant factors that affects the useful life and performance of LIBs. The polarization inside the LIB rises as the current level increases. As a result, the higher the C-rate, generally, the shorter the cycle life of LIB. There are numerous methods in the literature for determining and recommending the charging current at each stage. To determine the charging current at each stage, researchers have employed analytical techniques, optimization methods, and empirical approaches. The details of each method are discussed in the following.

3.2.1. Empirical approach

An empirical approach was employed in the literature to determine the optimal C-rate of each stage. However, the C-rate was first chosen randomly, and the optimal C-rates were determined through laboratory experiments. In ref. [58], the authors conducted thirty-six experiments to find the optimal C-rate (0.6, 0.3, 0.15, and 0.1 C). Therefore, much experimentation is generally required when using the empirical approach to determine the optimal C-rate. This method is also not standardized yet. Table 3 lists a few references that employed an empirical approach to determine the C-rate to charge the LIBs. Fig. 5 illustrates the complete procedure used to evaluate the LIB performance and lifetime, where N indicates the specific number of cycles after which the capacity and lifetime of LIB are analyzed. The conclusions from the numerous articles [50,58,60,71] are diverse, where no similarities are found. The authors used different transition criteria for switching from one stage to the next one. Distinct C-rates have different effects on charging time and performance at each stage. In Section 4, the effect of different numbers of stages, different stage transition criteria, and the C-rate will be discussed in more detail.

3.2.2. Analytical technique

An analytical technique can also determine the optimal C-rate for charging the LIB with the MSCC strategy. The authors analyzed the differential equations through circuit modeling and employed the first-order derivative test to minimize the charging time [51,75]. The optimal C-rate is determined numerically using Eq. (4) and then validated through experiments [41,62].

$$I_n = \sqrt{I_{n-1} \times I_{n+1}} n \geq 3 \tag{4}$$

In this case, I_n represents the n-stage current, with I_{n-1} representing the previous stage current and I_{n+1} expressing the next stage current. Eq. (4) is only utilized when the first and last stage charging currents are predetermined by the manufacturer, and the number of stages must be odd numbers.

3.2.3. Optimization methods

To determine the optimal charging current for LIBs, several prior studies employed optimization methods, as indicated in Table 4. In the literature, the authors utilized the Taguchi method [30,47,76,82,86,89], particle swarm optimization [68,80,88], genetic algorithm [73], ant colony system [87], numerical optimization [92], and grey wolf optimization [52] for finding the optimal charging pattern. Regarding the C-rate for each stage, the literature provides rather diverse results. There are a variety of optimization methods and the different number of stages used to determine the ideal charging profile. With the objective of finding the optimal charging current, the general problem formulation is represented in the following Eqs. (5)–(10) [29].

Objective function:

$$\min f(x) = \{I_1, I_2, \cdots .I_n\} \tag{5}$$

Subject to:

$$t_c \leq t_{\max} \tag{6}$$

$$\mathrm{SOC_c} \geq \mathrm{SOC_{min}} \tag{7}$$

$$T_c(t) = T_{\max} \quad \forall\, t\epsilon[t_0, t_c] \tag{8}$$

$$\Delta T_c(t) \leq \Delta T_{\max} \quad \forall\, t\epsilon[t_0, t_c] \tag{9}$$

$$I_{lb} \leq I_j \leq I_{ub} \quad \forall\, j\epsilon[1, n] \tag{10}$$

The objective function changes depending on the application. The main objective is to find the optimal charging pattern that reduces charging time while providing a sufficient cycle life to LIBs

Table 3
Empirical approach for finding the optimal C-rate.

