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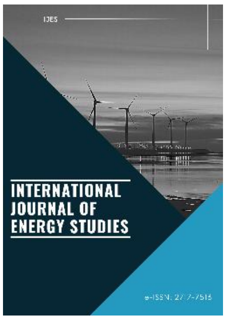

Research Article

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Design, simulation, and comparative evaluation of charging strategies for electric vehicles

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Highlights

- Fast-charging strategies (CC, Pulse, MSCC) were modeled in MATLAB/Simulink and evaluated in terms of charging time, temperature rise, and voltage behavior.
- The MSCC method was optimized using the Taguchi approach, improving both charging efficiency and thermal performance.
- Simulation results indicate that optimized MSCC offers a superior balance between speed and temperature compared to CC and Pulse techniques.

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ABSTRACT

Efficient and reliable charging strategies are essential for improving the performance, lifetime, and safety of modern battery energy storage systems, particularly under diverse operating conditions. This study presents a systematic analysis and comparative evaluation of three representative charging approaches: the Constant-Current (CC) method, the Pulse Charging method, and the Multistage Constant-Current (MSCC) method, each investigated at different C-rates. The mathematical principles and operational mechanisms of these methods are first introduced, followed by the development of a simulation model. Performance evaluation is conducted in terms of critical indicators, including temperature rise, charging time, and terminal voltage dynamics. The results indicate that the MSCC method achieves a more favorable balance between charging efficiency and thermal management compared to conventional techniques. Furthermore, the Taguchi optimization method is employed to determine the optimal charging parameters within the MSCC framework, thereby enhancing overall performance and safety. These findings underscore the potential of combining advanced charging strategies with systematic optimization techniques to improve battery management systems and support the development of next-generation energy storage technologies.

Keywords: Fast charging, Traditional charge methods, Taguchi method

1. INTRODUCTION

The combustion of fossil fuels releases harmful gases, including carbon dioxide, sulfur dioxide, and nitrogen oxides, into the atmosphere, substantially contributing to air pollution and environmental degradation. As the emission of greenhouse gases from vehicles, the depletion of fossil fuel resources, and the growing need for clean energy storage have become global concerns—particularly highlighted in the Paris Climate Agreement—the significance of rechargeable batteries for electric vehicles has markedly increased. Beyond their pivotal role in transportation electrification, the rechargeable nature and compact design of these batteries have rendered them indispensable components in a wide range of electronic devices [1] and [2]. Global projections estimate that electric vehicle (EV) sales will reach approximately 20 million units by 2025, indicating a significant acceleration in the shift toward sustainable mobility. This growth trend implies a gradual decline in the dominance of fossil fuel–powered vehicles, while the penetration of EVs is expected to increase steadily in the coming years [3].

Lithium-ion (Li-ion) batteries exhibit significant advantages over conventional lead-acid batteries, including longer cycle life, higher energy density, and lower self-discharge rates. Owing to these superior characteristics, Li-ion batteries have become the predominant energy storage technology in EVs [4]. The charging process is a critical factor in the safe operation of these batteries as well as their performance and lifespan. Therefore, various charging methods have been designed and studied to increase battery durability, improve charging efficiency, and ensure reliable operation under different conditions [2]. Traditional charging techniques, including CC, Constant Voltage (CV), Constant Current–Constant Voltage (CC–CV), Pulse Charging, and MSCC, have been widely utilized for many years. These methods are considered reliable due to their simple control structure and proven stability, even though they may not fully optimize charging efficiency and temperature rise compared to intelligent approaches.

Several studies in the literature have investigated conventional charging techniques. In reference [5], temperature and charging duration as key performance indicators, highlighting that battery charging strategies are primarily determined by current, power, and voltage parameters. In references [6] and [7], the pulse charging technique was reported to be the most favorable among the CC, CV, and CC-CV charging methods. In references [8] and [9], it was observed that the pulse charging method is more efficient than CC-CV, and reduction in charging time. Furthermore, in [10], the pulse charging method and smart charging method were combined and compared with the CC method by charging with a 1C current rate, and 37.78% faster charging was achieved compared to the CC method. In references [11] and [12], the Positive Pulse Charging (PPC) technique was evaluated against conventional CC–CV charging methods. The results showed that PPC improves charging performance. By optimizing the charging frequency, efficiency reached 98.5% in normal mode and 94.5% in fast mode, while reducing the total charging time by 38.7%. Compared to CC–CV charging, PPC increased charging speed and efficiency by 14% and 3.4%, respectively. Overall, these studies demonstrate that while pulse charging strategies can significantly reduce charging time, their effectiveness strongly depends on parameter selection and thermal constraints.

In [13], the CC method and the MSCC method were compared, and it was reported that the MSCC method charged 28% faster than the CC method. In [14], a comparative analysis was conducted between the CC and MSCC charging methods for current rates of 0.5C, 0.7C, and 1C. The results indicated that increasing the current rate led to reductions in both charging time and battery temperature. Furthermore, Particle Swarm Optimization (PSO) was applied to both the MSCC and CC charging techniques to minimize temperature and time variations. As a result, significant reductions in charging time and temperature were achieved compared to conventional charging methods. In [15], the experimental results show that the proposed five-stage MSCC charging strategy reduces the charging time by approximately 12% compared to the conventional CC–CV method. In addition, a 0.54% improvement in charging efficiency and a 1.8% reduction in charging energy are achieved. In [16], experimental results showed that while both multi-stage and two-stage charging approaches adhered to acceptable current profiles, the multi-stage method exhibited superior performance, achieving a reduction of 138 seconds (11.73%) in charging time compared to the two-stage approach.

