IAES Journal of Electrical and Electronics Engineering
Vol. 9, No. 2, December 2022, pp. 31~35
ISSN: 2338-7432, DOI: 10.11591/jeee.v9i2.pp31-35

Fast charging technologies for electric bicycle batteries: a review of charging algorithms, thermal management, and battery lifetime

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Article Info

Article history:

Received Jul 25, 2020
Revised Jan 5, 2021
Accepted Feb 13, 2021

Keywords:

Battery degradation
Battery lifetime
Battery thermal management
CC–CV algorithm
Electric bicycle
Fast charging
Lithium-ion battery

ABSTRACT

Electric bicycles have become an important form of lightweight electric mobility, but their practical usability is constrained by battery charging time, thermal safety, and long-term capacity retention. Fast charging can reduce downtime; however, elevated current and unsuitable temperature conditions may accelerate lithium plating, electrolyte degradation, and loss of usable capacity. These risks are particularly relevant to compact e-bike battery packs, where low mass, limited cooling space, cost, and variable charger quality restrict thermal-management options. This review examines fast-charging technologies for lithium-ion batteries with emphasis on their application to electric bicycles. It evaluates conventional constant-current/constant-voltage charging, multistage current, pulse-based, and model-based adaptive algorithms, together with air, liquid, phase-change, and hybrid thermal-management approaches. The relationships among charging rate, temperature, state of charge, degradation mechanisms, and battery lifetime are synthesized from research published through 2021. A comparative framework highlights the trade-offs between charging duration, implementation complexity, thermal control, and durability. The review identifies a shortage of e-bike-specific validation and recommends pack-level testing, temperature-aware charging, improved battery-management systems, and lifetime-oriented optimization for safer and more durable fast charging under realistic rider and ambient operating conditions.

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1. INTRODUCTION

Electric bicycles have become an increasingly important option for personal mobility because they combine human-powered transportation with electrical assistance. Their performance and usability depend strongly on the energy capacity, charging time, safety, and service life of their battery packs. Lithium-ion batteries are widely used in this application because of their relatively high energy density, low self-discharge, and favorable power-to-weight characteristics. However, lengthy charging periods and gradual battery degradation can reduce user convenience and increase the lifetime cost of electric bicycles [1], [2].

Fast charging offers a practical way to reduce the time required to restore battery energy, particularly for users who depend on their bicycles for daily commuting or commercial activities. Increasing charging current, however, does not necessarily provide a sustainable solution because high-rate charging can generate additional heat and accelerate electrochemical degradation. Lithium plating, solid-electrolyte interphase growth, electrolyte decomposition, and electrode damage may reduce usable capacity and increase internal resistance. These mechanisms become particularly important when batteries are charged at high current or outside their recommended temperature range [3]–[6].

Existing fast-charging research has primarily focused on electric vehicles and laboratory lithium-ion cells, while compact electric-bicycle battery packs have received comparatively less attention. Directly transferring high-power charging strategies from passenger vehicles to electric bicycles may be inappropriate because e-bike packs

have different capacity, packaging, cooling capability, cost constraints, and charging infrastructure. This review therefore evaluates established lithium-ion fast-charging methods and considers their suitability for electric-bicycle applications. It connects charging algorithms, thermal management, battery degradation, and lifetime optimization to identify a practical research direction for safe and durable e-bike charging.

2. CHARACTERISTICS AND CHARGING REQUIREMENTS OF E-BIKE BATTERIES

Battery characteristics determine the charging limits and practical fast-charging capability of an electric bicycle. Commercial e-bike packs commonly use lithium-ion cells assembled into series-parallel configurations to achieve the required voltage and capacity. Their battery-management systems (BMSs) monitor cell voltage, pack current, and temperature while providing protection against overvoltage, undervoltage, overcurrent, and excessive temperature. Differences in cell chemistry, capacity, internal resistance, and pack configuration mean that a charging profile suitable for one battery cannot automatically be applied to another [7]–[10].

The charging rate is commonly expressed relative to battery capacity, allowing the current demand to be compared across different battery sizes. A higher charging rate can reduce charging duration, but it also increases polarization and heat generation within the cells. The actual safe charging current depends on cell chemistry, state of charge (SOC), temperature, cell age, and manufacturer specifications. Therefore, fast charging should be defined as controlled charging within validated electrical, thermal, and electrochemical limits rather than simply applying the highest available charger current [3], [11], [12].

3. FAST-CHARGING ALGORITHMS

3.1. Conventional CC–CV charging

Constant-current/constant-voltage (CC–CV) charging is a widely used approach for lithium-ion batteries because of its relatively simple implementation and compatibility with conventional BMS architectures. During the constant-current stage, the charger supplies a controlled current until the battery reaches its specified voltage limit. The charger then maintains constant voltage while the charging current gradually decreases toward a termination threshold. This two-stage process provides a practical balance between charging speed and voltage protection, although the final constant-voltage stage can account for a substantial portion of the total charging duration [2], [4], [13].

