

Various Techniques for Charging Lithium-Ion Batteries in Electric Vehicles Using Wireless Power Transfer Chargers

Marouane El Ancary^{1*}, Abdellah Lassioui¹, Hassan El Fadil¹, Anwar Hasni¹, Yassine El Asri¹, Abdelhafid Yahya²

¹ISA Laboratory, National School of Applied Sciences (ENSA), Ibn Tofail University, Kénitra 14000, Morocco

²L2ISEI Laboratory, EST of Meknes, Moulay Ismail University, Meknes 50050, Morocco

Abstract. Precise voltage and current regulation is essential to ensure the required power output and maximum efficiency in charging stations, particularly those utilizing Wireless Power Transfer (WPT) systems. Effective regulation techniques are necessary to manage voltage and current in Battery Electric Vehicles (BEVs) operating under various charging modes. This study outlines the controller design for different methods for charging lithium-ion batteries in a WPT charger. Initially, the fundamental concepts of WPT systems and their equivalent circuit are introduced. Subsequently, the control strategy for current regulation is detailed for the Constant Current (CC) mode, the Multi-stage Current Method (MCM), and the Pulse Charging Method (PCM). Finally, the resilience and validity of this innovative approach to controlling various techniques for charging lithium-ion batteries are demonstrated through simulations.

1 Introduction

Electric Vehicles (EVs) are vital in addressing climate change by significantly reducing greenhouse gas emissions. Unlike traditional gasoline-powered vehicles that rely on fossil fuels, EVs are powered by electricity, which can be generated from renewable energy sources like solar, wind, and hydropower [1]. By transitioning to electric transportation, we can decrease our reliance on oil and diminish the carbon footprint associated with the transportation sector. Moreover, EVs produce zero direct emissions, which helps improve air quality and reduce pollution-related health concerns in urban areas. The widespread adoption of electric vehicles is not only a step towards sustainable mobility but also a critical component in the global effort to mitigate climate change and transition to a low-carbon economy [2]. Investing in EVs infrastructure and advancing EVs technology is essential for accelerating this transition and ensuring a cleaner, more sustainable future for the planet [3]. The widespread adoption of EVs is heavily dependent on the availability and accessibility of a robust charging infrastructure. Charging stations are essential for supporting the daily use

* Corresponding author: marouane.elancary@gmail.com

of EVs, mitigating range anxiety, and encouraging more consumers to transition from conventional vehicles [4]. A well-distributed charging station network enables EV owners to recharge their vehicles conveniently, whether at home, work, or on the road. Public charging stations, especially fast-charging options, enable long-distance travel and make EVs viable for a broader range of drivers. Furthermore, integrating charging stations with renewable energy sources further enhances the environmental benefits of EVs, ensuring that they contribute to a reduction in carbon emissions throughout their lifecycle [5]. Investing in the development and expansion of EV charging infrastructure is crucial for accelerating the transition to electric mobility, promoting sustainable transportation, and effectively addressing the challenge of climate change [6].

WPT chargers represent a significant advancement in EV charging technology, offering a convenient and efficient alternative to traditional plug-in chargers [7]. As shown in Fig. 1, WPT chargers use electromagnetic fields to wirelessly transfer energy between a charging pad on the ground and a receiver installed on the vehicle, enabling seamless charging without the need for physical connectors [5]. This technology enhances user convenience, as drivers can simply park over the charging pad to initiate charging, eliminating the hassle of handling cables. Additionally, wireless charging systems can be integrated into parking lots, driveways, and even roadways, enabling dynamic charging scenarios where vehicles can charge while stationary or in motion [8]. This innovation not only boosts the practicality of EVs but also supports the widespread adoption of electric mobility by addressing infrastructure and convenience challenges. As WPT technology continues to evolve, it holds the potential to further reduce the environmental impact of transportation, contributing to the global efforts to combat climate change [9].