In [12], the performance of a five-stage CC charging method was further improved and optimized by applying the Sequential Orthogonal Array (COA) technique to determine the optimum charging scheme. In [17], the Taguchi method, combined with scalarization and weighting approaches, was applied to optimize the charging scheme and current level for the MSCC method. Results indicate that equal weighting extends charging time but yields higher nominal capacity, while unequal weighting reduces cell temperature rise. In [18] the Taguchi optimization approach was implemented within the MSCC charging framework, revealing that the MSCC method achieved a 5.7% reduction in charging duration at a 1C rate compared to the conventional CC strategy. Similarly, in [19], the integration of the Taguchi method with the MSCC technique was benchmarked against the traditional CC-CV approach, demonstrating a shorter charging period, a higher temperature rise, and a 0.5% decrease in efficiency relative to the 5SCC CC-CV configuration. Furthermore, in [20], the Taguchi method was employed to analyze the influence of stage number in the MSCC charging process. The findings indicated that the Three-Stage Constant Current (3SCC) technique provided superior charging performance compared to the Four-Stage (4SCC) and Five-Stage (5SCC) configurations. Collectively, these studies underscore the significance of optimizing parameters such as temperature rise, charging time, and battery lifetime to enhance the overall performance and reliability of multi-stage charging methodologies. These findings indicate that multi-stage charging strategies can outperform conventional CC–CV methods; however, their performance is highly sensitive to the number of stages and current allocation.

In this paper, a comprehensive comparative investigation of Li-ion battery charging strategies, namely CC, Pulse Charging, MSCC, and a Taguchi-based optimization framework, is performed under controlled thermal conditions with the ambient temperature fixed at 30 °C. Unlike many existing studies that rely on a limited number of operating points, this work conducts an extensive simulation-based evaluation by performing eight distinct tests for both Pulse and MSCC charging strategies across a wide current range from 1C to 3C, thereby strengthening the statistical reliability of the analysis and clearly differentiating this study from prior literature. The primary focus is placed on minimizing charging duration while maintaining acceptable thermal behavior and voltage stability. Accordingly, all charging strategies are modeled and simulated in MATLAB/Simulink, and their performances are assessed in terms of charging time, temperature rise, and terminal voltage response. To further enhance the MSCC strategy, the Taguchi optimization method is applied, where specific experiments are designed for 2C and 3C charging conditions using an L9 orthogonal array and providing a robust basis for parameter selection. Unlike existing studies that either apply Taguchi optimization to single-stage CC or CV charging strategies or focus on a single C-rate, the proposed approach integrates Taguchi-based optimization into a multi-stage CC framework and simultaneously evaluates multiple high C-rate conditions. This enables a systematic identification of optimal current stage combinations with respect to charging time and thermal behavior. In addition, an unequal weighting approach is adopted within the Taguchi-based decision framework, motivated by the fast-charging orientation of this study; Although temperature variation and terminal voltage are critical indicators of battery safety and aging, they are primarily treated as constraint-related performance metrics that must remain within safe operating limits. Once these constraints are satisfied, charging time becomes the dominant optimization objective, particularly in fast-charging-oriented applications. Therefore, the highest weighting coefficient is intentionally assigned to charging time, while temperature variation and terminal voltage are assigned lower weights to ensure thermal safety and voltage compliance without compromising fast-charging performance. This weighting strategy reflects a practical engineering trade-off between user demand for rapid charging and long-term battery health, consequently, charging time is assigned the highest weight compared to temperature and voltage criteria. The optimized MSCC results are then benchmarked against CC and Pulse charging methods to demonstrate the effectiveness of the proposed approach. The remainder of this paper is organized as follows: Section 1 introduces the study, Section 2 presents the CC, Pulse, MSCC, and Taguchi-based optimization techniques, Section 3 describes the system model, the employed DC–DC converter, and the corresponding simulation results, and Section 4 provides a comparative discussion of the findings and concludes the paper.

2. METHODS

2.1. Constant Current Charge Method

The constant current charging technique, which is one of the traditional methods, is considered easy and basic. As seen in Figure 1 (a), the application of this method is to give a constant current to the battery until the desired voltage level is reached. The charging duration of a battery is strongly influenced by the applied current. Specifically, lower current values result in extended charging times, whereas higher current values reduce the charging duration. Consequently, the selection of an appropriate current level is a critical parameter in optimizing battery charging performance. When excessive current is given in the constant current charging technique, the battery life is shortened, while the voltage level formed in the cells is high [8]. Moreover, since the excessive current charging technique is uncontrolled, the excessive voltage and temperature increase formed in the battery shorten the life of the battery [21].