Ref.	Cell chemistry	Cell type	Cell capacity	No. of stages	Criteria of transition between stages	C-rate of each stage
[50]	NCM	Cylindrical	2.8 Ah	Three	SOC	1, 0.5, 0.3
[71]	NCM	Pouch	-	Three	Time	1.8, 1.5, 0.9
[58]	NCM	Cylindrical	2 Ah	Four	Cut-off voltage	0.6, 0.3, 0.15, 0.1
[60]	$LiFePO_4$	Cylindrical	1.37 Ah	Ten	Cut-off voltage	1, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1

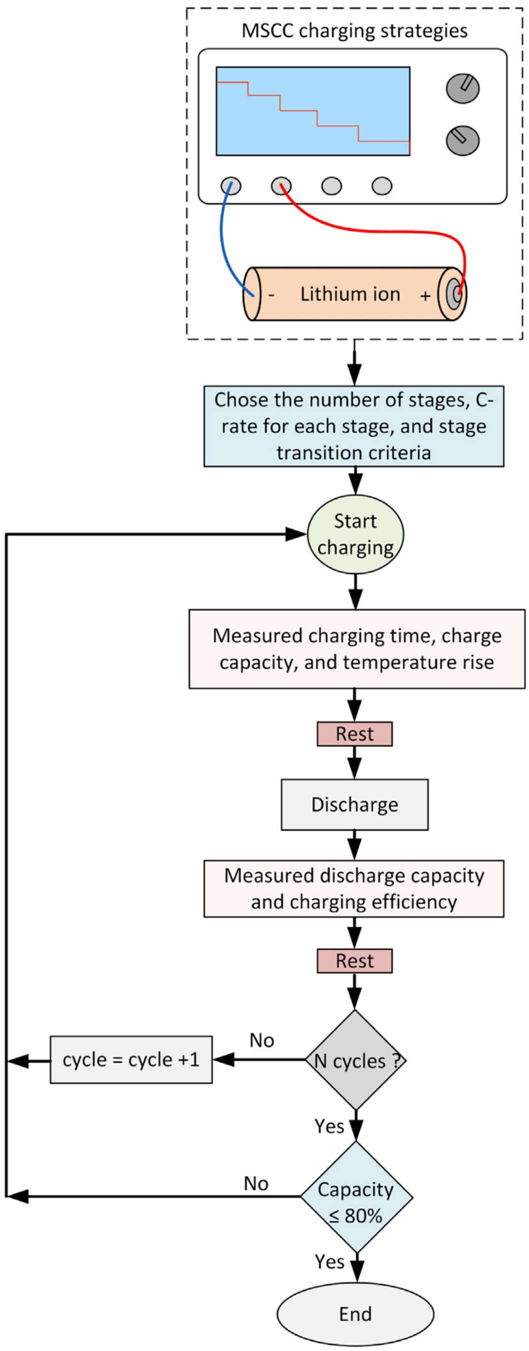

Fig. 5. Flow chart for charging and discharging cycles for evaluation of MSCC charging strategy and its impact on the LIB performance and lifetime.

for EV applications. Therefore, the objective function defined in Eq. (5) is to find the lower currents at each stage while maintaining good performance and lifetime. In Eq. (6), t_{max} is adjusted to increase charging currents and balance the objective function. Eq. (6) is used to reduce the charging time (t_c). Eq. (7) is incorporating the minimum SOC charge (SOC_{min}) into the MSCC charging strategy (SOC_c) during the charging. The thermal constraint is represented via Eqs. (8) and (9). T_c is the temperature during charging, and ΔT shows the temperature change. The current constraint in Eq. (10) includes both the upper (I_{ub}) and lower (I_{lb}) bounds of the current range. The impact of the different optimization methods with a distinct number of stages and the optimal C-rate on the charging performance and LIB lifetime will be explored in greater depth in Section 4.

4. Impact of MSCC charging on LIB

The benefits of the MSCC charging strategy have been demonstrated by many researchers. However, the MSCC charging strategy does not always have a positive influence on the performance and lifetime of LIB. Therefore, it is necessary to explore the MSCC charging strategy with a varying number of stages and distinct transition conditions. The LIB performance is determined by four parameters: charging time, charging efficiency, discharge capacity, and temperature rise during charging. In the literature, some researchers more exclusively concentrate on certain parameters. The primary impact factor on the performance and lifetime is the stage transition criteria and C-rate during the charging.

