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Advancements in electrical systems for E-bike battery charging: a technical examination of conventional and wireless power transfer technologies

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ABSTRACT

Electric bicycles (E-bikes) are becoming key to making transportation more eco-friendly, leading to cleaner air, and lower carbon emissions. The rising popularity of E-bikes calls for innovative battery charging solutions that cater to their specific needs, emphasizing faster charging, high energy efficiency, safety, compact design, smart features, and compliance with international standards. This paper reviews existing and new charging technologies for E-bikes, focusing on their design, charging processes, and safety features. It points out the issues with traditional chargers, such as their negative effects on power quality and grid stability, and introduces wireless power transfer (WPT) as a groundbreaking approach to E-bike charging. WPT enhances convenience by removing the need for physical cables and is seen as a step forward with the integration of power factor correction techniques for better efficiency and energy use. The discussion extends to the future of E-bike charging, exploring emerging technologies that could redefine electric transportation. The study aims to deepen the understanding of E-bike battery charging technologies, their challenges, and future directions, contributing to the advancement of E-bike technology.

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1. INTRODUCTION

The reliance on internal combustion engines fueled by petroleum derivatives in the transportation industry highlights major issues, especially worsened by worldwide concerns about petroleum shortages. The significant rise in fuel prices is a major difficulty for users of conventional vehicles [1]. The automotive sector worldwide has shifted towards new and environmentally friendly vehicle technology, with electric vehicles (EVs) leading the way. This shift is driven by increasing concerns about planetary health as well as a substantial rise in carbon emissions, which harm the atmosphere. Adopting electric vehicles is considered a crucial step in lowering harmful greenhouse gas emissions and helping mitigate global warming [2]. The transportation industry is a major contributor to greenhouse gas emissions, making up around 59% of the total emissions [3]. The increasing worldwide awareness of sustainability is leading to a widespread transition towards electrification in several sectors, as EVs emerge as a practical and effective solution to reduce the environmental footprint of transportation. This shift reduces the sector's carbon footprint and eliminates energy dependence by utilizing electric vehicles with little energy usage and zero-emission operation [4]. The paper explores deep the technical foundations and advancements in vehicle electrification, providing an in-depth examination of the shift towards sustainable and advanced transportation systems.

An EV is characterized as a vehicle powered by one or more electric motors, utilizing energy from batteries or other forms of energy storage devices. This definition broadly encompasses electric bicycles, which are equipped with electric motors or motor-assist technology, and hence, are classified under the umbrella of EVs. Known as E-bikes, these electrically assisted bicycles are experiencing a surge in global popularity, fueled by heightened awareness of health and environmental benefits. While the automotive sector is at the forefront of the electrification movement, the integration and acceptance of E-bikes pose their unique set of challenges. E-bikes, which primarily rely on rechargeable lithium-ion batteries, represent an efficient and eco-friendly transportation alternative. Given the rapid evolution in electrification demands within the automotive industry, there is an escalating pressure on manufacturers to innovate and improve E-bike technologies, including the development of advanced charging solutions and accessories, to meet the growing expectations for sustainable and efficient transportation options.

Battery charging systems for E-bikes are fundamentally divided into two categories: wired (plug-in) and wireless systems. Wired charging necessitates a physical linkage between the E-bike and the charging apparatus, typically facilitated by a cable or wire. In contrast, wireless charging systems eliminate the need for a direct physical connection, leveraging the principles of electromagnetic induction or capacitive coupling. These systems employ magnetic fields through inductive coupling between two coils or utilize electric fields via capacitive coupling between metallic electrodes to transfer energy. While the majority of E-bike charging solutions currently employed are wired, available for use in a variety of settings such as residential homes, workplaces, and public charging stations, wireless charging technology, underpinned by wireless power transfer (WPT) principles, is emerging as a compelling alternative. Wireless charging presents several advantages, including improved efficiency in power transfer, enhanced convenience by eliminating the need to manually plug in the device, and increased safety by reducing the risks associated with electrical connections [5].

This paper thoroughly examines the technical components of E-bike charging systems, providing a detailed evaluation of both wired and wireless charging methods within the evolving environment of EVs technologies in environmentally conscious transportation. The study primarily examines typical battery chargers for E-bikes, providing a thorough examination of the technology, performance metrics, and safety precautions. The studies then dive into examining power quality issues found in E-bike charging systems, specifically focusing on the difficulties caused by low power factors and increased harmonic levels. The study explores WPT technologies and their several configurations, highlighting the complexities of this new method for charging E-bike batteries. The discussion also covers power factor adjustment, highlighting its importance in enhancing reactive power management and reducing overall energy usage. An energy analysis comparing wired and wireless E-bike charging systems is discussed, offering insights into charging time and energy efficiency for both methods. This paper provides valuable insights into advancements in E-bike charging systems by analyzing interrelated components, combining electrical and electronics engineering with sustainable transportation technologies.

2. AN OVERVIEW OF STANDARD BATTERY CHARGING SOLUTIONS FOR E-BIKE

E-bikes typically display varying voltages depending on their model and design, with the 36 V, 48 V, and 52 V ranges emerging as the standard benchmarks within the E-bike industry [6]-[9]. The choice of voltage plays a crucial role in determining the performance and power output of E-bikes. Lower voltage systems, such as 36V, are generally suited for entry-level or commuter models, whereas higher voltage systems, like 48V or 52V, are employed in more powerful electric mountain bikes or high-performance models.

In this ecosystem, the E-bike battery charger assumes a critical role, utilizing a wired AC-DC power supply connection with a specific voltage and current rating designed to meet the E-bike's needs [10]. The charger comprises three key components: an AC-DC power converter (rectifier), which converts alternating current (AC) to direct current (DC); a charging cable equipped with a connector to facilitate the electricity supply to the E-bike; and a charge controller, located within the external power supply, that oversees the battery charging process, ensuring safety, communication, and precise control.