2.2. Pulse Charge Method

Pulse charging technique has been introduced as an effective method to reduce charging time, minimize temperature rise, and extend the lifetime of lithium-ion batteries [11], [22]. As shown in Figure 1(b), current pulses are applied to the battery at specific intervals. This approach regulates critical battery parameters and promotes a more uniform distribution of electrolyte ions within the cell. Depending on the charging requirements, different pulse characteristics can be achieved by adjusting parameters such as frequency, amplitude, and duty cycle. Previous studies have reported that well-designed pulse charging strategies can improve charge acceptance and energy efficiency, extend cycle life, and shorten charging duration. However, the selection of an appropriate pulse frequency remains a key factor in achieving these benefits [12], [23], [24].

2.3. Multistage Constant Current Charge Method

The MSCC method is a charging strategy that fully charges the battery by applying CC mode [1]. This technique aims to divide the charging process into specific time intervals and charge with a constant current at each stage to shorten charging time, increase charging efficiency, and extend battery life. In the first stage, the battery is charged with a high current, and as charging progresses, the reference currents are gradually reduced depending on the battery charge level, as shown in Figure 1(c). Figure 2 shows a flowchart for gradually decreasing the current value in the MSCC charging technique. Four different criteria can be used to transition from one stage to another: time-based, cut-off voltage-based, SOC-based, and threshold voltage-based transitions [5]. There are three key parameters in the MSCC application: 1. Number of stages, 2. Transition criteria from one stage to another, and 3. The charging current is applied at each stage.

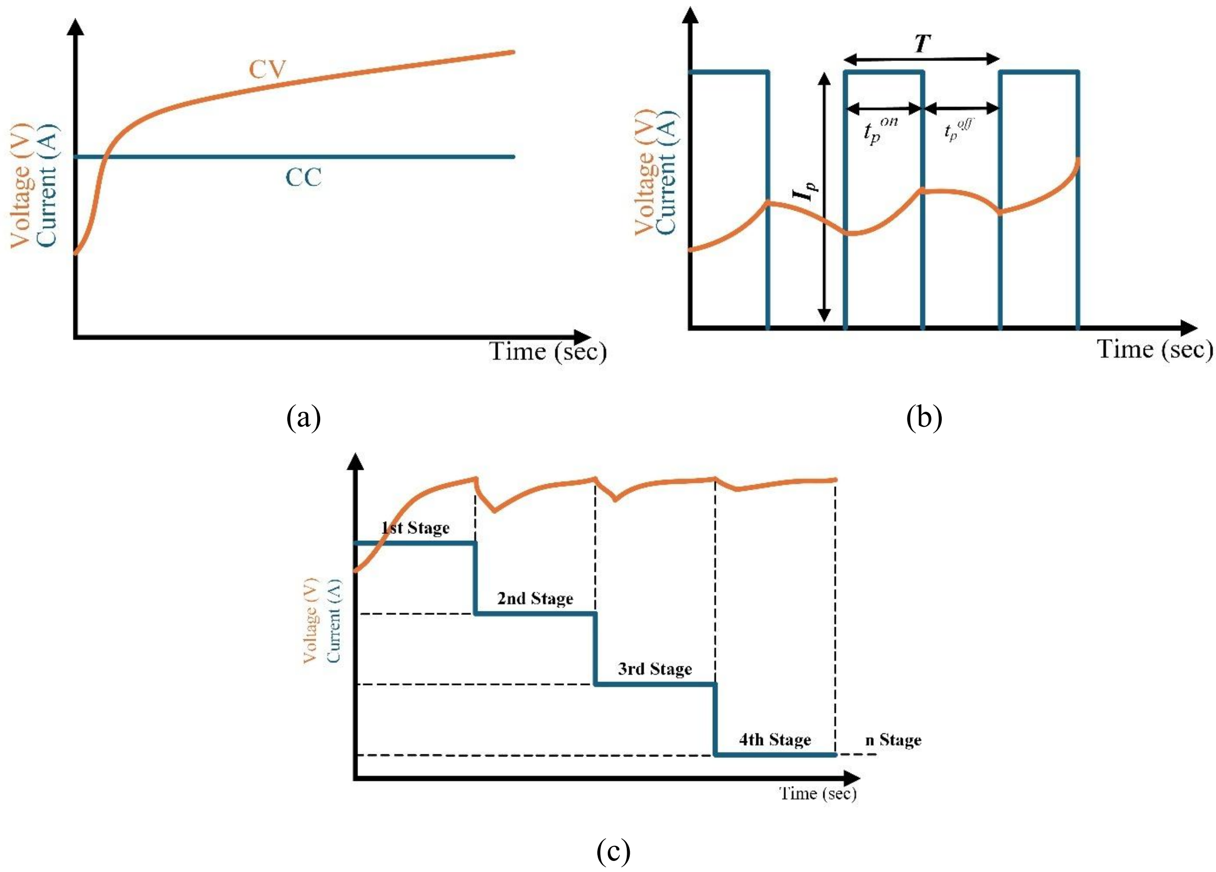


Figure 1. Different charging techniques for Li-Ion battery (a) CC Method, (b) Pulse Charging Method, (c) MSCC Method