The main limitation of conventional CC–CV charging is that its fixed current setting may not respond adequately to changing battery conditions. Cell temperature, SOC, internal resistance, and aging can influence the safe current that a battery can accept. A charging current that is acceptable for a new cell at moderate temperature may be unsuitable for an aged cell or a battery operating in cold conditions. Consequently, fixed CC–CV charging provides a useful baseline, but adaptive control is needed to improve fast-charging performance without unnecessarily accelerating degradation [3], [5], [6].

3.2. Multistage and adaptive charging

Multistage constant-current charging divides the charging process into several current levels rather than maintaining one constant current throughout the initial stage. The current can be adjusted according to SOC, voltage, temperature, or estimated internal battery conditions before the final voltage-limited stage. This method can reduce excessive polarization and improve the balance between charging duration and battery degradation. Optimization studies have demonstrated that multistage profiles can achieve useful trade-offs between charging time, energy efficiency, and capacity retention [14]–[16].

Model-based charging provides a more advanced method for determining suitable charging current profiles. Equivalent-circuit and electrochemical models can estimate battery voltage, temperature, and internal states that cannot be measured directly through ordinary pack sensors. Optimization algorithms can then select charging currents while respecting voltage, temperature, and degradation constraints. However, model accuracy, parameter identification, computational demand, and cell-to-cell variation remain important considerations when transferring these methods into low-cost e-bike BMS hardware [6], [14], [17].

3.3. Pulse and other alternative charging methods

Pulse charging applies controlled current intervals separated by rest periods or lower-current intervals. The proposed benefits include changes in concentration polarization, heat generation, and electrochemical relaxation during charging. Other alternatives include boost charging, variable-current charging, and sinusoidal-ripple-current approaches. Their performance depends on pulse amplitude, frequency, duty cycle, cell chemistry, temperature, and the criteria used to compare charging time and battery degradation [2], [4], [18].

Although alternative charging methods may improve selected performance indicators, their advantages should not be assumed to apply universally. Some methods require more sophisticated power converters and control algorithms than conventional CC–CV charging. Their benefits can also vary between cell chemistries and operating conditions, making standardized experimental comparisons essential. For electric bicycles, an alternative charging algorithm is practically useful only when its additional complexity is justified by measurable improvements in charging time, safety, and battery lifetime.

4. THERMAL MANAGEMENT DURING FAST CHARGING

Thermal management is essential because fast charging increases the rate of heat generation inside lithium-ion cells. Temperature affects electrochemical reaction rates, ionic transport, internal resistance, charging acceptance, and degradation processes. Excessive temperature can accelerate aging and increase the risk of thermal runaway, while low temperature can restrict lithium-ion diffusion and promote lithium plating during charging. Temperature uniformity is also important because differences between cells can cause unequal aging and reduce the reliability of the complete battery pack [9], [10], [19].

Air cooling is an attractive thermal-management option for electric bicycles because it can be relatively lightweight, inexpensive, and mechanically simple. Natural convection may be sufficient for some low-power applications, but its cooling capability is limited when charging current and ambient temperature increase. Forced-air cooling can improve heat removal, although fans introduce additional power consumption, noise, and maintenance requirements. The design must also consider enclosure protection against water, dust, and mechanical damage [12], [20], [21].

Liquid cooling can provide higher heat-transfer capability and better temperature regulation than basic air cooling. However, pumps, coolant channels, seals, and additional components increase system weight, cost, and design complexity. Phase-change materials can absorb heat during melting and help reduce temperature fluctuations without requiring continuous pumping. Hybrid systems combine active and passive methods to improve heat dissipation and temperature uniformity, but their practical suitability for e-bikes depends on packaging space, weight, cost, and the expected charging power [10], [16], [22], [23].

Temperature monitoring is as important as the physical cooling method. Thermistors and thermocouples are commonly used to measure battery temperature, while advanced approaches can estimate internal temperature using electrical or electrochemical information. Surface temperature alone may not accurately represent the hottest region inside a cell, particularly under high-rate operation. Therefore, an e-bike BMS should combine reliable temperature sensing with conservative charging limits and appropriate responses to sensor faults [19], [24].

5. BATTERY DEGRADATION AND LIFETIME

Battery degradation is a gradual process that reduces the capacity and power capability of lithium-ion cells over time. Calendar aging occurs even when a battery is not being cycled, whereas cycle aging is associated with repeated charging and discharging. Both processes depend on temperature, SOC, depth of discharge, current rate, cell chemistry, and storage conditions. Fast charging can intensify degradation when high current or unsuitable temperature promotes lithium plating, loss of cyclable lithium, and increased internal resistance [5], [25]–[27].