According to Navaneeth *et al*. [11], the architecture of these chargers primarily involves an iron core toroidal transformer and a full bridge diode rectifier. The transformer is responsible for drawing power from the electrical grid and adjusting the voltage levels to suit the battery's requirements, while the full bridge rectifier converts the AC voltage from the grid into DC voltage, suitable for charging the battery. By employing a high-frequency ferrite core transformer, such chargers manage to significantly reduce weight compared to traditional models. Furthermore, these systems achieve the elimination of DC voltage ripple through various stages of conversion between DC to AC and back to AC to DC, employing (1) for calculating the necessary inductance and capacitance for the LC filter [12]. This exploration contributes a detailed understanding of the technical foundations behind E-bike charging systems, effectively merging electrical and electronics engineering disciplines to advance efficient and sustainable urban transportation solutions.

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

In the quest to enhance battery longevity through refined charging strategies, recent focus has shifted towards the sinusoidal ripple-current (SRC) charging algorithm [13]. This innovative charging method integrates two key components: an AC ripple component and a DC component. To reduce the internal impedance of lithium-ion batteries, the SRC algorithm dynamically adjusts the amplitude and frequency of the ripple component [14]. Such adjustments facilitate charging under conditions of minimal internal impedance, leading to lower battery temperatures, and consequently, improvements in both power and energy efficiency during the charging process.

However, the SRC and pulse charging techniques face several challenges, including their high cost, large physical size, and the complexities involved in their implementation [15]. These factors limit their practical application and widespread adoption. Figure 1 depicts the standard configuration of the cost-effective battery charger. Despite the common use of wired connections, they introduce several challenges, such as reduced reactive power due to power quality issues, risks of wire breakage, and concerns over potential damage [16].

The design and operational principles of battery chargers for E-bikes greatly influence their performance, irrespective of power quality considerations. Nonetheless, addressing power quality issues is crucial for improving the charging process's efficiency and reliability. By tackling these concerns, it is possible to ensure a more effective charging experience for E-bike users, ultimately contributing to the broader adoption and sustainability of E-bikes.

Figure 2 illustrates the setup of a conventional wire-connected charging system. The depicted E-bike, manufactured by STonBike (Model: CHR-48V/LI), is equipped with a wire-connected charger designed to charge the battery from 41.28 V (0% charge) to 54.94 V (fully charged at 100%). This specific E-bike model serves as the basis for a comparative performance analysis between wire-connected and wireless battery charging systems. The findings and detailed analysis of this comparison are presented in the subsequent section.

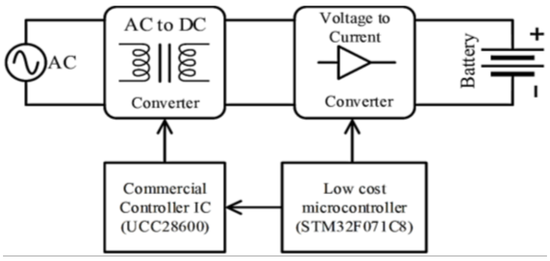

Figure 1. Standard configuration of the low-cost battery charger

Figure 2. Set up wire-connected charging tests

3. ADDRESSING POWER QUALITY ISSUES IN E-BIKE CHARGING SYSTEMS

Researchers are increasingly focusing on power quality issues, prompted by the escalating dependence on nonlinear loads. According to the IEC Standard 61000-2-2:2002-03 [17], power system harmonics are identified as sinusoidal voltages and currents that occur at frequencies which are integral multiples of the primary generating frequency, or the fundamental frequency. These harmonics necessitate defined limits for harmonic current distortion to mitigate their potential adverse impacts on both consumer and system equipment. The IEEE STD 519-2022 further elucidates the dynamic interaction between sources and loads, detailing expectations for waveform distortion that system designers must consider, and characterizes the voltage and current waveforms within the system [18]. Nonlinear electronic circuits, which are prevalent in components of power electronics, such as rectifiers, adjustable speed drives, and computers, are significant generators of highly distorted currents, thus producing substantial harmonics. This results in power quality (PQ) issues within the electric power distribution system, significantly elevating the system's sensitivity to PQ levels, with harmonics as a primary concern.

The critical role of the battery in electric bikes (E-bikes), serving as the primary energy source for the current electric vehicle (EV) transportation system, cannot be overstated. Since most batteries demonstrate capacitive characteristics, employing a non-power factor correction charging approach leads to the generation of high harmonic currents from the mains supply. This condition poses a significant risk of damage to the distribution transformer and adjacent equipment [19], [20]. Beyond the inherent heating caused by the power supply's fundamental component, the presence of current harmonics flowing through power cables can cause irregular heating patterns.

The integration of a charger into a residential electrical system introduces a spectrum of advantages and disadvantages [21]. The electric 2 wheelers charger (E2WC) exemplifies this, revealing distorted current waveforms that significantly deviate from a sine wave [22]. The drawbacks identified in this analysis include harmonics, voltage instability, and other PQ issues adversely affecting connected electrical devices. Notably, the total harmonic current distortion generated by the charger was found to be an exceptionally high 135.22%, exceeding the limits prescribed by the IEEE STD 519-2022 standard. The elevated harmonic distortion compromises the system's efficiency, as demonstrated by the current waveform's non-sinusoidal characteristics with spikes. These irregularities are directly attributable to current harmonics, which impact the system's overall performance. E-bike battery charging systems, consisting of multiple power electronic converters, and analog electronic subsystems, operate as non-linear loads that induce harmonics in the grid current, consequently increasing harmonic pollution. The effects of these harmonics extend beyond the power system components themselves, affecting interconnected systems and causing distortion across the network [23]. The detrimental impact of harmonics on the functionality of associated equipment represents a significant risk, potentially leading to severe malfunctions and incurring considerable financial losses. Harmonics not only disrupt equipment operation but also tend to create imbalances in the power system. Negative sequence components can introduce an imbalance, evident as a second-order harmonic ripple in the DC link voltage. This imbalance further distorts the input currents from the grid. The (2) provides a critical analysis tool to understand the complex effects of harmonics on the DC-link, offering insights into the intricate relationship between harmonics and the charging system's efficiency.