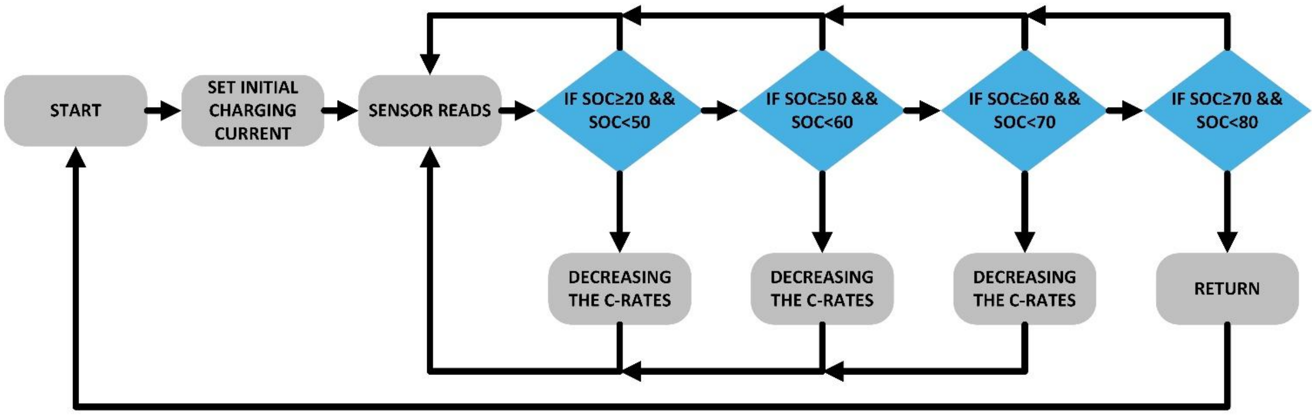


Figure 2. Flowchart for multi-stage charging technique

2.4. Taguchi-Based Optimization Approach

The Taguchi method is an improvement method applied by reducing the number of experiments to increase product quality and speed up the experiment process, and was proposed by Genichi Taguchi. It processes the best parameter values according to orthogonal design and S/N (signal-to-noise ratio). It finds the optimum optimization values for optimization problems found in a product with a certain cost. The Taguchi method is built on the OA (Orthogonal Arrays) concept to be systematic. The first important feature of OAs is that they have a fractional factorial structure. The second basic feature is that they provide a balanced experiment environment thanks to the equal representation of all possible parameter combinations. In addition, OAs provide high efficiency because accurate results can be obtained without having to test all possible combinations, and time is saved [19], [25]. In battery charging applications, the Taguchi method enables the systematic optimization of critical parameters affecting battery performance and health under practical design constraints. In this study, although different MSCC stage structures are comparatively analyzed, the Taguchi-based optimization is specifically applied to a four-stage MSCC (4SCC) charging configuration. The charging currents at each stage are treated as control factors. Two C-rate levels (2C and 3C) are considered, and an OA L9(3^4) orthogonal array is employed to evaluate the effects of current combinations (I_1, I_2, I_3, and I_4), as presented in Table 1.

The signal-to-noise (S/N) ratio is calculated based on charging time, temperature, and voltage parameters for the MSCC charging strategies, as defined in Equation (1) [19], [26].

$$\frac{S}{N_{f\,l}} = \begin{matrix} -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\left(y_{ij.k}{}^{2}\right)\right), STB \\ -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\left(y_{ij.k}{}^{-2}\right)\right), LTB \end{matrix} \tag{1}$$

Where n is the number of replicates for each experimental condition, with k = 1, 2, 3, …, n. The signal-to-noise (S/N) ratio is evaluated based on two response categories: smaller-the-better (STB) and larger-the-better (LTB). In this study, charging time and temperature variation are classified as STB parameters, as lower values indicate improved charging performance and reduced thermal stress. Conversely, the terminal voltage of the battery is considered an LTB parameter, since a higher terminal voltage reflects improved charge acceptance and more effective utilization of the charging process. Among the evaluated performance metrics, charging time is assigned the highest priority, followed by temperature variation and terminal voltage, due to its critical importance in fast-charging applications.

According to the formula given in Equation 2, $Temp_i'$ represents the temperature value, in Equation 3, T_i' represents the charging time (reversed because it should be a lower value), in Equation 4, $V_{norm,i}$ represents the normalization voltage, and in Equation 5, w_1 represents the charging time weight, w_2 represents the temperature weight, and w_3 represents the voltage weight.

$$Temp_i' = 1 - \frac{Temp_i - Temp_{min}}{Temp_{max} - Temp_{min}} \tag{2}$$

$$T_i' = 1 - \frac{t_i - t_{min}}{t_{max} - t_{min}} \tag{3}$$

$$V_{norm,i} = \frac{V_i - V_{min}}{V_{max} - V_{min}} \tag{4}$$

$$S_i = w_1 \times T_i' + w_2 \times Temp_i' + w_3 \cdot Vnorm_{,i} \tag{5}$$

Table 1. Charging patterns based on $L_9(3^4)$

Experiment No	S_1	S_2	S_3	S_4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3. SIMULATION AND RESULTS

3.1. Circuit Topology

The general structure of the charging system is shown in Figure 3. Energy from the source is transmitted through a bidirectional DC-DC converter to manage the power flow between the load and the battery. This converter facilitates bidirectional power flow, enabling both the charging of the battery and the transfer of energy from the battery to the load when required.

A battery model was created to reflect the electrical and thermal behavior of the battery, and a separate measurement block was added to measure key parameters such as voltage, current, temperature, and charge level.