4.1. MSCC charging impact on performance

The impact of the MSCC charging strategy on the LIB performance is evaluated based on the stage transition criteria. The time-based transition is used in ref. [71] to analyze the impact of different charging patterns and temperatures on the LIBs performance. The optimal charging current pattern is found using the empirical approach. The result indicates that the MSCC charging strategy with time-based transition greatly reduced the charging time and had a good capacity retention compared to constant current (CC). The polarization effect is also small compared to the CC charging method.

The voltage-threshold-based transition is another type of criterion for stage transitions. In accordance with this criterion, various voltage levels are established to shift the stages and implement the optimal charging pattern. A numerical optimization technique was employed to determine the optimal charging current [29]. The technique implemented has a beneficial impact on the charging time. The charging time is considerably shortened. In addition, the threshold voltage has no detrimental effect on the polarization and SEI growth since the LIB is below the cutoff voltage limit for the majority of the time. The battery is not subject to any stress.

SOC-based transition is another method of stage transition. The influence of the MSCC charging strategy with SOC-based transition was investigated [50,68,74,80–82]. However, the optimal charging current for each stage was determined using an empirical technique [50] and an optimization method [68,74,80–82]. The finding indicated that SOC-based transitioning improves the performance of LIBs. However, the implementation and estimation of SOC is difficult due to the nonlinear behavior of LIBs.

Table 4
Optimization methods for finding the optimal C-rate for MSCC charging strategy.

Ref.	Cell chemistry	Cell type	Cell capacity	No. of stages	Optimization technique	Criteria of transition between stages	Optimal C-rate of each stage
[74]	Li-ion	Cylindrical	0.84 Ah	Four	Taguchi method	SOC	1.4, 1, 0.7,0.4
[82]	Li-Poly	Pouch	5 Ah, 5.8 Ah	Four	Taguchi method	SOC	1.8, 1.3, 0.9, 0.5
[86]	Li-ion	Cylindrical	0.84 Ah	Four	Taguchi-based Particle swarm optimization	Cut-off voltage	1.23, 1.08, 0.66, 0.26
[30]	Li-ion	Cylindrical	0.84 Ah	Four	Taguchi	Cut-off voltage	1.4, 0.9, 0.75, 0.2
[73]	Li-ion	Cylindrical	3.5 Ah	Four	Genetic algorithm	Cut-off voltage	Starting from 1 C, then adaptive at each stage
[87]	Li-ion	Cylindrical	0.93 Ah	Five	Ant-colony system	Cut-off voltage	2.1, 1.7, 1.5,1.3, 1
[88]	Li-ion	Cylindrical	2.2 Ah	Five	Particle swarm Optimization	Cut-off voltage	1.44, 1.18, 0.87, 0.71, 0.41
[76]	Li-ion	Cylindrical	3.15 Ah	Five	Taguchi method	Cut-off voltage	1.55, 1, 0.6, 0.3, 0.2
[89]	Li-ion	-	0.6 Ah	Five	Taguchi method	Cut-off voltage	1.5, 1.2, 0.9, 0.65, 0.4
[90]	Li-ion	-	0.65 Ah	Five	Taguchi method	Cut-off voltage	1.45, 1.05, 1,0.7, 0.1
[52]	Li-ion	Cylindrical	2.5 Ah	Five	Grey wolf optimization	Cut-off voltage	0.83, 0.47, 0.31, 0.21, 0.14
[80]	$LiFePO_4$	Pouch	8 Ah	Eight	Particle swarm optimization	SOC	4.9, 4.55, 3.76, 1.75, 1.63, 1.55, 1, 1.25
[29]	NMC	Cylindrical	3 Ah	Ten	Numerical optimization	Threshold voltage	2.1, 2.37, 1.8, 1.6, 1.43, 1.1, 1.06, 0.73, 0.4, 0.3
[92]	Li-ion	Cylindrical	3.25 Ah	Adaptive	Particle swarm optimization	Cut-off voltage	Starting from 1 C, then adaptive at each stage