$$V_{dc} = \frac{3}{4C}[I_{dc} + \frac{I_2}{4\pi f}\sin(4\pi f t - \alpha_2) + \frac{I_4}{8\pi f}\sin(8\pi f t - \alpha_4) + \frac{I_6}{12\pi f}\sin(12\pi f t - \alpha_6) + \frac{I_8}{16\pi f}\sin(16\pi f t - \alpha_8) + \frac{I_{12}}{24\pi f}\sin(24\pi f t - 12)] \quad (2)$$

Nonlinear loads, such as those found in power electronic converters used in switched-mode computer power supplies, adjustable speed drives, and various types of converters, are known to induce harmonics within electrical systems [24]. These converters, when integrated into the electrical grid, significantly amplify harmonic distortion due to their dual role in consuming and generating energy at frequencies that deviate from the system's fundamental frequency [25], [26]. The impact of harmonics is extensive, affecting both low and high frequency ranges. This includes phenomena like flicker, increased temperatures in equipment, higher losses within the electrical network, interference with communication systems, and inaccuracies in both control systems and digital meters [27], [28].

The characteristics of voltage and current disturbances vary widely across this broad frequency spectrum, particularly in terms of their duration and frequency [29], [30]. High-frequency distortions, for example, are characterized by more rapid fluctuations in frequencies and amplitudes, whereas low-frequency distortions tend to change more slowly over time. Therefore, to effectively analyze and mitigate these distortions within each frequency range, it is crucial to employ time-frequency analysis techniques that utilize well-defined sample windows. This approach ensures a comprehensive understanding and addressing of the diverse impacts of harmonics.

Given these considerations, it is clear that power quality considerations are essential throughout the design and construction process of wireless battery chargers for E-bikes. Ensuring that these devices adhere to power quality standards is paramount to preventing the adverse effects of harmonics on the electrical grid and connected devices, thereby enhancing the overall efficiency and reliability of E-bike charging systems.

4. DESIGN AND IMPLEMENTATION OF A WIRELESS BATTERY CHARGING SYSTEM FOR E-BIKES

This section delves into the critical role of battery chargers in supporting the operation of E-bikes, examining the limitations associated with traditional cable connections, including vulnerability to damage, constrained mobility, and risk of theft. It argues for the adoption of WPT technology as a superior alternative for E-bike charging. This comprehensive review covers the historical background, technical details, and operational principles of WPT, with a particular focus on its application in inductive power transfer (IPT) for medium and high-power E-bike charging scenarios [31].

Traditional E-bike charging methods typically require a battery charger to connect to a standard wall outlet via a cable linked to the E-bike battery. This section highlights the drawbacks of physical cable connections, thereby setting the stage for the wireless solution provided by WPT. Distinguished as a revolutionary technology, WPT facilitates energy transmission across an air gap through electromagnetic fields, thereby obviating the need for physical connections [32].

Recognizing Nikola Tesla's seminal work in establishing the fundamental principles of WPT in the late 19th century, this discourse categorizes three main wireless charging technologies: radio waves (RW-WPT), capacitive power transfer (CPT), and particularly, IPT. It delves into IPT's appropriateness and effectiveness for medium to high-power transfers, making it the preferred method for E-bike charging. The section elaborates on the operational mechanisms of IPT, emphasizing its dependence on magnetic field interactions to transfer power between the primary coil, which is part of the charging station, and the secondary coil, located on the E-bike. The inherent technical advantages of IPT render it an exemplary solution for E-bike charging needs [32].

Further, the discussion elucidates the principles underpinning WPT, focusing on electromagnetic induction and resonant coupling. It highlights the crucial alignment of transmitter and receiver coils, explaining how their resonation at the same frequency significantly enhances the efficiency of power transfer [33]. This analysis affirms the technical superiority of WPT, especially IPT, as an innovative approach for E-bike charging, addressing the limitations of traditional conductive charging methods. Through an in-depth exploration of both historical developments and technical advancements, this narrative provides valuable insights into the evolution and potential of E-bike charging systems [34]-[38].

Resonant inductive power transfer (RIPT) systems have garnered widespread attention and adoption among researchers and various industrial sectors due to their ability to efficiently transmit a wide range of power levels, even across increased distances and in the presence of coil misalignment. For optimal efficiency in power transfer, it is essential that both the transmitting and receiving coils are positioned in proximity and aligned as accurately as possible [39], [40]. In resonant systems, energy oscillates between potential and kinetic forms, allowing these systems to effectively store energy. It is critical to maintain a balance where the energy injected into the system is greater than or equal to the energy lost; otherwise, the system's efficiency would deteriorate. Should the energy loss exceed the energy being injected, the system's capacity for power transfer and energy storage would be compromised [41]. Isolated resonators are characterized by their resonant frequency ω_o and inherent loss, Γ rate. These two elements form the resonator's quality factor, or Q, which quantifies energy storage ($Q = \omega_o/2\Gamma$) [42]. Figure 3 illustrates an electromagnetic resonator circuit, which encompasses an inductor, a capacitor, and a resistor.

