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INTELLIGENT BATTERY CHARGING STRATEGIES FOR SOCIETY 5.0

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Abstract:
This paper reviews intelligent battery charging strategies for Society 5.0 and their relevance to electric vehicles, microgrids, and energy storage systems. Conventional and advanced charging methods are discussed, together with the role of state estimation, adaptive control, optimization, and artificial intelligence. The analysis shows that intelligent charging can improve efficiency, safety, battery lifetime, and sustainability. Key challenges and research opportunities are also identified for the development of smarter, more user-centered battery charging systems.

Keywords: *Society 5.0; intelligent battery charging; battery charging strategies; energy storage systems; electric vehicles.*

1. Introduction

Society 5.0 promotes a human-centered vision of development in which advanced digital technologies are used to address social needs efficiently and sustainably [1]. In this context, rechargeable batteries have become essential for a wide range of applications, including electric vehicles, energy storage systems, and smart microgrids [2,3]. Therefore, intelligent battery charging strategies have emerged as a key research area.

Traditional battery charging methods remain widely used because of their simplicity. However, their limitations in charging time, degradation, safety, and adaptability have driven the search for more advanced solutions [4,5]. Currently, strategies based on adaptive control, state estimation, optimization, and artificial intelligence are being actively investigated to improve performance, extend battery lifetime, and respond to varying operating conditions [5,6].

This paper reviews intelligent battery charging strategies in the context of Society 5.0, with emphasis on their relevance to electric vehicles, microgrids, and energy storage systems. It discusses conventional methods and advanced strategies based on control and artificial intelligence, and it identifies key challenges and research opportunities

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for developing more efficient, sustainable, and user-centered battery charging systems.

2. Intelligent Battery Charging Strategies

Battery charging strategies have evolved from simple conventional methods to more advanced approaches that can adapt to the battery's state, operating conditions, and application requirements. In general, intelligent charging strategies can be grouped into conventional methods, advanced control techniques, and artificial intelligence-based methods [4–6]. These categories differ in complexity, performance, sensing requirements, and adaptability.

2.1. Conventional Methods

Conventional charging methods still form the basis of many battery charging systems. Among them, the most widely used approach is constant current–constant voltage (CC–CV) charging. In this method, the battery is first charged with a constant current until a predefined voltage threshold is reached. The voltage is then held constant while the current gradually decreases. CC–CV charging has been widely adopted due to its simplicity, low cost, and ease of implementation [4,5]. However, this method has important limitations. It does not explicitly account for internal battery conditions such as temperature or state of health, and it offers limited flexibility under fast-charging conditions or dynamic operating profiles [5,6]. Other conventional approaches, such as pulse charging, multistage charging, and constant power charging, have also been explored to improve charging performance [4,7]. Nevertheless, these approaches are generally predefined and offer limited adaptability. As a result, conventional methods may not fully satisfy the requirements of future battery applications. Their limitations in charging time, safety, degradation, and adaptability have spurred the development of more advanced solutions [5,6].

2.2. Advanced Control-Based Strategies

Advanced control-based strategies improve battery charging performance by adjusting charging actions in real time according to system conditions and operational constraints. Unlike conventional methods, they use feedback instead of fixed charging profiles, making them more suitable for applications that require greater flexibility, accuracy, and responsiveness [6,8]. These strategies are often supported

by state estimation techniques, which provide real-time information about battery conditions such as state of charge, state of health, and temperature [9]. This information enables more effective charging adaptation under varying operating conditions.

Adaptive control adjusts controller parameters in response to battery aging, thermal variations, or parameter uncertainty. Predictive control uses system models to anticipate future behavior and optimize charging actions under constraints on current, voltage, and temperature. Optimal and robust control methods have also been investigated to improve charging performance and maintain reliable operation under uncertain conditions [6,8]. A key advantage of advanced control strategies is their ability to address multiple objectives simultaneously, including degradation reduction, thermal constraint satisfaction, coordination with renewable energy sources, and response to grid conditions. For this reason, they are highly relevant to Society 5.0 [8,10].