The most often utilized criterion for stage transition is the cut-off voltage. The cut-off voltage-based criterion was employed [30,51,52,55,58,60,73,75,76,86–90,92,93]. However, different authors employed distinct approaches to figure out the optimal charging pattern. Compared to the CCCV technique, the results indicate that charging time is shortened by 56.8% [88], charge and discharge capacity is enhanced by 1.8% [51], the temperature is lowered by 9.3 °C [76], and charging efficiency is improved by 2.8% [76]. The cut-off voltage-based criteria have the largest influence on the performance metrics.

Table 5 provides an overview of the impact of the MSCC charging technique on performance. The conclusion drawn from the literature is that, as claimed by numerous researchers, the MSCC charging strategy reduces charging time and enhances charging efficiency; both are important parameters. However, due to the diversity in the methods for determining the optimal C-rate and number of stages, there is some inconsistency in the literature regarding the temperature rise during charging and charge/discharge capacity compared to CCCV. Some authors observed an increase in temperature and a decrease in charge/discharge capacity when comparing the MSCC charging technique to the standard CCCV method. The MSCC charging strategy has a positive impact on charging time and charging efficiency but also has a negative impact on temperature rise and charge/discharge capacity. Further discussion on the impact of C-rate and variation in stages is discussed in Section 5.

4.2. MSCC charging impact on lifetime

To investigate the impact of the MSCC charging strategy on the lifetime of LIB, various authors have employed different MSCC charging techniques. The authors [92] combined a semi-empirical aging model with an adaptive MSCC charging strategy. Different scenarios were constructed to determine the optimal charging current and number of stages. The results demonstrate that the balancing charging technique improves the lifetime of LIB by 3.6% compared to the 0.5 C-CCCV charging method. In a similar manner, the Taguchi method is utilized to figure out the optimal charging pattern for a five-stage charging strategy [90]. A total number of 54 experiments were performed, and the results demonstrate that the MSCC charging strategy provides 57% more cycle life in comparison to the CCCV method. Similarly, the same Taguchi method is applied [89], and the result indicates that the acquired charging pattern gives 60% more cycle life than the CCCV method. Grey wolf optimization is used [52] to determine the optimal charging pattern. The obtained results suggest a 79.6% improvement in cycle life compared to the CCCV method. The particle swarm optimization and the ant colony algorithm were employed to determine the optimal charging pattern [88]. The results indicate a 21% and 25% improvement in life cycles compared to the CCCV method. Thus, Table 6 provides a summary of the impact of the MSCC charging strategy on the lifetime of LIBs. The conclusion from Table 6 is that the MSCC charging strategy improves lifetime regardless of the number of stages, cell chemistry, or transition criteria. However, the majority of the researchers conducted their investigations utilizing a five-stage charging strategy with a cut-off voltage as the transition criterion.

5. Analysis and discussion

This section discusses how the key variables of various MSCC charging strategies affect the lifetime and performance characteristics (charging time, charge/discharge capacity, charging efficiency, and temperature rise during charging) of LIBs. The number of stages, the charging C-rate, and the criterion for stage transitions are the primary impact factors of the MSCC charging procedure. First, the impact factors of the main parameters are assessed. The last part represents a discussion of the above overview.

5.1. Impact of a variable number of stages

The literature has a wide range of results that can be used to explore the impact factor of a different number of stages on lifetime and performance of LIB. The optimal numbers of stages and LIB performance characteristics have been investigated [81]. As the number of charging stages increases from one to five, the charging efficiency and charging time are improved significantly. However, when the number of stages exceeds five, only marginal improvement can be achieved [9,51,52,68,75,81,88,93]. Therefore, it is not suggested to employ more than five stages since this would increase the complexity of the charger control circuitry without significantly enhancing the LIB performance and lifetime.

