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Advances in electric bicycle battery charging technologies: a review of topologies, control strategies, and energy efficiency

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ABSTRACT

Electric bicycle adoption has increased the demand for battery chargers that are efficient, affordable, compact, and electrically safe. However, conventional low-cost chargers may provide limited power quality, moderate conversion efficiency, and relatively simple charging control. These limitations create opportunities to improve charger architectures without introducing excessive cost or complexity. This review examines advances in electric bicycle battery charging technologies, emphasizing AC–DC and DC–DC converter topologies, power factor correction, conversion efficiency, and control strategies. It draws on research concerning electric bicycles and broader electric vehicle charging systems published up to 2024, while considering the differences in power levels and application requirements. The analysis compares conventional rectifiers, boost PFC converters, bridgeless architectures, isolated converters, and non-isolated DC–DC stages. It also evaluates constant-current–constant-voltage charging, feedback control, and emerging intelligent approaches. The review identifies the need for integrated designs that balance power quality, battery protection, thermal performance, and manufacturing cost. The findings provide a technical foundation for developing more efficient and reliable charging systems for future electric bicycles.

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1. INTRODUCTION

Electric bicycles have become an important option for short-distance transportation because they offer relatively low operating costs, convenient mobility, and reduced dependence on conventional fuels. Their performance and practical usability depend substantially on battery capacity, charging time, charging safety, and the reliability of the associated power electronics. Nevertheless, many commercially available chargers prioritize low manufacturing cost and basic functionality rather than optimized power quality and conversion efficiency. These characteristics create a research problem involving the development of compact charging systems that can improve electrical performance without significantly increasing equipment cost.

An electric bicycle charger typically converts single-phase alternating-current electricity into regulated direct-current power suitable for its battery pack. Conventional designs commonly employ a rectifier, filtering components, and a regulated DC–DC converter, although some architectures integrate several functions into a single conversion stage [1], [2]. The charger must regulate battery voltage and current while maintaining acceptable input power quality and preventing unsafe operating conditions. Consequently,

its performance depends on the interaction between converter topology, semiconductor switching, control algorithms, battery characteristics, and thermal management.

Research on electric vehicle charging has extensively examined AC–DC conversion, DC–DC regulation, power factor correction (PFC), and bidirectional charging [3]–[8]. However, many proposed architectures target passenger vehicles with substantially higher power ratings than those typically required by electric bicycles. Directly transferring these designs to electric bicycles may introduce unnecessary component costs, control complexity, and physical dimensions. This review therefore evaluates the relevance of established EV charging technologies to lower-power electric bicycle applications, identifies their technical trade-offs, and discusses opportunities for improved charger design.

2. AC–DC CHARGER TOPOLOGIES

The AC–DC stage establishes the electrical interface between the utility supply and the charger's internal DC bus. The simplest architecture uses a diode bridge rectifier followed by a filtering capacitor, providing a relatively inexpensive solution with limited circuit complexity. However, the capacitor-input rectifier can draw distorted current from the supply, particularly when the current flows in short pulses near the voltage peaks. This behavior reduces power factor and increases harmonic distortion, making conventional rectification less attractive when power quality is an important design objective [5], [6].

Active PFC converters improve input-current characteristics by controlling the current waveform to follow the shape of the supply voltage. The boost converter is widely used because it provides a relatively simple circuit structure, continuous input current, and effective regulation of the DC-link voltage. Buck, buck–boost, SEPIC, Ćuk, and Zeta configurations offer alternative voltage-conversion characteristics, although their component requirements and control complexity differ [5]. In 2024, a study specifically addressing electric bicycle battery charging investigated a single-phase AC–DC boost PFC rectifier, demonstrating the direct relevance of active PFC research to low-power electric bicycle systems [9].

Bridgeless PFC architectures reduce conduction losses by removing or reducing the number of conducting devices associated with the conventional input diode bridge. A bridgeless isolated SEPIC charger has demonstrated the potential to improve input power quality and conversion performance while supporting constant-current–constant-voltage charging [10]. Nevertheless, bridgeless designs may introduce more complicated current paths, common-mode electromagnetic interference, and demanding control requirements. Their practical suitability for electric bicycles should therefore be evaluated using measured efficiency, electromagnetic compatibility, component temperature, and manufacturing cost rather than topology alone.