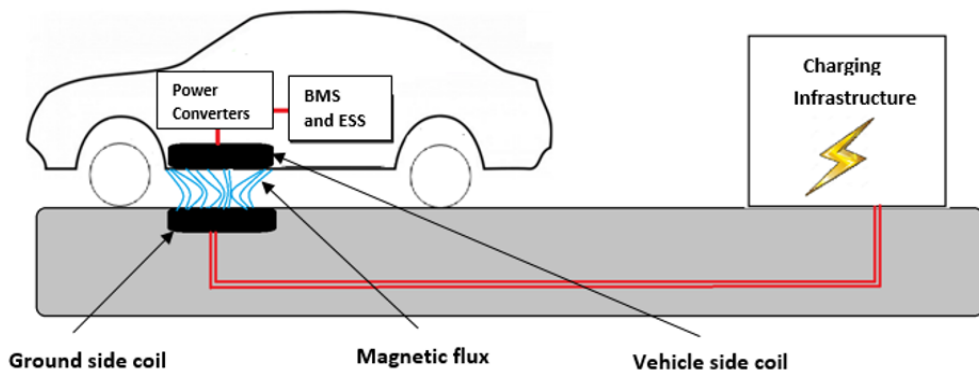


Fig. 1. Wireless Power Transfer Charger for EV.

WPT technology for EVs is not solely about convenience, but also about optimizing battery health and longevity [10]. Advanced WPT systems can incorporate various charging techniques that intelligently manage the charging process to enhance battery life. For example, adaptive charging methods can adjust the power output based on the battery's state of charge, temperature, and health status, ensuring that the battery is charged at an optimal rate to prevent overcharging and overheating [11]. Another innovative technique, pulse charging, delivers intermittent bursts of power, which can reduce the stress on battery cells and improve their lifespan [12]. Additionally, WPT systems can be integrated with smart grid technology, enabling them to charge during off-peak hours or when renewable energy sources are most available, further reducing the environmental impact. By employing these sophisticated charging strategies, WPT technology not only makes EV charging more

convenient but also plays a crucial role in maintaining battery health, thereby enhancing the overall efficiency and sustainability of electric vehicles [13].

This paper is organized as follows: Section II introduces the wireless charger, compensation systems, and the equivalent circuit. Section III illustrates the controller design, as well as the charging modes of the electric vehicle battery. Section IV presents the simulation results of the different control methods and their performances. Section V lists the conclusions drawn from the simulation results, and also, some perspectives are given.

2 WPT charger

2.1 Compensation

The WPT charging coils typically have high leakage inductance and excitation inductance, resulting in a highly inductive coil. As a result, the coils must absorb a considerable amount of reactive power before delivering active power to the load. This leads to a large reactive current in the circuit and increased converter losses. To address this issue, a compensation network model can be introduced in the system to eliminate the reactance parameters in the transmitting and receiving circuits and effectively offset the reactive power generated by the coil's inductance. This improves the system's output power factor, transmission efficiency, and load power [14].

Fig. 2 depicts the four compensation structures commonly employed in WPT coil systems: S-S, S-P, P-S, and P-P. In WPT systems utilizing S-S and S-P topologies, the value of capacitance does not impact the resistance of the load R_L , and then the variations in R_L at the receiving side do not affect the resonant frequency. Moreover, these structures are uncomplicated and easy to install, with the S-S topology capable of handling higher power levels.

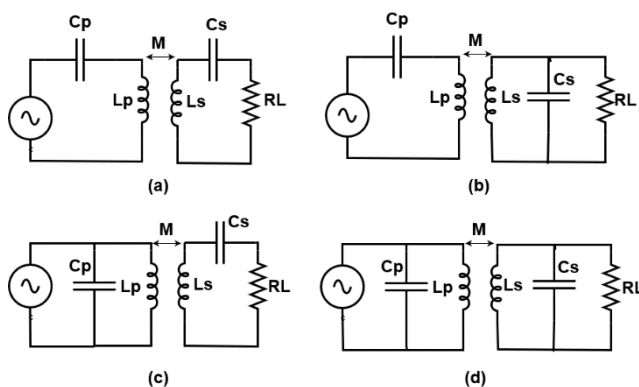


Fig. 2. Compensation topologies: (a) S-S; (b) S-P; (c) P-S and (d) P-P.