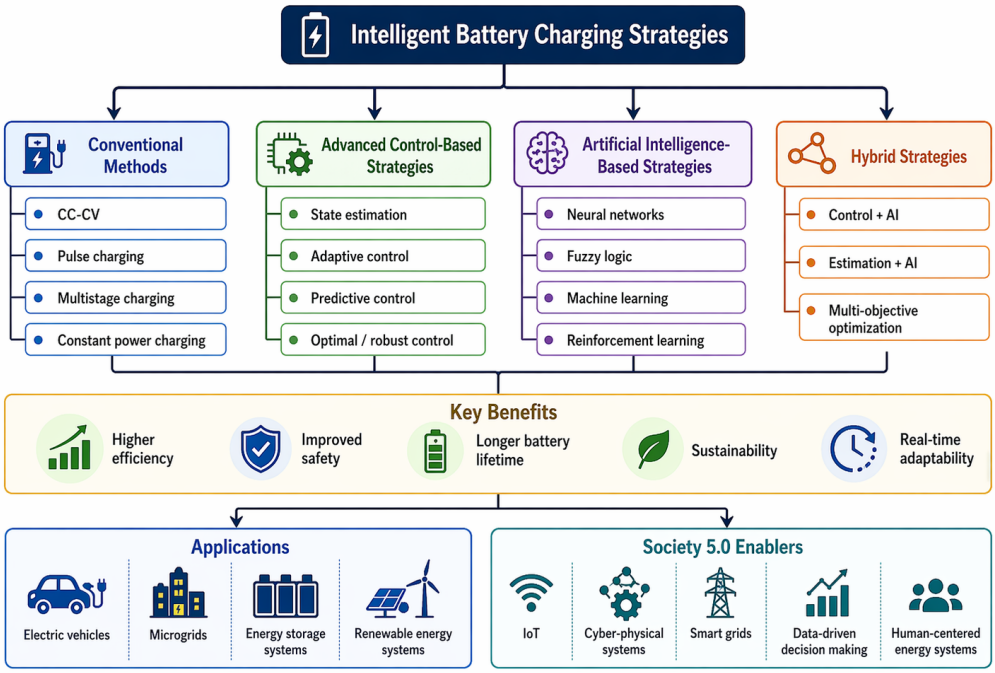
2.3. Artificial Intelligence-Based Strategies

Artificial intelligence-based charging strategies have attracted increasing attention because they can learn complex patterns, capture nonlinear relationships, and adapt to changing operating conditions without relying solely on detailed physical models. These features make AI a valuable tool for improving decision-making in intelligent charging systems [11,12]. Among the most widely used techniques, artificial neural networks can estimate internal variables such as state of charge, state of health, and temperature, while also supporting the prediction of future battery behavior. However, their performance depends heavily on the availability of representative training data [13]. Fuzzy logic has also been widely applied because it enables heuristic decision-making without requiring an exact mathematical model [14]. In addition, machine learning and reinforcement learning create new opportunities for charger development, particularly in dynamic operating scenarios [12]. A major advantage of AI-based methods is their integration with broader digital ecosystems, including IoT platforms, remote monitoring systems, big data analytics, and cloud services. Such integration is especially relevant in the context of Society 5.0. However, the practical implementation of AI-based charging strategies still faces important challenges in data reliability, interpretability, robustness, and computational requirements [10–12].

2.4. Comparison of Strategies

Each family of battery charging strategies has its own strengths and limitations. Conventional methods are simple and low-cost, but offer limited adaptability [4–7]. Advanced control-based strategies can handle multiple objectives and operational constraints. However, they usually require greater design complexity and computational effort. Artificial intelligence-based approaches provide high adaptability, especially in data-rich environments. However, they still face important challenges related to validation, robustness, and data requirements [11–13]. Therefore, no single method can be considered universally superior. The most suitable strategy depends on the application. In the context of Society 5.0, hybrid solutions that combine advanced control and artificial intelligence appear especially promising [10–12].

Picture 1 summarizes the main intelligent battery charging strategies discussed in this paper, along with their benefits, applications, and enabling technologies in the context of Society 5.0.