3. DC–DC CONVERTER TOPOLOGIES

The DC–DC stage regulates the output voltage and current according to the requirements of the connected battery pack. Non-isolated converters, including buck, boost, and buck–boost circuits, are attractive for low-power applications because they generally require fewer components and can achieve relatively high efficiency. Their main limitation is the absence of galvanic isolation between the input and output sides, which may restrict their suitability depending on the charger architecture and applicable safety requirements. Isolated converters incorporate a high-frequency transformer to provide electrical separation and voltage adaptation, although this arrangement generally increases component count and design complexity [3], [4].

Flyback, forward, half-bridge, full-bridge, and resonant LLC converters represent important isolated DC–DC options. Flyback converters are particularly relevant to relatively low-power chargers because of their simple transformer-based structure and ability to provide isolation. LLC resonant converters can achieve reduced switching losses through soft-switching operation, making them attractive where higher efficiency and power density justify additional design effort [11], [12]. The selection between isolated and non-isolated architectures should consider battery voltage, output power, safety requirements, transformer size, ripple, and total system cost.

Table 1 compares representative converter configurations according to their operating characteristics and potential suitability for electric bicycle battery chargers. The comparison emphasizes engineering trade-offs rather than claiming that one topology is universally superior. The preferred architecture depends on the battery voltage range, required charging current, isolation requirements, and available implementation budget. These factors should be considered together during charger development and component selection.

Table 1. Comparison of AC–DC and DC–DC converter topologies

Topology	Main advantages	Main limitations	Potential application
Diode bridge rectifier	Low cost and simple construction	Poor input power factor without PFC	Basic low-cost chargers
Boost PFC	Improved power factor and regulated DC link	Additional switching and control components	AC-input chargers
Bridgeless PFC	Reduced conduction losses	More demanding EMI and control design	High-efficiency AC chargers
Buck converter	Simple step-down regulation	Cannot increase output voltage	Battery voltage regulation
Buck–boost converter	Flexible output-voltage regulation	Higher component stress in some operating regions	Wide battery voltage ranges
Flyback converter	Galvanic isolation and compact structure	Transformer and switching stresses	Low-power isolated chargers
LLC resonant converter	Soft switching and high efficiency potential	More complex design and regulation	Higher-performance chargers
Interleaved DC–DC	Reduced ripple and distributed current	Increased component count	Higher-current charging systems

4. POWER FACTOR CORRECTION AND POWER QUALITY

Power factor correction is important because the charger behaves as a nonlinear load when its input current is not proportional to the supply voltage. A low power factor increases the apparent power required from the electrical network for a given amount of useful charging power. Harmonic currents can also increase electrical losses and interfere with other equipment connected to the same supply. Active PFC converters address these problems by shaping the input current and regulating the intermediate DC voltage [5], [13].

Conventional boost PFC provides a practical balance between circuit simplicity, current regulation, and power quality. Bridgeless boost and SEPIC configurations can further reduce conduction losses, although their switching behavior and electromagnetic characteristics require careful evaluation. A 2024 investigation of a boost PFC converter for electric bicycle battery charging directly connects these design considerations with the intended application [9]. For low-power chargers, the additional cost and standby consumption of an active PFC stage should be compared with the actual benefits obtained under realistic operating conditions.

5. CHARGING CONTROL STRATEGIES

Charging control determines how the converter supplies energy to the battery while respecting voltage, current, and temperature limitations. Constant-current–constant-voltage (CC–CV) charging is widely used for lithium-ion batteries because it provides a practical balance between charging speed and voltage limitation. During the constant-current stage, the charger supplies a controlled current until the battery reaches its specified upper voltage. The controller then maintains the voltage while the charging current gradually decreases toward the termination threshold [14], [15].

Feedback control improves charging accuracy by continuously comparing measured voltage or current with their reference values. Proportional–integral controllers are commonly employed in converter regulation because they are relatively straightforward to implement using digital controllers or dedicated control circuits. More advanced methods, including model predictive control, sliding-mode control, and intelligent algorithms, have also been investigated for improving transient response and handling changing operating conditions [13], [16]. However, their computational requirements and implementation costs should be justified by measurable improvements in charging performance.