2.2 Equivalent circuit

The proposed WPT uses a primary coil and a secondary coil, this configuration is illustrated in Fig. 3. The single-phase WPT charger comprises a DC input power supply, a voltage inverter composed of four MOSFETs, and a compensation capacitor connected in series with the primary coil. The primary side coil generates a voltage in the secondary coil, which is connected in series with the secondary compensation capacitor. Subsequently, a single-phase

diode-based rectifier composed of four diodes converts the generated AC voltage into a DC voltage, filtered to supply the battery on board the electric vehicle [11].

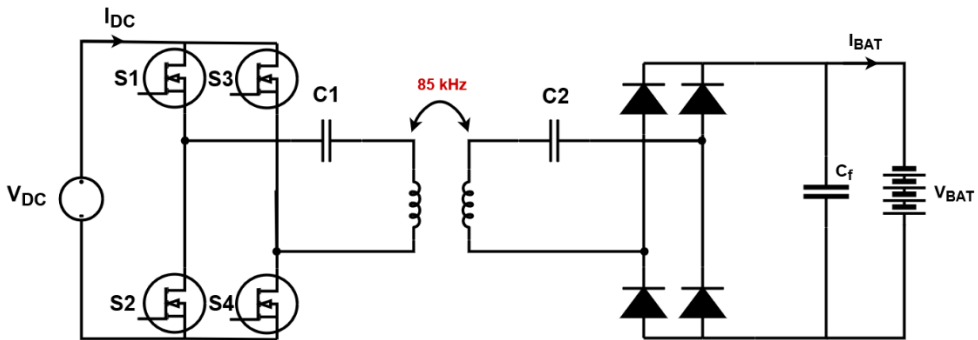


Fig. 3. Simplified circuit of the WPT charger

L_1 and L_2 are the self-inductance of the primary and secondary coils. C_1 is the transmitting side compensation capacitor in series with L_1 and C_2 is the receiving capacitor in series with L_2 . The capacitance value is:

$$C = \frac{1}{\omega^2 L} \quad (1)$$

Where L is the inductance of the coils, $L = L_s = L_p$. And C is the compensation capacitance, $C = C_1 = C_2$.

3 Controller design for various techniques of charging

This section describes various charging modes for EVs utilizing a WPT charger without cables. The section begins with an overview of different charging techniques, including CC-CV, MCM, and pulse current charging. Finally, the design of an effective controller for managing these charging modes is presented.

3.1 Constant current and constant voltage (CC-CV)

CC and CV charging are the most commonly employed methods for electric vehicle batteries. The charging process consists of two phases. The first phase involves delivering a constant current, during which the maximum current that the battery can safely handle is considered while the voltage increases. In the second phase, as the voltage reaches its maximum value, the current gradually decreases, and the battery is charged at a constant voltage. The charging process is deemed complete when the current falls to a predefined threshold. Fig. 4 illustrates this charging process [15]. The curve in Fig. 4 indicates that the state of charge (SOC) capacity reaches 80% during the constant current charging phase. Consequently, the control loop for this system will be examined with a focus on maintaining a constant charge current.

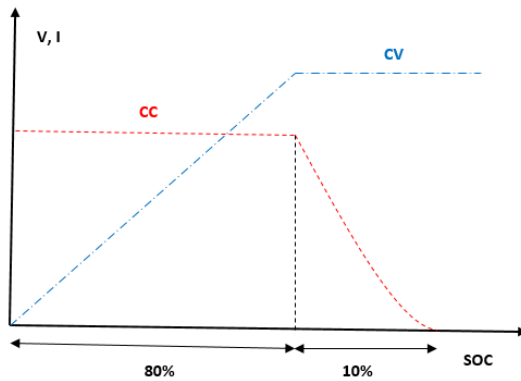


Fig. 4. CC-CV charging method

3.2 MCM

Considering the characteristics of the selected battery, the multi-stage current method (MCM) proposes several charging phases with progressively decreasing or increasing currents. To design an optimal MCM, it is essential to account for parameters such as temperature variation, current rate dependence, and changes in internal resistance. Additionally, it is imperative to ensure that current and voltage limits are not exceeded. The proposed technique employs a Four-Stage Constant Current (FSCC) approach. The scheme involves dividing each charging stage into increments of 25% of the SOC, as illustrated in Fig. 5. When properly implemented, the MCM method offers substantial advantages in achieving both efficient and rapid recharging [16].