The control structure consists of a two-stage PI controller. The first stage handles current control, and the second stage handles voltage control. This structure allows for the implementation of different charging methods, such as a multi-stage constant current strategy. Finally, all obtained data were monitored and analyzed through scope blocks.

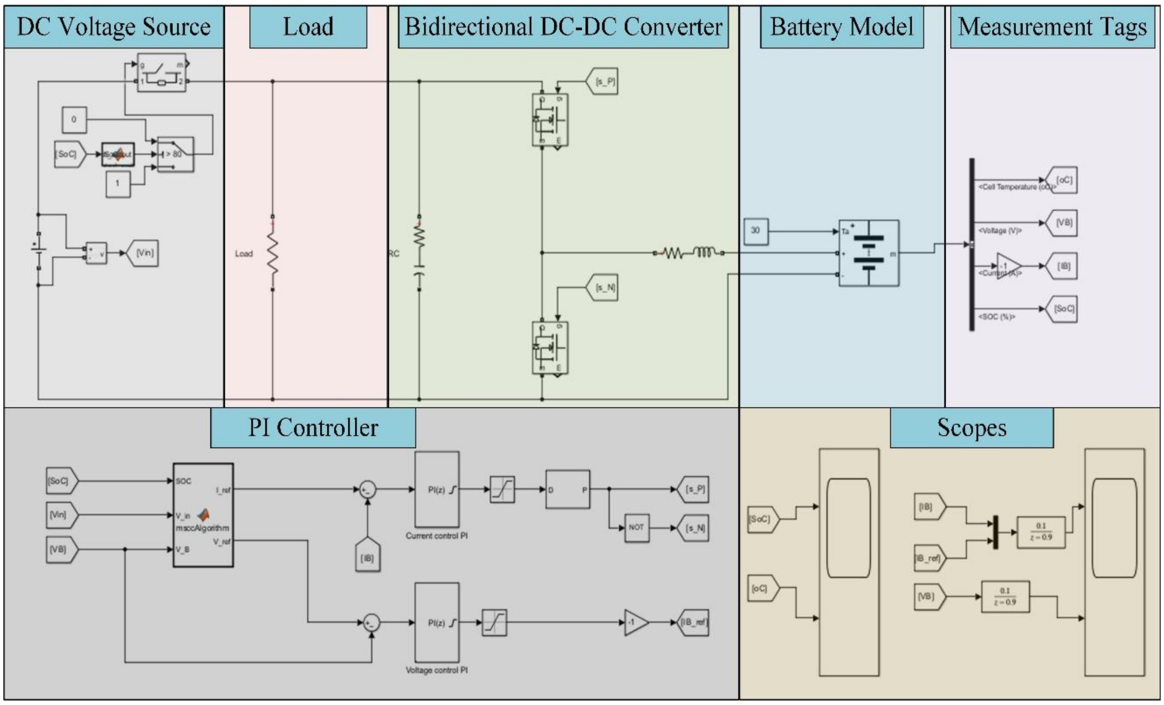


Figure 3. The simulation model of charging system

3.2. Battery Modelling

Figure 4 illustrates an equivalent circuit model to provide a simplified representation of the internal structure of real batteries and to capture their electrical characteristics more effectively [7]. The model consists of three main components: the open-circuit voltage (V_{oc}), the internal resistance (R_b), and an R_t. V_{oc} denotes the terminal voltage when no external load is applied and is typically correlated with the state of charge. R_b accounts for the ohmic losses occurring during current flow. The most distinctive feature of the model is the parallel RC branch, where R_t and C_t represent the transient behavior. The Rt–Ct branch represents the polarization effects and diffusion dynamics of the battery, modeling the transient voltage response under load variations. Specifically, R_t reflects the dynamic resistance, while C_t serves as the charge storage element, enabling the model to reproduce time-dependent responses such as sudden voltage fluctuations under load variations and subsequent recovery [27].

The detailed parameters employed in the modeling process are presented in Table 2. Consequently, this equivalent model can represent both steady-state and transient electrical behavior in a simple yet effective manner. Owing to these characteristics, it is widely adopted in battery management systems, simulation studies, and control algorithms.

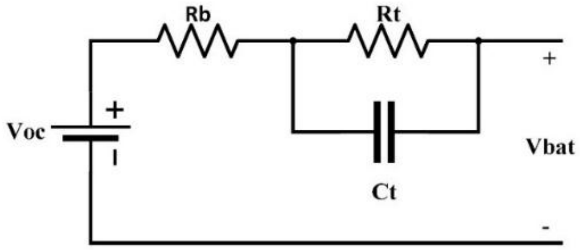


Figure 4. The Thevenin equivalent circuit model representing the electrical behavior of the lithium-ion battery

Table 2. Parameters of LiFeMgPO4

Nominal Voltage	12,6 V
Rated Capacity	40 Ah
Cut-Off Voltage	10,5 V
Full Charged Voltage	13,8 V
Nominal Discharge Current	20 A

3.3. DC-DC Bidirectional Converter

The bidirectional DC–DC converter topology is shown in Figure 5. The circuit structure consists of two switching elements (S1 and S2), an inductor (L), and input/output filter capacitors (C), enabling the battery to operate in both charging and discharging modes. Clearly, the converter is located between the DC source and the battery, allowing bidirectional power transfer. During charging, power flows from the DC source to the battery and the converter operates in buck mode, whereas during discharging, the power direction is reversed from the battery to the DC source and the converter operates in boost mode [28]. The converter is supplied by a 48 V DC input voltage and delivers a regulated 13.7 V DC output voltage. The key parameters of the converter are presented in Table 3; accordingly, the inductor value was selected as 50.7 mH and the capacitor value as 1000 μF. These parameters were optimized to reduce current ripple and ensure voltage stability. PI controllers are commonly employed to regulate both the DC-side and AC-side of battery chargers; however, the use of multiple PI controllers for different charging stages increases the number of required controllers in the system and makes the tuning of control parameters more complex [29]. The applied current levels differ by 0.1C and are listed in Table 4.