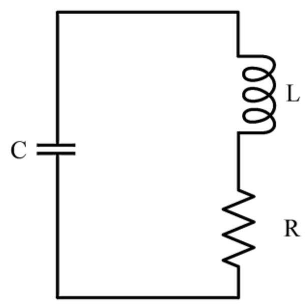

Figure 3. Typical resonator

The inductor and capacitor store energy in their magnetic and electric fields, respectively, and oscillate at a resonant frequency before dissipating in the resistor. According to Raabe *et al*. [43], the receiver-side quality factor Q, short circuit current *Isc*, and open circuit voltage *Voc* can all be used to determine the power output as in (5). The resonator's quality factor and resonant frequency can be expressed as (3)-(5).

$$\omega_o = 2\pi f = \frac{1}{\sqrt{LC}} \tag{3}$$

$$Q = \frac{\omega_o}{2\Gamma} = \sqrt{\frac{L}{C}}\,\frac{1}{R} = \frac{\omega_o L}{R} \tag{4}$$

$$P_{out} = P_{su}\,Q = V_{oc} I_{sc}\,Q = \omega M I_1 \frac{M I_1}{L_2} Q = \omega {I_1}^2 \frac{M^2}{L_2} Q \tag{5}$$

The quality factor of the system will increase in accordance with the formula for in (2) if the circuit's loss, or *R*, is decreased. In order to achieve high power transfer, resonant inductive power transfer systems need a high Q [44]-[46]. Conductors and components with low radiative and absorptive losses and relatively small resonant frequency ranges are frequently used to build high electromagnetic resonators (also known as ohmic, resistive, and series resistive) [47]. Figure 4 shows a schematic of the circuit resonant power converter topology and the sensing measurements [48].

Greater efficiency for coupling resonators between transmitter coil and receiver coil requires a high coupling coefficient k and quality factor Q. The k would increase as the coupler's size to gap ratio increased, and the Q would increase as the wire's thickness and ferrite section area increased. Since Q is equal to $\omega_o/2\Gamma$, high frequency is often utilized to increase Q value [49]. The electromagnetic field produced by the first coil will transmit the electricity from the *L1* to the *L2*. This occurs because the flow of current through the conductor (coil) will generate magnetic flux. Consequently, the magnetic flux generated by the first coil will transfer to the second coil, *L2*, and lead the coil to cut. Based on the basic electromagnetic induction, electromotive force (EMF) is induced when the conductor is cut off by magnetic flux. Subsequently, the AC current will flow to the load. The current then depend on the load whether it is AC or DC, if it is DC the current must be converts from AC to DC using a rectifier [50]. According to Figure 5, the generator was a sinusoidal voltage source with amplitude V_g at frequency and generator resistance R_g. The mutual inductance M_i [51]-[54], which connects the inductors *L1* and *L2*, represents the transmitter and receiver resonator coils and expressed as (4).

$$M_i = \frac{V_{so}}{\omega I_1} \tag{4}$$

A coupling coefficient, denoted as [55], is used to express coefficient k the degree of coupling between two coils L_1 and L_2, as in (5).

$$k = \frac{M_i}{\sqrt{L_1 L_2}} \tag{5}$$

The power transferred to the load resistor according to this circuit's analysis was as (6).

$$\frac{P_L}{P_{g,max}} = \frac{4U^2 \frac{R_g R_o}{R_1 R_2}}{\left(\left(1+\frac{R_g}{R_1}\right)\left(1+\frac{R_o}{R_2}\right)+U^2\right)^2} \tag{6}$$

Where,

$$U = \frac{\omega M}{\sqrt{R_1 R_2}} = k\sqrt{Q_1 Q_2} \tag{7}$$

Then, as demonstrated by [56], the following is supplied to maximize the efficiency of power transmission, as shown in (8).

$$\eta_{max} = \max\left(\frac{P_{out}}{P_{in}}\right) = \frac{U^2}{\left(1+\sqrt{1+U^2}\right)^2} = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2} \tag{8}$$

Systems with high values of U could transfer energy with a high degree of efficiency. In (6) and (7) emphasize estimating the wide range of applications that WPT systems utilizing RIPT can handle. These equations highlight the importance of the coupling factor and quality factor, respectively. To maximize the capabilities of resonance technology and high switching frequency with no switching losses, zero-voltage switching (ZVS) could be achieved by correlating the resonance frequencies at the primary (f_p) and secondary (f_d) sides. Additionally, both f_p and f_d should be correlated with the inverter switching frequency (f_{ch}) [57], [58]. Therefore, the wireless battery charger needs power factor correction to maintain optimal power quality during the charging process.

Figure 6 presents the configuration utilized for testing the wireless charging system. The design of this wireless battery charger is informed by the output parameters (voltage and current) of a traditionally wired battery charger. The wireless charging system is specifically engineered to enhance the input power factor, aiming to meet the requirements of the MS IEC 60038 standard.