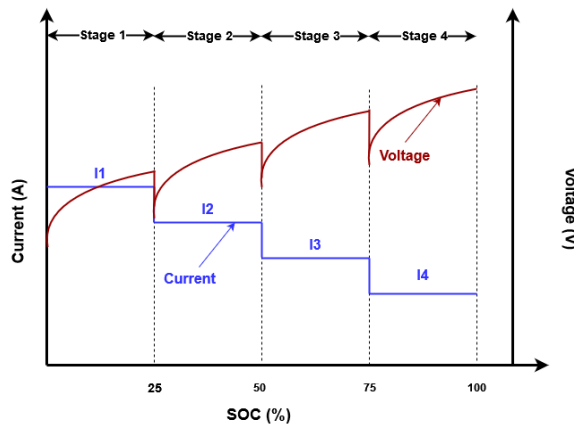


Fig. 5. MCM charging method

3.3 Pulse charging method (PCM)

The pulsed current technique is an innovative charging method for lithium-ion batteries that enhances both charging efficiency and battery lifespan. This approach involves delivering electrical energy in short bursts, or pulses, rather than a continuous flow. Each pulse allows the battery to relax and recover, reducing the risk of overheating and minimizing the buildup of harmful lithium plating on the anode. Additionally, pulsed charging can improve the overall SOC and accelerate the charging process by optimizing the ion movement within the

electrolyte. Recent studies have demonstrated that this technique can lead to better cycle stability and increased capacity retention over extended usage periods. Consequently, the pulsed current technique represents a promising advancement in battery management systems, particularly for applications demanding high performance and rapid recharging capabilities [12].

The standard PCM mode consists of a constant current phase interspersed with periodic rest intervals, as illustrated in Fig. 6. The current during the positive pulse is maintained at a constant value, denoted as I_p , while the current is zero during the relaxation period. The duration of the positive pulse period is represented as T , with the frequency f defined as $f = \frac{1}{T}$. Within each cycle, the width of the pulse current is denoted as t_p , and the duration of the relaxation time is represented as t_r ($T = t_r + t_p$).

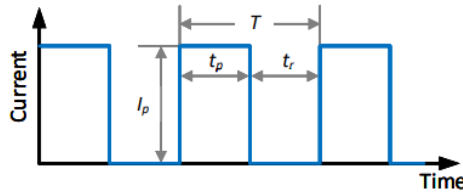


Fig. 6. PCM charging method [12]

3.4 Controller design

As previously mentioned, this study will focus on the constant current (CC) charging option of the CC-CV method, as well as the MCM and PCM methods. Figure 7 illustrates the closed-loop control of the lithium-ion battery current for the WPT charger. In this configuration, the proportional-integral (PI) controller and the Phase shifter (PS) generator collaborate to manage the control signal, ensuring that the battery current remains consistently close to the reference current. The gains of the PI controller are determined using the trial and error method.

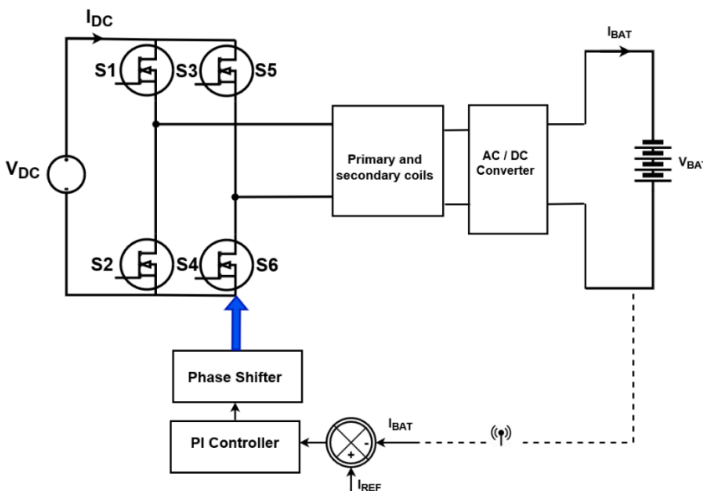


Fig. 7. Control loop of the WPT charger

4 Simulation results and discussion

The proposed control technique's effectiveness has been validated through a series of simulation scenarios. This section discusses the results obtained from these simulations, highlighting the proposed control strategy's efficacy. The simulation parameters are given in Table 1.