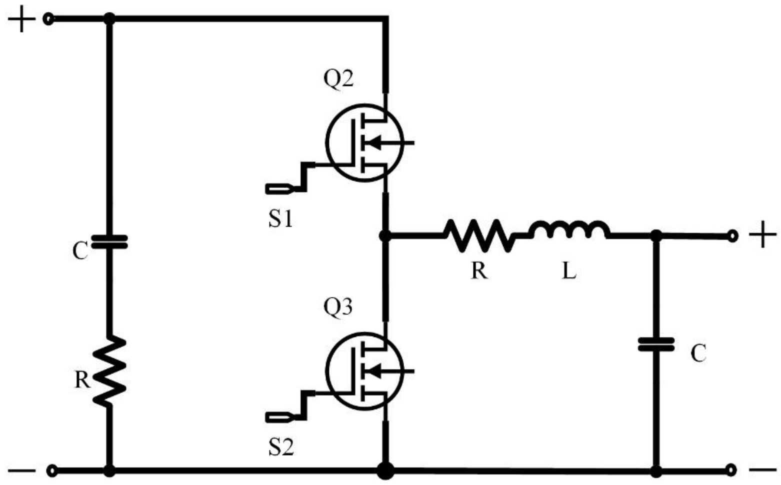


Figure 5. Schematic of the bidirectional DC–DC converter topology

Table 3. Filter parameters of the DC–DC bidirectional converter

L	50,7 mH
C	1000 μF
L, Inductor; C, Capacitor	

Table 4. Charging current of each segment for 2C and 3C

Experiment No	C-Rate	I_1	I_2	I_3	I_4
1	2C	2.0C	1.6C	1.2C	0.8C
2		1.9C	1.5C	1.1C	0.7C
3		1.8C	1.4C	1.0C	0.6C
1	3C	3.0C	2.6C	2.2C	1.8C
2		2.9C	2.5C	2.1C	1.7C
3		2.8C	2.4C	2.0C	1.6C

4. RESULTS AND DISCUSSION

In this study, the effects of CC charging, pulse charging, and MSCC charging methods on battery performance were comparatively analyzed in terms of charging temperature, duration, and maximum voltage at different C-rates (1C–3C). For MSCC, SoC-based stage transitions were employed, and additional optimization was carried out using the Taguchi method. Summary of case studies are summarized in Table 5. Table 6 presents the results of CC, pulse, and MSCC techniques across 1C–3C rates, while Table 7 summarizes the Taguchi-based optimization for MSCC.

Table 5. Summary of case studies

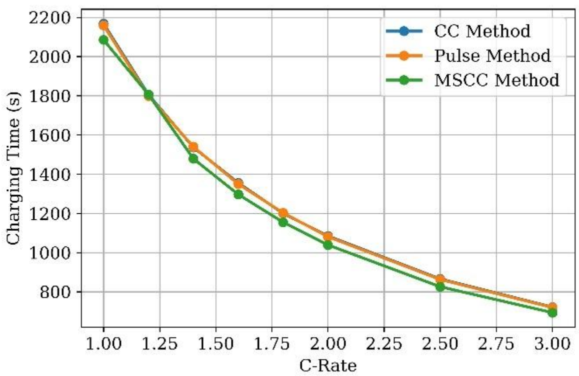
Experiment No	C-Rates	Stages	Method	SoC Rates
CC Charging	1C,1.2C,1.4C,1.6C, 1.8C,2C,2.5C,3C	1	Traditional	20%-80%
Pulse Charging	1C,1.2C,1.4C,1.6C, 1.8C,2C,2.5C,3C	1	Traditional	20%-80%
MSCC Charging	1C,1.2C,1.4C,1.6C, 1.8C,2C,2.5C,3C	4	Current Proportional	20%-50%,50% - 60%,60%-70% and 70%-%80
MSCC Charging	2C,3C	4	Taguchi	20%-50%,50% - 60%,60%-70% and 70%-%80