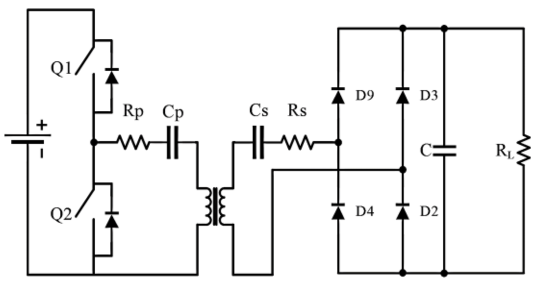

Figure 4. Topology of resonant power converter

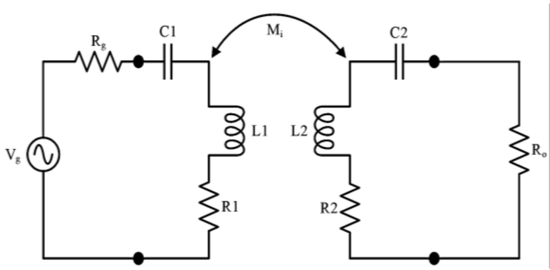

Figure 5. The connected resonator system's equivalent circuit

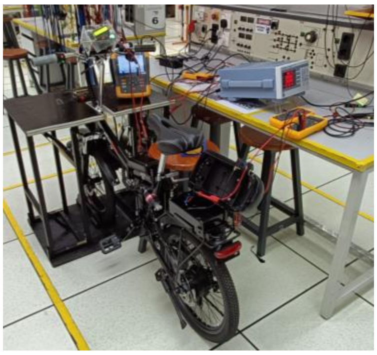

Figure 6. Setup for wireless charging test

5. ENHANCEMENT OF POWER FACTOR CORRECTION

The rising demand for clean energy, along with goals for environmental preservation and energy conservation, has catalyzed progress in distributed generation, smart distribution networks, AC/DC long-distance transmission, and the pursuit of sustainable development objectives. Power electronics technology is instrumental across a variety of domains, including power system production, transmission, distribution, and storage. It enables enhanced energy consumption, efficient utilization, and flexible management of electric energy [59], [60]. Nonetheless, the widespread adoption of power electronic devices introduces nonlinear characteristics into electrical systems, engendering harmonic pollution that detrimentally impacts power systems and poses environmental risks [56], [61]-[64]. This harmonic pollution has the potential to significantly disrupt the electrical environment and compromise the economic efficiency, operational safety, and reliability of power systems.

Within the context of power factor correction (PFC), a crucial component for AC-DC converters in power electronics, especially in applications like rectifiers, three primary strategies are identified: active power filter (APF), passive power filter (PPF), and hybrid power filter (HPF). AC-DC converters as illustrated in Figure 7, essential for high-efficiency power conversion, often produce a distorted supply current that deviates from the ideal supply voltage waveform. This results in a low power factor (PF) and elevated levels of total harmonic distortion (THD). To improve system efficiency and achieve a high PF while minimizing THD, integrating a filtering circuit, such as an APF or PPF, is critical for rectifiers. Implementing these corrective measures is vital for enhancing power quality within the supply system. This is particularly relevant for wired-connected battery chargers for E-bikes, which frequently lack PF correction, leading to lower PF and increased energy losses. Addressing these issues is crucial for meeting sustainability targets and ensuring the dependable operation of power systems in alignment with environmental and energy efficiency standards.

The primary strategy for achieving PF correction, aimed at attaining unity PF and reducing supply current harmonics, involves the utilization of APFs in wireless battery charging systems for E-bikes. APFs are broadly categorized into two types: shunt APF and series APF. Among these, the shunt APF is recognized for its foundational role and widespread adoption, marking its significant presence in industrial applications [65]-[67]. The core goal of any APF-based control system is to engineer an APF that can effectively reintroduce current into the power line, thereby efficiently mitigating harmonic content [68]. APFs are available in several configurations, including series APF, shunt APF, and hybrid APF, each serving distinct operational needs. Figure 8 presents a block diagram that outlines various power circuit arrangements for APFs, highlighting their critical role in enhancing the power quality of wireless battery charger systems for E-bikes.

Figure 9 illustrates a series APF connected to the distribution line via a matching transformer. The series APF functions by isolating harmonics present between the nonlinear load and the supply. This isolation is accomplished by injecting specific harmonic voltages (V_f) through the interface transformer. The system either adds or subtracts the source voltage from these injected harmonic voltages to ensure the maintenance of a sinusoidal voltage waveform across the nonlinear load. Series APF is capable of eliminating voltage harmonics [70], thereby supplying the load with a pure sinusoidal waveform. This is particularly crucial for voltage-sensitive equipment, including power system protection devices and power electronics components [69], ensuring their optimal operation and longevity.

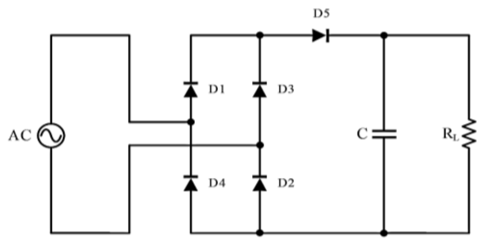

Figure 7. Fundamentals of AC-DC conversion

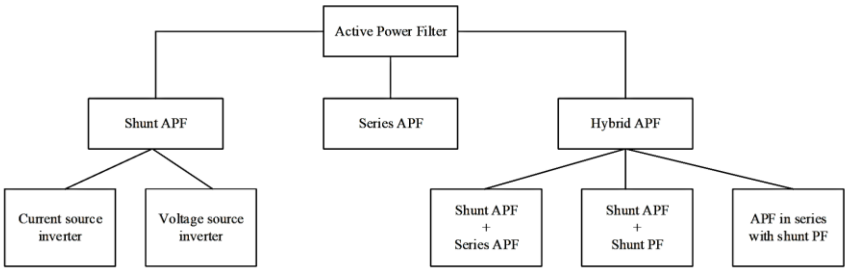

Figure 8. Classification of active power filters based on power circuit configurations [69]

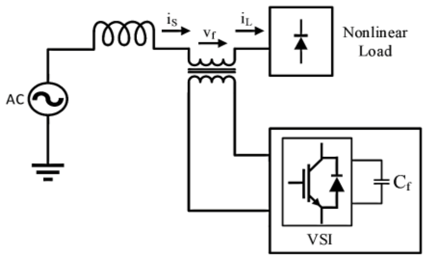

Figure 9. Configuration of a VSI-based series APF [69]

The shunt APF is designed to connect in parallel with nonlinear loads to address grid current distortion, enhance utility PF, and balance unbalanced loads. It achieves these objectives by injecting compensatory negative harmonic currents into the grid, thereby facilitating the generation of a pure sine wave output [71]. Commonly, the shunt APF is employed for the mitigation of source current harmonics and the compensation of reactive power, which contributes to PF improvement [72]. Figure 10 depicts the topology of a shunt APF. A notable requirement for the shunt APF is a high bandwidth, which introduces an additional challenge in terms of current control [73]. It is important to note that shunt APF is primarily effective against low-order current harmonics and requires harmonic traps for optimal performance. Furthermore, for the same capacitive rectifier load, the shunt APF necessitates a higher current rating than its series APF counterpart if the impedance is lower than 0.03 per unit [74].