Table 5
Impact of the MSCC charging strategy on the performance of LIBs (Y: Yes, N: No, S: Similar, -: no data available).

Ref	Cell chemistry	Cell type	Cell capacity	Compared with	Transition criteria between stages	No. of stages	Method for finding optimal C-rate	Performance parameters			
								Shortened charging time	Enhance charge/ discharge capacity	Temperature rise	Improved charging efficiency
[71]	NCM	Pouch	-	CC	Time	Three	Empirical	Y	Y	-	-
[29]	NCM	Cylindrical	3 Ah	CCCV	Threshold voltage	Ten	Optimization	Y	-	-	-
[50]	NCM	Cylindrical	2.8 Ah	CCCV	SOC	Three	Empirical	Y	Y	N	-
[81]	Li-ion	-	1 Ah	CCCV	SOC	Four	Optimization	18.25%	-	-	-
[80]	$LiFePO_4$	Pouch	8 Ah	-	SOC	Eight	Optimization	Y	-	4.1 °C	-
[68]	NMC	Cylindrical	2.6 Ah	CCCV	SOC	Five	Optimization	Y	-	N	-
[82]	Li-poly	Pouch	5 Ah, 5.8 Ah	CCCV	SOC	Four	Optimization	Y	N	N	Y
[74]	Li-ion	Cylindrical	0.84 Ah	CCCV	SOC	Four	Optimization	15.3%	N	N	N
[83]	Li-ion	Coin cell	3.8 mAh	CCCV	SOC	Five	Empirical	20%	-	-	-
[30]	Li-ion	Cylindrical	0.84 Ah	CCCV	Cut-off voltage	Four	Optimization	Y	N	Y	Y
[75]	Li-ion	Cylindrical	2.6 Ah	CCCV	Cut-off voltage	Five	Analytical	12%	-	-	0.54%
[60]	$LiFePO_4$	Cylindrical	1.37 Ah	CCCV	Cut-off voltage	Ten	Empirical	Y	Y	S	-
[58]	NCM	Cylindrical	2 Ah	CCCV	Cut-off voltage	Four	Empirical	Y	Y	S	-
[86]	Li-ion	Cylindrical	0.84 Ah	CCCV	Cut-off voltage	Four	Optimization	43.7%	-	-	-
[73]	Li-ion	Cylindrical	3.5 Ah	CCCV	Cut-off voltage	Four	Optimization	Y	-	-	N
[51]	Li-ion	Cylindrical	2.6 Ah	CCCV	Cut-off voltage	Five	Analytical	12%	1.8%	N	0.54%
[87]	Li-ion	Cylindrical	0.93 Ah	CCCV	Cut-off voltage	Five	Optimization	Y	-	-	-
[88]	Li-ion	Cylindrical	2.2 Ah	CCCV	Cut-off voltage	Five	Optimization	56.80%	N	-	0.4%
[89]	Li-ion	-	0.6 Ah	CCCV	Cut-off voltage	Five	Optimization	Y	N	N	1%
[90]	Li-ion	-	0.65 Ah	CCCV	Cut-off voltage	Five	Optimization	11.2%	-	-	1.02%
[92]	Li-ion	Cylindrical	3.25 Ah	CCCV	Cut-off voltage	Adoptive	Optimization	37%	-	-	-
[55]	$LiFePO_4$	Prismatic	20 Ah	CCCV	Cut-off voltage	Five	Optimization	Y	Y	N	-
[76]	Li-ion	Cylindrical	3.15 Ah	CCCV	Cut-off voltage	Five	Optimization	Y	N	9.3 °C	2.8%
[52]	Li-ion	Cylindrical	2.5 Ah	CCCV	Cut-off voltage	Five	Optimization	5.33%	-	N	0.48%

Table 6
Impact of the MSCC charging strategy on the lifetime of LIBs (Y: Yes).