Considering charging duration, the CC strategy yielded the fastest improvement with increasing C-rate, as the time decreased from 2168 s at 1C to 722 s at 3C. Nevertheless, this reduction was coupled with a noticeable thermal rise, where the temperature increased from 29.79 °C to 41.54 °C, and the maximum voltage reached 15.50 V at 3C, exceeding the values of the other techniques. In contrast, the Pulse charge method provided comparable charging durations (e.g., 720 s at 3C) but caused the highest thermal stress. At 3C, the cell temperature reached nearly 49 °C—approximately 18% higher than the CC case—indicating a potential limitation in terms of thermal management under high C-rate conditions. Despite this, the maximum voltage remained relatively low, with 13.86 V observed at 3C. The MSCC approach, however, delivered a more balanced outcome. At 3C, charging was completed in 694 s (3.9% faster than CC), with temperature stabilizing at 42 °C. Although the maximum voltage values were close to those of CC, the moderate thermal rise highlights MSCC as a comparatively safer and more efficient alternative within the investigated operating range. According to the results presented in Table 6, the highest overall performance based on the proposed scoring approach was achieved by the MSCC method at a 3C rate. This operating condition yielded the maximum score among all tested charging strategies, indicating a favorable balance between charging time, temperature rise, and voltage behavior. Figure 6(a) compares the charging time performances of three different charging techniques. The results show that the MSCC technique achieved the shortest charging time. This method provided 3.98%, 4.43%, and 4.03% faster charging compared to CC at 1C, 2C, and 3C rates, respectively. Compared to Pulse charging, it offers a time advantage of 3.55%, 4.04%, and

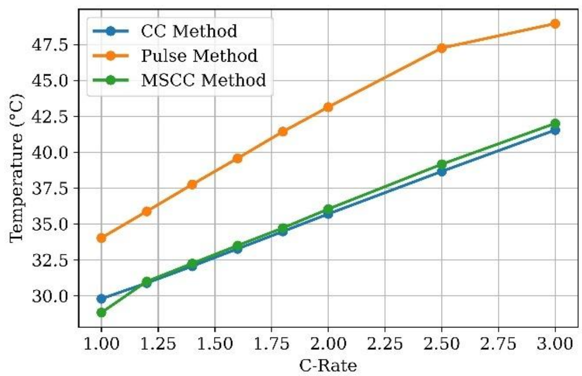
3.75% at the same rates. On the other hand, there is no significant difference in charging time between the CC and Pulse charging methods; both methods complete in very similar times.

Figure 6 (b) confirms this trend, showing that the Pulse charging method consistently produced the highest thermal values, whereas CC and MSCC followed similar patterns. Importantly, MSCC achieved lower temperatures than CC by 3.35% at 1C, 0.94% at 2C, and 1.10% at 3C.

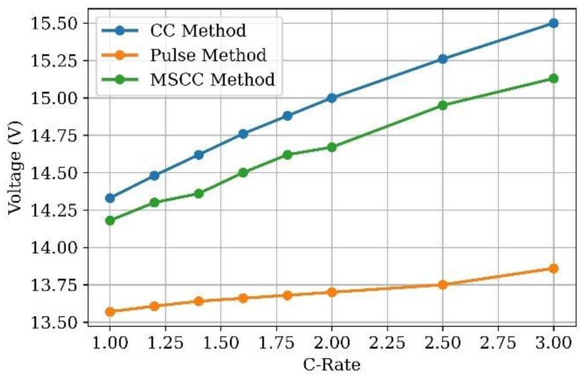
Figure 6 (c) compares the voltage behaviors of the three techniques. The Pulse charging method yielded the most consistent results with the nominal charging voltage (13.8 V). Throughout the experiments, the voltage values achieved with the Pulse charging method remained in the range of 13.57–13.86 V. In contrast, the voltage values measured in the CC and MSCC methods showed a wider distribution, reaching levels of 14.33 V and 15.50 V. The results given in Table 6 reveal that these two methods exceed the nominal value. This indicates that the pulsed charging technique exhibits a more balanced characteristic in terms of voltage regulation. These observations support the adopted optimization strategy, where charging time is prioritized while voltage behavior is constrained within acceptable operational limits.



(a)



(b)



(c)

Figure 6. Comparison of MSCC, CC, and Pulse charging techniques at different C-rates: (a) temperature variation, (b) charging time, and (c) voltage profile.

Table 6. Analysis results for CC, Pulse, and MSCC methods

Experiment No	Charging Method	C-Rate	Charging Time(sec)	Temperature	Voltage	Score
1	CC	1.0C	2168	29.795	14.33	0.2267
2		1.2C	1806	30.89	14.48	0.3980
3		1.4C	1537	32.06	14.62	0.5265
4		1.6C	1356	33.27	14.76	0.6066
5		1.8C	1200	34.48	14.88	0.6775
6		2.0C	1085	35.7	15.00	0.7323
7		2.5C	866	38.66	15.26	0.8166
8		3.0C	722	41.54	15.50	0.8604
1	Pulse	1.0C	2159	34.03	13.57	0.1368
2		1.2C	1799	35.88	13.607	0.2915
3		1.4C	1540	37.75	13.64	0.3986
4		1.6C	1350	39.57	13.66	0.4721
5		1.8C	1203	41.43	13.68	0.5248
6		2.0C	1081	43.14	13.70	0.5837
7		2.5C	863	47.25	13.75	0.7033
8		3.0C	720	48.95	13.86	0.6918
1	MSCC	1.0C	2085	28.83	14.18	0.2654
2		1.2C	1807	31.00	14.30	0.3870
3		1.4C	1479	32.25	14.36	0.5412
4		1.6C	1297	33.5	14.50	0.6152
5		1.8C	1155	34.72	14.62	0.6814
6		2.0C	1039	36.04	14.67	0.7302
7		2.5C	826	39.16	14.95	0.8134
8		3.0C	694	42	15.13	0.8650