Bunyamin *et al*. [75] presents a novel circuit design incorporating an APF alongside an AC-DC converter, as depicted in Figure 11. The integration of the APF plays a crucial role in effectively tackling power quality issues, particularly harmonic distortion. This innovative topology goes beyond merely addressing harmonic concerns; it significantly improves the performance and stability of wireless E-bike battery charger systems. Incorporating PF correction mechanisms within the design of wireless battery chargers is vital. It ensures not only efficient energy transfer but also contributes to the enhancement of overall power quality and system stability during the charging of E-bikes.

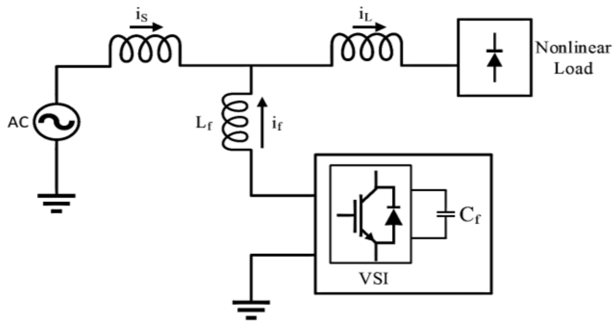

Figure 10. Configuration of a VSI based shunt APF

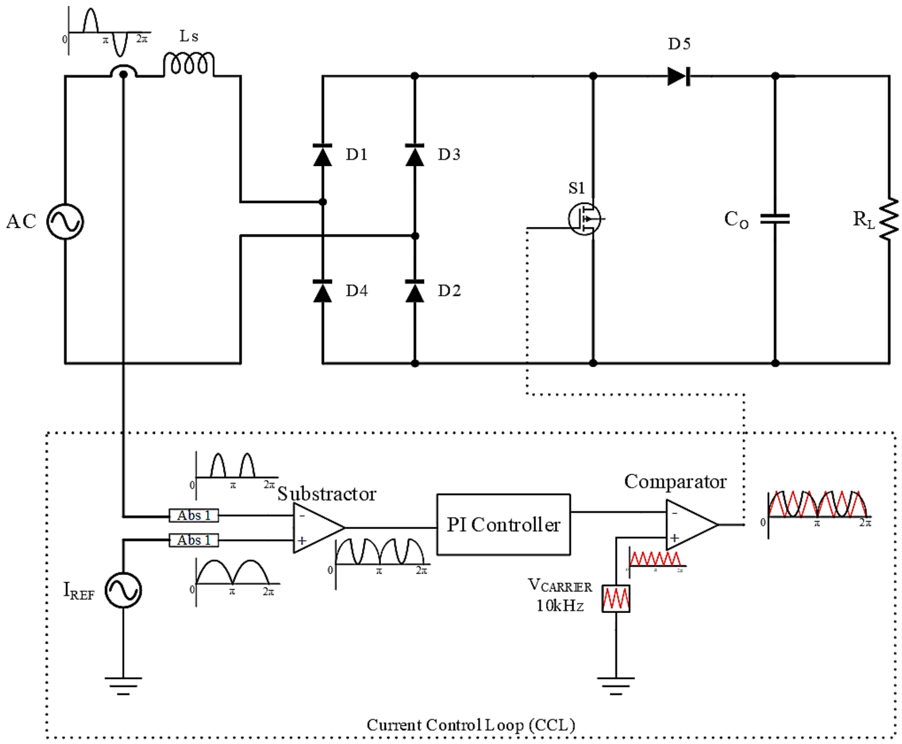

Figure 11. AC-DC converter incorporating APF functionality

6. RESULTS AND DISCUSSION

This section examines the performance of an AC-DC converter integrated with an active power filter (APF) for wireless electric bicycle (E-bike) battery charging systems. Figure 12 presents the performance of a conventional rectifier without APF, typically utilized to address power quality issues and harmonic distortion. A fast fourier transform (FFT) analysis of the supply current waveform without a filter, shown in Figure 13, reveals the total harmonic distortion (THD) and its frequency components. The distorted supply current waveform depicted in Figure 12 leads to a high THD level, which does not meet the IEEE STD 519-2022 requirement that the THD of supply current should be below 5%.

In contrast, Figure 14 displays the waveforms of the supply current for the AC-DC converter equipped with APF functionality. This illustration shows a sinusoidal and in-phase supply current relative to the supply voltage waveform. An FFT analysis of the supply current waveform with an APF, depicted in Figure 15, indicates a significant reduction in THD and frequency components, achieving a continuous, sinusoidal, and in-phase supply current. The incorporation of power factor correction (PFC) results in improved power factor (PF) and reduces the THD levels to 1.54%, thereby ensuring compliance with IEEE STD 519-2022.

The pulse width modulation (PWM) signal waveforms, generated to control the IGBT switch in the full-bridge inverter for the first and second operation cycles, are shown in Figure 16. Figure 17 provides a detailed view of the high-frequency AC voltage at the transmitter coil, offering insights into its waveform, amplitude, and timing characteristics. Extending this analysis, Figure 18 graphically represents the amplitude and timing characteristics of the AC voltage at the receiver coil. Collectively, these results validate the effectiveness of the proposed AC-DC converter topology with APF for the wireless E-bike battery charger in enhancing power quality and adhering to industry standards.