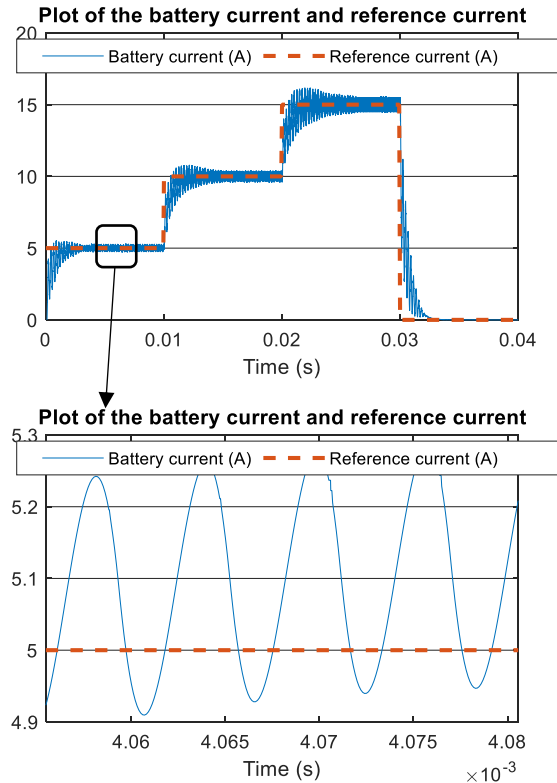
Table 1. Simulation parameters

Designation	Value
DC bus voltage for the primary side	400 V
Self-inductance of the ground side coil L1	416 μ H
Self-inductance of the vehicle side coil L2	116 μ H
Mutual inductance	20 μ H
Primary side compensation capacitor C1	8.5 nF
Secondary side compensation capacitor C2	30 nF
Output Filter capacitor Cf	0.5 mF
Resonance frequency f	85 KHz
Capacity of the electric vehicle battery	100 Ah
Voltage of the electric vehicle battery	48 V

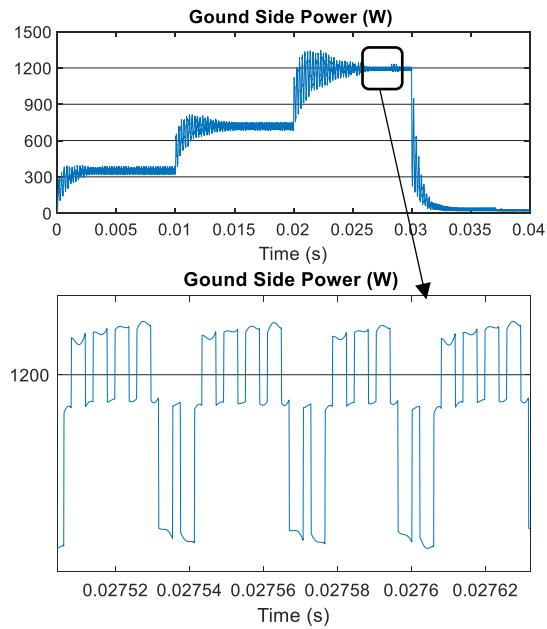
To assess the performance of the charge current control loop for the electric vehicle battery, three discrete current steps were applied as reference signals for the I_{ref} . Fig. 8(a) presents the results of this evaluation. The simulation outcomes demonstrate the control loop's ability to accurately track the current reference signal, ensuring that the battery is charged with a constant current proportional to the power delivered by the inverter on the primary side. Fig. 8(b) and 8(c) further illustrate that the control signal from the phase shifter precisely follows the variations in the reference current, which is similarly reflected in the power flow on the primary side. Notably, when the input is set to zero, the current in the battery, along with the control signal and power flow, also approaches zero. The phase shifter control delivers a signal that varies between 0 and 1, corresponding to phase shifts ranging from 0 to π .

Based on this tracking test of the control loop, the capacity and performance of this regulation loop in efficiently charging the lithium-ion battery in constant current (CC) mode can be observed. The loop effectively follows the reference charging current, which may vary depending on the battery's capacity, state of charge, and desired recharge time. Additionally, the low level of residual ripples enables CC charging without any issues regarding the battery's integrity and lifespan.