Ref.	Cell chemistry	Cell type	Cell capacity	Method for finding optimal C-rate	No. of stages	Transition parameter between stages	Compared with	Improved lifetime
[71]	NCM	Pouch	-	Empirical approach	Three	Time	CC	Y
[58]	NCM	Cylindrical	2 Ah	Empirical approach	Four	Cut-off voltage	CCCV	Y
[94]	$LiFePO_4$	Pouch	7 Ah	Empirical approach	Four	SOC	CCCV	Y
[29]	NMC	Cylindrical	3 Ah	Optimization method	Ten	Threshold voltage	CCCV	Y
[87]	Li-ion	Cylindrical	0.93 Ah	Optimization method	Five	Cut-off voltage	CCCV	25%
[88]	Li-ion	Cylindrical	2.2 Ah	Optimization method	Five	Cut-off voltage	CCCV	21%
[52]	Li-ion	Cylindrical	2.5 Ah	Optimization method	Five	Cut-off voltage	CCCV	79.6%
[89]	Li-ion	-	0.6 Ah	Optimization method	Five	Cut-off voltage	CCCV	60%
[90]	Li-ion	-	0.65 Ah	Optimization method	Five	Cut-off voltage	CCCV	57%
[92]	Li-ion	Cylindrical	3.25 Ah	Optimization method	Adaptive	Cut-off voltage	CCCV	3.6%
[83]	Li-ion	Coin Cell	3.8 mAh	Empirical approach	Five	SOC	CCCV	Y
[59]	NMC	Cylindrical	2 Ah	Empirical approach	Five	Threshold voltage	CCCV	Y

Table 7 shows the relationship between the number of stages and the performance parameters, lithium plating, and lifetime. Generally, the optimal MSCC charging strategy can prevent the precipitation of lithium metal during the charging process [29,59,71]. Based on the results in the literature, the five-stage charging strategy is generally a suitable strategy compared to other stages in terms of better performance parameters and lifetime.

5.2. Impact of different C-rate

The performance and lifetime of the LIBs are greatly impacted by the charging pattern applied to the MSCC charging strategy. Various authors have utilized different techniques to determine the optimal C-rate, including empirical approaches [58], analytical techniques [51], and optimization methods [52]. However, as the

Table 7
Impact factor of the different number of stages on LIBs performance and lifetime (+: positive impact, N/A: no data available).

Ref.	Strategy	Compared with	Shortened charging time	Improved charging efficiency	Enhanced charge/ discharge capacity	Reduction in temperature rise	Improved lifetime	Reduction in lithium plating
[71]	Three stages	CC	+	N/A	+	N/A	+	+
[58]	Four stages	CCCV	+	N/A	+	+	+	N/A
[52]	Five stages	CCCV	+	+	N/A	+	+	N/A
[59]	Five stages	CCCV	+	N/A	N/A	N/A	+	+
[80]	Eight stages	CCCV	+	N/A	N/A	+	N/A	N/A
[29]	Ten stages	CCCV	+	N/A	N/A	N/A	+	+

charging current increases, charging time decreases [95], the temperature rises [95], and charging efficiency and cycle life decrease. On the one hand, the high charging current, e.g., 2 C, results in low energy efficiency, short charging time, and high-temperature rise. On the other hand, the low charging current, e.g., 0.3 C, results in high energy efficiency, long charging time, low-temperature rise, and potentially improved lifetime [82]. Thus, the combination of the various C-rates is required to balance all performance characteristics and the lifetime of LIBs. Furthermore, the analytical method would give a solid foundation for moving forward. For determining the optimal charging profile, only the information of the charging current levels of the first stage and last stage is required. These current limits are usually provided by manufacturers in terms of high charge current and nominal charge current. The charging capacity usually depends upon the last stage of the charging current. The charged capacity is inversely proportional to the last stage charging current and charging time. As low as the last stage charging current as much energy is stored in the LIB. But the charging time would increase. However, finding the optimal charge pattern using the 1-resistor-capacitor (RC) circuit [51] is not as accurate as 2RC model. The optimal charging pattern utilizing the 2RC model will be more accurate. The charging current must also have an impact based on the cell chemistry.