Picture 1. *Overview of intelligent battery charging strategies*

Table 1 summarizes the main battery charging strategies, including their advantages, limitations, and implementation complexity.

Table 1: *General comparison of battery charging strategies*

Strategy	*Advantages*	*Limitations*	*Complexity*
CC/CV/CC-CV	Simple and low-cost	Limited adaptability	Low
Pulse charging	Reduced polarization	Profile-dependent design	Medium
Multistage charging	Better balance between charging speed and safety	Limited adaptability	Medium
Adaptive control	Adjustment to variations	Complex design	High
Predictive control	Constraint handling	High computational burden	High
Robust/optimal control	Improved overall performance	Complex implementation	High
Fuzzy logic	Does not require an exact model	Rule-dependent	Medium
Neural Networks / Machine Learning	Captures nonlinearities	Requires large datasets	High
Reinforcement learning	Autonomous optimization	Complex validation	High
Hybrid strategies	High adaptability and accuracy	Demanding integration	Very high

Overall, intelligent battery charging strategies represent an important evolution beyond conventional methods. They integrate adaptation, estimation, and decision-making capabilities to improve efficiency, safety, and battery lifetime [8,9,11,12].

3. Relationship with Society 5.0

Society 5.0 promotes the integration of physical space and cyberspace. In this framework, intelligent, sustainable, and human-centered technologies are used to address social challenges [1,10]. In this context, intelligent battery charging strategies are particularly relevant. They enable real-time adaptation of the charging process to variables such as

state of charge, temperature, state of health, and operating conditions. This adaptability is essential in applications such as electric vehicles, microgrids, stationary energy storage, and renewable energy systems. In these applications, efficient energy management is a key requirement. Moreover, intelligent charging contributes to sustainability by reducing energy losses, limiting degradation, and extending battery lifetime [6,8,12]. The integration of technologies such as the Internet of Things, artificial intelligence, and cyber-physical systems supports the development of connected chargers. These chargers can interact with smart grids and monitoring platforms [10,11]. In this way, intelligent charging strategies have become an enabling element of Society 5.0. They support more efficient, personalized, and socially oriented energy systems. In this sense, intelligent battery charging is not only a technical necessity but also a structural requirement of modern energy systems [6,8]. However, large-scale implementation still faces significant challenges. These include estimation accuracy, computational complexity, safety, cost, and technological integration [11,12].

4. Challenges and Opportunities

The development of intelligent battery charging strategies faces important challenges related to balancing charging speed, safety, and battery lifetime. Increasing the charging rate can accelerate degradation and raise temperature, making it necessary to design methods that optimize the process without compromising battery integrity [8,12]. Another key challenge is the accurate estimation of internal variables such as state of charge, state of health, and temperature. These variables are essential for decision-making, but their real-time estimation may be affected by parameter uncertainty, aging, and changing operating conditions. In addition, the implementation of advanced algorithms on low-cost embedded platforms and the availability of reliable data for artificial intelligence techniques remain significant limitations [11,12]. Important opportunities also arise from the integration of intelligent charging strategies with smart grids, microgrids, electric mobility, and predictive maintenance. In this sense, intelligent battery charging is emerging as a key enabler for building more efficient, sustainable, and Society 5.0-oriented energy systems [1,10,11].

5. Conclusions

Intelligent battery charging strategies represent a clear advancement over conventional methods by improving adaptability, safety, and overall battery performance. In the context of Society 5.0, they are especially relevant because they support the development of more efficient, sustainable, and human-centered energy systems.

Traditional methods such as CC–CV charging remain widely used due to their simplicity. However, they are often insufficient for modern applications that require fast charging, reduced degradation, and operation under dynamic conditions. In contrast, advanced control and artificial intelligence-based approaches offer greater flexibility and improved charging performance.

Overall, intelligent charging plays an important role in the integration of energy storage, electric mobility, smart grids, and renewable energy systems. Although challenges remain in areas such as estimation accuracy, thermal management, and real-time implementation, these strategies show strong potential for supporting the goals of Society 5.0.

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