Efficiency evaluation of the charger includes an examination of its power factor. Utilizing Fluke 435-II power quality and energy analysers, the power factor for both wire-connected and wireless chargers was assessed. As depicted in Figure 19, the power factor for the wire-connected charger starts at a maximum of 0.6 and diminishes to 0.48 as the battery approaches full charge, indicating potential inefficiencies in the power system that could lead to increased consumption of reactive power and impact the overall efficiency of the charging process. Conversely, Figure 20 shows that the power factor for the wireless charger begins at a high of 0.94 and slightly decreases to 0.91 as the battery becomes fully charged. A high-power factor typically signifies more efficient electrical power usage, implying that the charger operates with minimal reactive power and maximizes efficient power consumption.

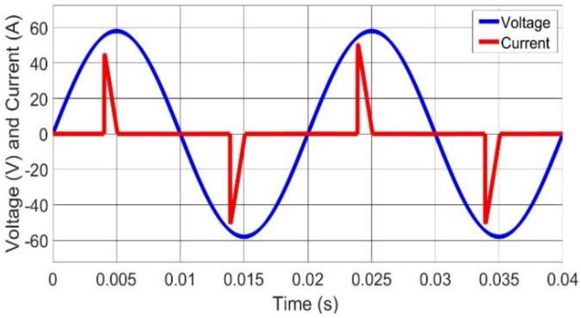

Figure 12. Comparison of supply current waveform and supply voltage waveform (Vs: Is= 1:1/10)

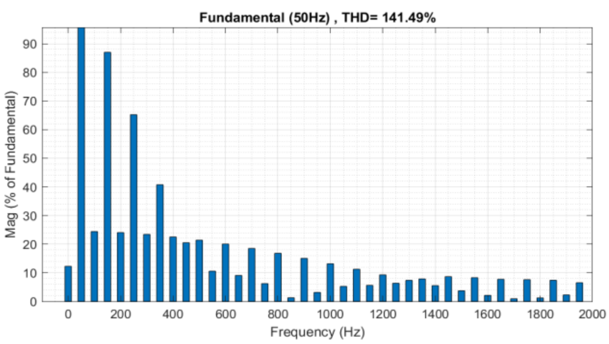

Figure 13. FFT analysis of the supply current waveform without a filter

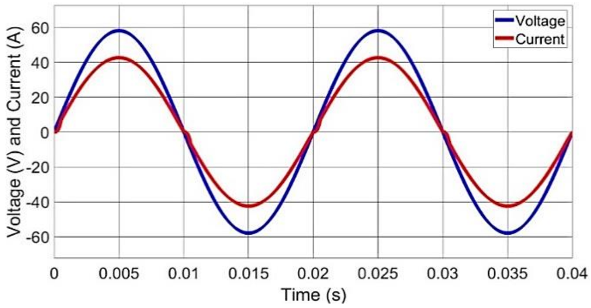

Figure 14. Supply current in phase with supply voltage waveforms (Vs: Is =1:1/10)