5.3. Impact of the stage transition criteria

The stage transition criterion has an effect on the performance and lifetime of the LIBs. As shown in Tables 5 and 6, the cut-off voltage-based transition is widely employed because it enhanced the performance and lifetime of LIBs. In the first stage, the voltage rises to cut-off voltage rapidly compared to other criteria. In this way, the cut-off voltage criteria increase the charging speed compared to other transition criteria. Table 8 illustrates the impact factor of different stage transition criteria based on some articles [50,52,59,71]. Generally, the most suitable criterion is the cut-off voltage. In addition, the cut-off voltage conditions are easier to implement in comparison to the SOC and threshold voltage criteria [52]. According to the previous research, when cut-off voltage-based criteria are utilized, the LIBs lifetime was extended by 79.6%, charging time was shortened by 5.33%, the temperature dropped by 26%, and charging efficiency was increased by 0.48% [52].

The following conclusions can be drawn from the aforementioned discussion and evaluation results.

- From all of the impact factors, the optimal C-rate of the MSCC charging strategy had the highest impact on the performance and lifetime of LIBs. Beginning with a charging current of 1–1.5 C, the lifetime is positively impacted; however, charging currents beyond 2 C have a negative impact on the LIB lifetime, discharge capacity, and charging efficiency.
- High C-rate charging is associated with increased polarization due to transport and kinetic overpotentials, which is favorable for lithium plating.
- Several factors influenced charging speed, including the number of stages and the first and last stage charge current. Increasing the number of stages improves capacity utilization and charging efficiency.
- The relationship between charging current and charging time is almost linear. However, the cycle life decreases as the charging current increases.
- A higher charging current led to a larger temperature variation. The rise in the temperature will have a negative impact on the safety and lifetime of LIBs.
- The overall impact of the MSCC charging strategy is positive on the performance and lifetime. The main challenge is to balance the charging speed and capacity utilization, where different factors will make the priority.

6. Conclusions

The MSCC charging techniques, i.e., three, four, five, eight, and ten, are all summarized in this article. Different methods for determining the optimal C-rate were investigated based on various MSCC charging strategies. An overview of MSCC charging methodologies and their impact on performance metrics and lifetime is

Table 8
Impact factor of the different stage transition criteria on performance parameters and lifetime of LIBs (+: positive impact, N/A: no data available).

Ref.	Stage transition criteria	Compared with	Shortened charging time	Improved charging efficiency	Enhanced charge/ discharge capacity	Reduction in temperature rise	Improved lifetime	Reduction in lithium plating
[52]	Cut-off voltage	CCCV	+	+	N/A	+	+	N/A
[59]	Threshold voltage	CCCV	+	N/A	N/A	N/A	+	+
[50]	SOC	CCCV	+	N/A	+	+	N/A	N/A
[71]	Time	CCCV	+	N/A	+	N/A	+	+

described. The key impact factors are studied and analyzed. The factors that had the most impact on both performance and lifetime were charging current, the number of stages, and stage transition condition. However, the primary factor that significantly affects the charging time, charge/discharge capacity, temperature rise, charging efficiency, and lifetime is the charging profile. The charging time is shortened as the charging current rises above a particular level, but at the same time, the charging efficiency and lifetime deteriorate. The second factor is the number of charging stages required for optimal performance. For a greater charge capacity and longer lifecycles, the five stages are appropriate. The charging efficiency and lifetime are somewhat enhanced by more than five stages, but it makes the system complex. Lastly, the criteria in between stages have a significant impact. The optimal criteria for changing from one stage to the next stage are the cut-off voltage. It is simple to implement and easy to control. Future research must also look into how the MSCC charging approach affects LIB temperature, charge/discharge capacity, lifetime, and speed in order to design an enhanced fast-charging algorithm for EVs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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