Table 7. MSCC Taguchi array method analysis results for 2C and 3C

Exp. No	Method	C-Rate	Charging Time	Temperature	Voltage	S/N Charging Time (STB)(dB)	S/N Temperature (STB) (dB)	S/N Voltage (LTB) (dB)	Score
1			1516	32.49	14.094	-63.614	-30.235	22.981	-52.053
2			1621	32.10	14.02	-64.196	-30.130	22.935	-52.483
3			1757	31.72	13.93	-64.895	-30.027	22.879	-52.998
4	Taguchi	2C	1721	31.80	13.93	-64.716	-30.049	22.879	-52.871
5			1618	31.91	14.10	-64.180	-30.079	22.984	-52.457
6			1640	31.89	14.02	-64.297	-30.073	22.935	-52.535
7			1699	31.61	14.02	-64.604	-29.996	22.935	-52.341
8			1740	31.60	13.93	-64.811	-29.994	22.879	-52.944
9			1634	31.69	14.11	-64.265	-30.018	22.991	-47.192
1			862	38.63	14.85	-58.710	-31.738	23.435	-51.626
2			887	38.28	14.68	-59.056	-31.659	23.335	-51.908
3	Taguchi	3C	914	37.92	14.61	-59.219	-31.577	23.293	-52.012
4			907	37.99	14.62	-59.152	-31.593	23.299	-51.972
5			897	38.08	14.76	-59.056	-31.614	23.382	-51.921
6			898	38.06	14.68	-59.066	-31.609	23.335	-51.924
7			916	37.79	14.70	-59.238	-31.548	23.346	-51.972
8			919	37.78	14.62	-59.266	-31.545	23.299	-51.991
9			907	37.85	14.77	-59.152	-31.561	23.388	-51.893

A comparative analysis was conducted between the MSCC charging results optimized by the Taguchi method and those obtained without optimization, as presented in Table 8. As summarized in Table 7, the Taguchi-based analysis reveals that the optimal performance at a 2C rate was obtained in Experiment 9, whereas at a 3C rate, Experiment 1 produced the most favorable result. These operating points provided the best compromise among charging duration, thermal response, and voltage characteristics according to the applied signal-to-noise evaluation. The results show that the Taguchi method provides lower temperature values compared to other techniques at all charge rates. The temperature difference is particularly significant compared to the Pulse charging method, with improvements of up to 30%. Compared to the CC and MSCC charging methods, the advantage is more limited, but in the 7–14% range. These results demonstrate that the Taguchi method is a more suitable alternative for temperature management at high charge rates.

As seen in Table 8, the Taguchi method required longer charging times compared to other techniques. In terms of voltage results, the Taguchi method produced lower values than the CC and MSCC techniques, but higher values than the Pulse method. This demonstrates that, despite Taguchi's disadvantage in charge times, it exhibits relatively balanced performance in terms of voltage regulation.

Table 8. Comparison of the Taguchi approach with other methods

C-Rates	Comparative Method	Temperature Reduction (%)	Time (%)	Voltage (%)
2C	CC Charging	9,879% – 12,974%	28,43% –38,25% (longer)	6,30% – 7,68% (lower)
2C	Pulse Charging	32,779% – 36,518%	28,69% – 38,47% (longer)	1,65% – 2,91% (lower)
2C	MSCC Charging	10,926% – 14,050%	31,46% – 40,86% (longer)	3,97% – 5,31% (lower)
3C	CC Charging	7,553% – 9,952%	16,24% – 21,43% (longer)	4,37% – 6,09% (lower)
3C	Pulse Charging	26,714% – 29,565%	16,47% – 21,65% (longer)	5,13% – 6,67% (lower)
3C	MSCC Charging	8,72% –11,17%	19,49% – 24,48% (longer)	1,88% – 3,55% (lower)

5. CONCLUSION

This study presented a comparative evaluation of three charging methods—CC, pulsed current, and MSCC—based on charging time, temperature behavior, and voltage performance at different C-rates. The MSCC technique was further optimized through a Taguchi-based framework with unequal weighting to explicitly prioritize fast-charging performance.

The results demonstrated that while the CC method provided shorter charging durations at higher C-rates, it also led to significant increases in temperature and voltage levels. The Pulse charging method offered comparable charging times but resulted in excessive thermal stress, which may pose challenges in terms of thermal safety under high C-rate operation. In contrast, the MSCC method delivered the most balanced performance, achieving faster charging with lower thermal rise and stable voltage characteristics. The application of the Taguchi approach further improved the temperature and highlighting its effectiveness as an optimization strategy for MSCC charging under fast-charging-oriented design constraints.

In conclusion, the MSCC technique stands out as a promising charging method that combines efficiency with safer thermal performance. Future research will focus on extending the analysis to long-term battery health, exploring advanced thermal management strategies, and integrating artificial intelligence-based approaches. In addition, future studies should incorporate experimental validation and extended thermal indicators, such as temperature gradients and heating rates (dT/dt), to better assess battery aging mechanisms and real-world safety implications, as the present study is limited to simulation-based analysis conducted in MATLAB/Simulink.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Furkan Görür. Writing, Methodology, Analysis, Simulation.

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CONFLICT OF INTEREST

There is no conflict of interest in this study.

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