Lithium plating is a particularly important concern during high-rate charging. It occurs when metallic lithium deposits on the negative electrode rather than being adequately intercalated into the electrode material. The risk increases under conditions such as low temperature, high charging current, and high SOC, although the exact threshold depends on cell design and operating history. Lithium plating can consume active lithium, reduce capacity, and in severe cases contribute to internal short-circuit risks [3], [18], [28].

Battery lifetime should therefore be evaluated through more than the number of charging cycles. State of health (SOH), capacity retention, internal resistance, power capability, and remaining useful life provide complementary information about battery condition. Model-based, data-driven, and hybrid estimation methods have been developed to assess SOH and predict battery lifetime. For e-bike applications, these methods can support maintenance decisions and adaptive charging limits, provided that the algorithms can operate with the limited sensing and computing resources of compact BMS hardware [25]–[32].

6. COMPARATIVE ASSESSMENT AND APPLICATION TO ELECTRIC BICYCLES

The main charging and thermal-management approaches reviewed in this paper are compared in Table 1. The comparison emphasizes that charging speed cannot be considered independently from temperature, degradation, implementation cost, and battery-pack design. CC–CV remains a practical baseline

because it is relatively simple and widely understood, while multistage and model-based methods offer opportunities for improved performance through adaptive current control. Thermal-management selection must also reflect the physical constraints of electric bicycles rather than simply reproducing the cooling systems used in larger electric vehicles.

Table 1. Comparison of fast-charging and thermal-management approaches for e-bike battery applications

Approach	Main advantage	Main limitation	Potential suitability for e-bikes
CC–CV charging	Simple, established, and relatively low-cost	Fixed current may not adapt to battery condition	High, with suitable BMS protection
Multistage CC–CV	Adjusts current across SOC ranges	Requires parameter tuning and validation	High, if implemented efficiently
Model-based adaptive charging	Can account for temperature and battery condition	Model and computation requirements	Moderate to high, depending on BMS capability
Pulse charging	May influence polarization and charging behavior	Results depend on pulse parameters and cell chemistry	Requires further validation
Natural or forced-air cooling	Relatively light and simple	Limited heat removal under demanding conditions	High for suitable low-power packs
Liquid cooling	Strong heat-transfer capability	Added weight, cost, and complexity	Limited for conventional compact e-bike packs
Phase-change or hybrid cooling	Can improve thermal buffering and uniformity	Material integration and packaging challenges	Promising for specialized designs

As indicated in Table 1, multistage charging combined with temperature monitoring offers a promising balance between performance and implementation complexity. A practical e-bike charging system should adjust current according to battery voltage, temperature, SOC, and, where possible, SOH. It should also reduce or stop charging when measurements exceed validated limits or when abnormal conditions are detected. These functions can be implemented through a BMS without requiring the advanced liquid-cooling infrastructure commonly associated with high-power automotive battery packs.

7. RESEARCH GAPS AND FUTURE DIRECTIONS

A major research gap is the limited availability of systematic fast-charging validation using complete electric-bicycle battery packs. Many published studies use individual laboratory cells or automotive battery modules, which may not represent the thermal and electrical behavior of compact e-bike packs. Future research should evaluate complete packs under realistic ambient temperatures, repeated charging cycles, vibration, aging, and different rider usage patterns. Standardized tests would make it easier to compare charging algorithms and determine whether laboratory improvements translate into practical service-life benefits [3], [7], [25].

Another important direction is the development of low-cost adaptive BMS platforms. These systems should estimate SOC, SOH, and temperature while monitoring cell imbalance and detecting abnormal charging conditions. Charging algorithms should use this information to select safe current profiles rather than applying a fixed fast-charging rate under all conditions. Further work is also needed to quantify the trade-off between charging time, battery lifetime, thermal-management energy consumption, and overall system cost [6], [17], [29]–[32].

8. CONCLUSION

Fast charging can improve the usability of electric bicycles by reducing battery charging time, but its implementation must account for thermal behavior and long-term battery degradation. CC–CV charging remains a practical baseline, while multistage, pulse-based, and model-based adaptive methods offer opportunities to improve charging performance. Thermal management through air cooling, liquid cooling, phase-change materials, and hybrid systems can help maintain suitable operating conditions, although their suitability depends on battery-pack size, cost, weight, and cooling requirements. Battery lifetime is influenced by charging current, temperature, SOC, and electrochemical degradation mechanisms, particularly lithium plating and loss of cyclable lithium. The most practical direction for electric bicycles is an integrated charging system combining validated current limits, temperature monitoring, and battery-health-aware control. Research should prioritize full-pack experiments rather than relying exclusively on individual-cell results, because pack-level temperature differences and cell imbalance can influence real-world performance. Low-cost BMS platforms should also be developed to support adaptive charging without adding excessive weight or complexity. Such developments can help deliver faster, safer, and more durable charging solutions for electric bicycles.

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