FSCC is another method for charging the battery, representing a simplified variant of the MCM method, as previously explained. To assess the system's ability to charge the battery using this method, a simulation was conducted. Fig. 9 illustrates the results of this test. At each charging interval, a reference current is applied to the input of the control loop. Additionally, another approach involves applying different reference currents based on the SOC. Generally, each phase lasts for 25% of the SOC; however, this method requires the measurement of the SOC. According to Fig. 9, the battery charging current closely follows the reference currents stably and smoothly with a residual current ripple equal to 0.5%.



(a)



(b)

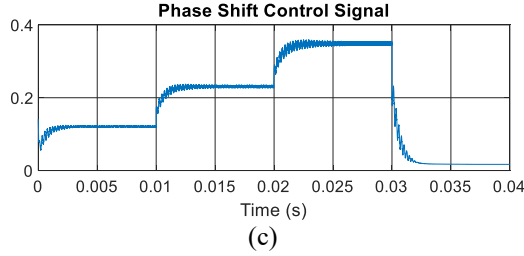


Fig. 8 (a) – (c): Tracking test performance

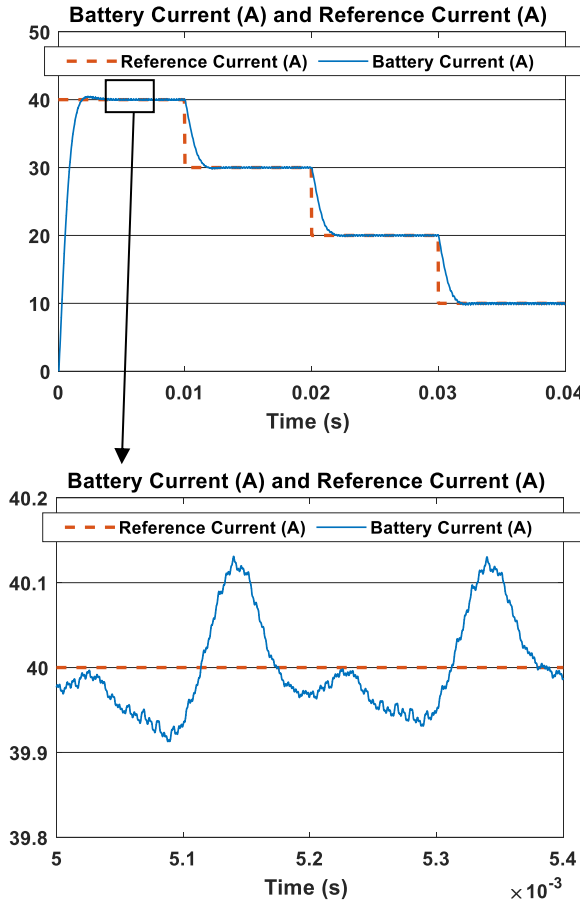


Fig. 9. FSCC charging method

The pulse current method is illustrated in Fig. 10, demonstrating how the battery current closely tracks the reference pulsed current. This charging technique utilizes a series of current pulses to optimize energy transfer while minimizing the risk of overheating. The graph clearly shows that during each pulse, the battery current rises to match the reference level and subsequently decreases during the relaxation phase. This tracking behavior highlights the effectiveness of the control mechanism in maintaining the battery current in alignment with the reference pulsed current, ensuring optimal charging and preserving battery health.

The smooth transitions between pulses further emphasize the stability of the charging process, showcasing the advantages of the pulse current method in managing battery performance.