Battery-aware control provides another important direction for electric bicycle charger development. Charging current and voltage should be adjusted according to battery chemistry, state of charge, temperature, and manufacturer-defined limits. Research on lithium-ion battery charging strategies has emphasized the importance of balancing charging speed with battery lifetime and operational safety [14], [17]. Therefore, an effective charger should coordinate converter-level regulation with battery-management-system information rather than relying exclusively on fixed charging parameters.

6. CONVERSION EFFICIENCY AND DESIGN TRADE-OFFS

Conversion efficiency represents the proportion of input electrical energy delivered usefully to the battery. It is affected by semiconductor conduction losses, switching losses, magnetic-component losses, filtering components, and auxiliary circuit consumption. Two-stage chargers provide independent control of the input PFC and battery-side DC–DC stages, but the cascaded conversion process introduces losses in both stages. Single-stage architectures can reduce component count and avoid some intermediate conversion losses, although they may complicate simultaneous input-current shaping and battery regulation [6], [10], [18].

Efficiency optimization requires more than selecting components with low nominal losses. Switching frequency, semiconductor characteristics, magnetic design, thermal conditions, and operating load all influence the actual conversion performance. A study of double-conversion battery chargers demonstrated that coordinated duty-cycle selection can improve efficiency while maintaining high power factor and low input-current distortion [18]. For electric bicycles, this approach is particularly relevant because the charger operates at comparatively low power, where fixed auxiliary losses and component cost can have a noticeable influence on overall performance.

Table 2 summarizes the principal design trade-offs that should guide the development of efficient electric bicycle chargers. The comparison shows that efficiency, power quality, isolation, and cost cannot always be optimized independently. For example, a more sophisticated PFC stage may improve input-current quality but increase the number of components and control requirements. Similarly, an isolated resonant converter may improve switching performance while requiring more careful magnetic and thermal design.

Table 2. Key design considerations for electric bicycle battery chargers

Design factor	Desired characteristic	Main engineering consideration
Input power factor	Close to unity	PFC topology and current control
Harmonic distortion	Low input-current THD	Switching strategy and input filtering
Conversion efficiency	High across operating loads	Semiconductor and magnetic losses
Battery current ripple	Low and controlled	DC–DC topology and output filtering
Electrical safety	Appropriate isolation and protection	Transformer design and protective circuitry
Charging accuracy	Stable voltage and current regulation	Feedback sensing and control algorithms
Thermal performance	Acceptable component temperature	Cooling, switching frequency, and enclosure
Manufacturing cost	Affordable implementation	Component count and circuit complexity

7. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite extensive research on EV charging technologies, electric bicycle chargers require more application-specific experimental evaluation. Many published converter studies focus on passenger vehicles or higher-power charging systems, which limits the direct transferability of their performance results to low-power applications. Research should establish consistent benchmarks for efficiency, power factor, total harmonic distortion, battery current ripple, temperature rise, and charging duration under representative electric bicycle operating conditions. Such measurements would provide a stronger basis for comparing conventional chargers with newer PFC and high-efficiency converter architectures.

Future research should prioritize compact single-phase PFC designs, low-cost isolated DC–DC converters, and digitally controlled CC–CV charging systems. The integration of battery temperature, state-of-charge estimation, and protective functions could further improve charging reliability and battery lifetime. Wide-bandgap semiconductors may provide opportunities for reducing switching losses and increasing power density, although their economic benefits at electric bicycle power levels require careful assessment [8], [12]. Ultimately, the most practical design will be the one that achieves an appropriate balance between energy efficiency, power quality, safety, reliability, and affordability.

8. CONCLUSION

Electric bicycle battery charger development requires coordinated improvements in converter topology, power factor correction, charging control, and conversion efficiency. Conventional rectifiers remain attractive because of their low cost, but their power quality limitations motivate the adoption of active PFC architectures. DC–DC converters provide the necessary battery-side voltage and current regulation, with isolated and non-isolated designs offering different advantages in safety, efficiency, and complexity. The CC–CV method remains a practical charging strategy, while feedback-based and intelligent control approaches provide opportunities for improved regulation and battery protection. The review indicates that no single converter architecture is optimal for every electric bicycle charging application. Topology selection should reflect battery specifications, power rating, isolation requirements, operating conditions, manufacturing cost, and maintenance considerations. Greater attention should also be given to experimental validation using actual electric bicycle battery packs rather than relying entirely on results from higher-power EV systems. These developments can support the design of compact, efficient, safe, and affordable chargers for the next generation of electric bicycles.

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