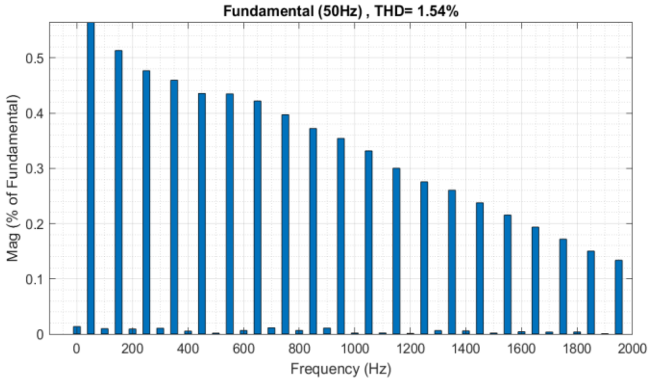

Figure 15. FFT analysis of the supply current waveform with APF

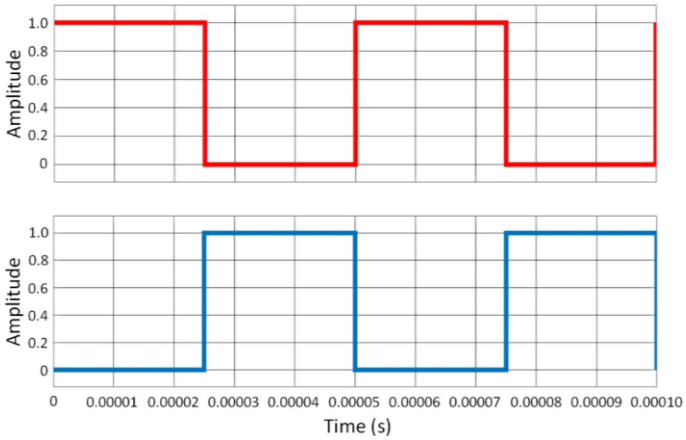

Figure 16. Switching sequence for WPT operation

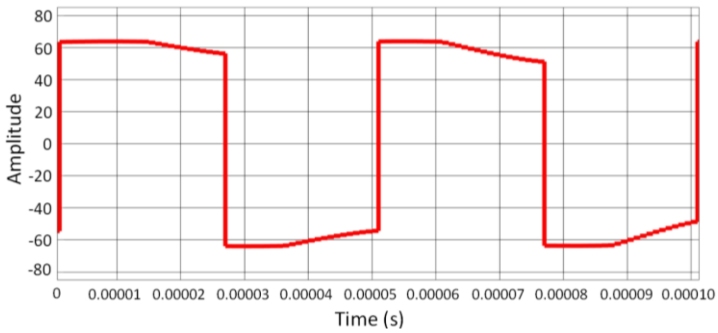

Figure 17. High switching frequency AC waveform at the transmitter coil

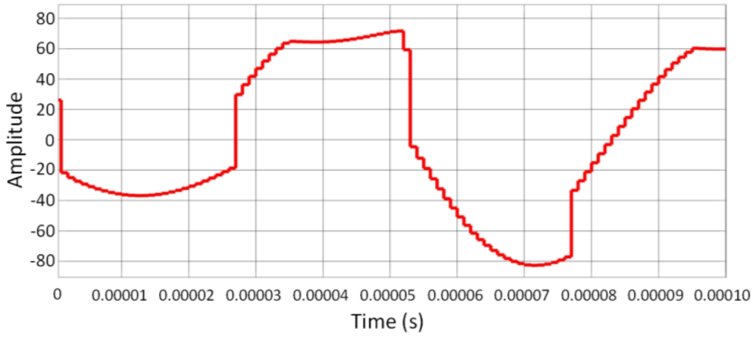

Figure 18. AC waveform at the receiver coil

Time (Min)	Power Factor (PF)	Time (Min)	Power Factor (PF)
0	0	115	0.56
1	0.60	120	0.56
5	0.55	125	0.56
10	0.54	130	0.56
15	0.54	135	0.56
20	0.54	140	0.55
25	0.54	145	0.54
30	0.54	150	0.52
35	0.55	155	0.51
40	0.55	160	0.51
45	0.55	165	0.50
50	0.55	170	0.50
55	0.55	175	0.49
60	0.55	180	0.49
65	0.55	185	0.49
70	0.55	190	0.49
75	0.56	195	0.49
80	0.55	200	0.49
85	0.55	205	0.49
90	0.55	210	0.49
95	0.56	215	0.49
100	0.56	220	0.48
105	0.56	225	0.48
110	0.56		

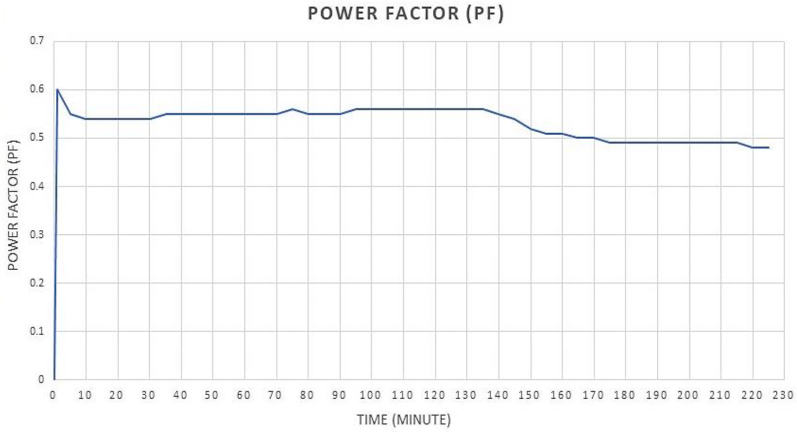

Figure 19. Power factor for wired-connected charger

Time (Min)	Power Factor (PF)	Time (Min)	Power Factor (PF)
0	0	100	0.93
1	0.94	105	0.93
5	0.94	110	0.93
10	0.94	115	0.93
15	0.94	120	0.93
20	0.94	125	0.93
25	0.94	130	0.93
30	0.94	135	0.93
35	0.94	140	0.92
40	0.94	145	0.92
45	0.94	150	0.92
50	0.94	155	0.92
55	0.94	160	0.92
60	0.94	165	0.92
65	0.94	170	0.92
70	0.94	175	0.92
75	0.94	180	0.92
80	0.94	185	0.91
85	0.94	190	0.91
90	0.94	195	0.91
95	0.94	199	0.91

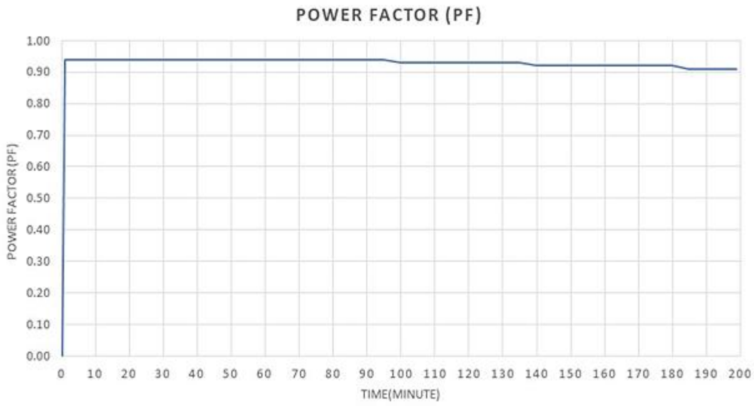

Figure 20. Power factor for wireless charger

7. CONCLUSION

This paper thoroughly investigates the significant role of E-bike battery chargers in ensuring effective and reliable E-bike operation, particularly focusing on addressing power quality issues that could inconvenience users. It highlights the necessity of resolving challenges related to harmonics and supply current for maintaining electrical system stability and efficiency. The study marks wireless battery charging for E-bikes as a notable technological advancement in sustainable transportation systems, aiming to enhance PF for optimal electrical power use, minimal energy wastage, and improved grid efficiency. The findings suggest that advancements in PF significantly boost system efficiency and reduce power consumption. Additionally, the convenience of wireless charging eliminates the need for physical connections, supplemented by stringent safety measures to ensure system reliability and mitigate potential risks. This comprehensive review emphasizes the importance of evolving E-bike battery charging systems, particularly through wireless technology integration, as a key step toward improving sustainability, efficiency, and user experience.

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