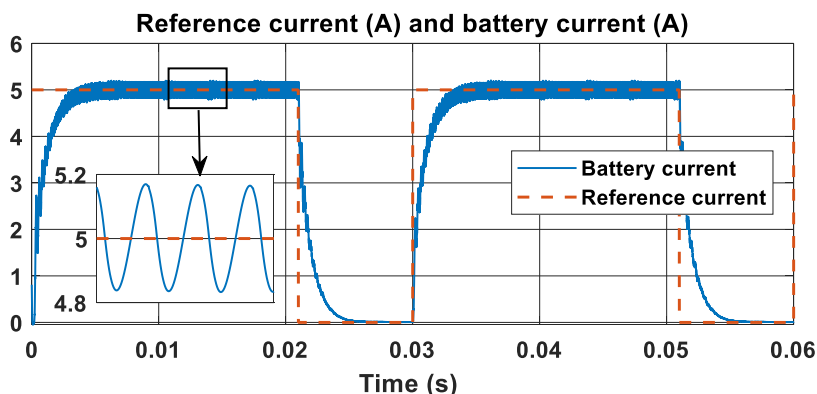


Fig. 10. PCM charging method

5 Conclusion and perspectives

In conclusion, the evaluation of the control loop for charging lithium-ion batteries in CC mode demonstrated its capacity and performance in effectively maintaining the reference charging current. The low level of residual ripples, measured at 0.5%, indicated that this method could charge the battery without compromising its integrity or lifespan. Additionally, the FSCC technique, as a simplified variant of the MCM method, showed promising results in simulations, particularly in its ability to adapt the reference current based on the desired charging profile. The pulse current method further enhanced charging efficiency by utilizing a series of current pulses, which optimized energy transfer while minimizing overheating risks. Overall, these findings underscored the effectiveness of the implemented control strategies in achieving stable, efficient, and reliable battery charging, thereby contributing to improved battery management systems. Future studies could explore the implementation of more sophisticated control algorithms, such as adaptive or predictive control strategies, to enhance the responsiveness and efficiency of charging systems under varying operational conditions.

References

1. S. Jagani, E. Marsillac, and P. Hong, *Sustainability* **16**, 1570 (2024)
2. S. Abdul Qadir, F. Ahmad, A. Mohsin A B Al-Wahedi, A. Iqbal, and A. Ali, *Energy Strategy Rev.* **53**, 101379 (2024)
3. F. Alanazi, *Appl. Sci.* **13**, 6016 (2023)
4. A. Mohammed, O. Saif, M. Abo-Adma, A. Fahmy, and R. Elazab, *Sci. Rep.* **14**, 283 (2024)
5. M. El Ancary, A. Lassioui, H. El Fadil, T. Bouanou, Z. El Idrissi, A. Rachid, A. Hasni, and Y. El Asri, in *2024 4th Int. Conf. Innov. Res. Appl. Sci. Eng. Technol. IRASET* (2024), pp. 1–6

6. R. R. Kumar, A. Chakraborty, and P. Mandal, *Transp. Res. Part E Logist. Transp. Rev.* **149**, 102295 (2021)
7. A. Lassioui, M. El Ancary, Z. El Idrissi, H. El Fadil, K. Rachid, and A. Rachid, *Processes* **12**, 1264 (2024)
8. C. S. Banothu, S. R. Gorantla, R. V. B. Attuluri, and G. R. Evuri, *E-Prime - Adv. Electr. Eng. Electron. Energy* **8**, 100561 (2024)
9. K. Obaideen, L. Albasha, U. Iqbal, and H. Mir, *Energy Strategy Rev.* **53**, 101376 (2024)
10. S. Iqbal, N. F. Alshammari, M. Shouran, and J. Massoud, *Sustainability* **16**, 2487 (2024)
11. A. Lassioui, M. Elancary, H. El Fadil, Z. El Idrissi, T. Bouanou, K. Rachid, A. Rachid, and M. Koundi, in *2024 4th Int. Conf. Innov. Res. Appl. Sci. Eng. Technol. IRASET* (2024), pp. 1–6
12. X. Huang, Y. Li, A. B. Acharya, X. Sui, J. Meng, R. Teodorescu, and D.-I. Stroe, *Energies* **13**, 2458 (2020)
13. A. Rajiv, R. Shree, P. Rohit Bhatt, and B. Islam, *Meas. Sens.* **34**, 101249 (2024)
14. M. Venkatesan, N. Rajamanickam, P. Vishnuram, M. Bajaj, V. Blazek, L. Prokop, and S. Misak, *Energies* **15**, 7816 (2022)
15. X. Zhang, C. Zhu, and H. Song, *Wireless Power Transfer Technologies for Electric Vehicles* (Springer Nature, Singapore, 2022)
16. M. Usman Tahir, A. Sangwongwanich, D.-I. Stroe, and F. Blaabjerg, *J. Energy Chem.* **84**, 228 (2023)