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Wireless Power Converters for Autonomous EV Charging and Renewable Energy Hubs

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ABSTRACT

The rapid growth of electric vehicles (EVs) and renewable energy integration has increased the need for advanced charging infrastructure that is reliable, flexible, and user-friendly. Wireless power transfer (WPT) technology has emerged as a promising solution for autonomous EV charging, especially when combined with renewable energy hubs such as solar and wind-based microgrids. Wireless power converters play a central role in enabling efficient energy transfer without physical connectors, improving safety, reducing maintenance, and supporting autonomous operation. This paper presents a comprehensive review of wireless power converter topologies, operating principles, control strategies, and system architectures for EV charging and renewable energy hubs. Both stationary and dynamic wireless charging methods are discussed, along with resonant converter designs and high-frequency power electronics used in WPT systems. Challenges related to efficiency, misalignment, electromagnetic compatibility, and grid integration are analyzed. Recent research trends and practical deployment issues are also highlighted. The study concludes that wireless power converters, when integrated with renewable energy hubs, can significantly enhance the sustainability and autonomy of future EV charging networks.

KEYWORDS: - *Wireless power transfer, Electric vehicle charging, resonant converters, Autonomous charging, Renewable energy hubs, Power electronics*

INTRODUCTION

The electrification of transportation is considered one of the key pathways to reduce greenhouse gas emissions and dependence on fossil fuels. Electric vehicles (EVs) are increasingly adopted for personal transportation, public transit, and industrial logistics. However, widespread EV deployment strongly depends on the availability of reliable and convenient charging infrastructure. Conventional plug-in charging systems involve mechanical connectors that are prone to wear, environmental exposure, and user handling issues. These limitations become more significant in autonomous vehicles and unmanned charging stations. Wireless power transfer (WPT) has gained attention as an alternative EV charging method that eliminates physical contact between the power source and the vehicle. By using electromagnetic coupling, electrical energy can be transferred across an air gap, improving safety and enabling automated charging without human intervention. This feature is particularly useful for autonomous EVs, robotic vehicles, and public charging systems.

In parallel, renewable energy hubs such as solar photovoltaic (PV) plants, wind farms, and hybrid microgrids are increasingly used to supply clean energy to EV charging stations. Integrating wireless charging systems with renewable energy hubs introduces new technical challenges related to power conversion, control, and system coordination. Wireless power converters serve as the backbone of such systems, enabling high-frequency energy conversion, impedance matching, and efficient power delivery.

This paper reviews the role of wireless power converters in autonomous EV charging systems and renewable energy hubs. The focus is on converter topologies, system architectures, control strategies, and practical challenges.

FUNDAMENTALS OF WIRELESS POWER TRANSFER FOR EV CHARGING

Wireless power transfer (WPT) technology enables the transmission of electrical energy from a source to a load without the need for physical electrical contacts. In electric vehicle (EV) charging applications, this is achieved mainly through electromagnetic field coupling between a primary coil installed on the ground side and a secondary coil mounted underneath the vehicle. The absence of mechanical connectors reduces wear, exposure to environmental conditions, and risks related to sparks or electric shock, making WPT especially attractive for autonomous and outdoor charging stations.

Depending on the operating frequency range and the dominant coupling mechanism, WPT systems used for EV charging can be broadly classified into inductive, resonant inductive, capacitive, and microwave-based systems. Among these, inductive and resonant inductive methods are the most widely researched and practically implemented due to their higher efficiency and better safety characteristics at medium power levels. Capacitive and microwave-based systems are still largely in experimental or niche application stages, mainly due to challenges related to power density, electromagnetic interference, and regulatory constraints.

1. Inductive and Resonant Inductive Coupling

Inductive power transfer is based on the principle of magnetic induction, similar to that of a conventional transformer but with a relatively large air gap between the primary and secondary coils. When an alternating current flows through the primary coil, it generates a time-varying magnetic field that induces a voltage in the secondary coil according to Faraday's law of electromagnetic induction. In EV charging applications, the air gap typically ranges from 100 mm to 300 mm, which is significantly larger than in traditional transformers.

Due to this large air gap and possible lateral or angular misalignment between coils, the magnetic coupling coefficient is usually low. As a result, inductive power transfer systems operating at low frequencies often suffer from reduced efficiency and limited power transfer capability. To compensate for weak coupling, higher currents are required in the primary coil, which increases conduction losses and thermal stress in the power converter and magnetic components.

Resonant inductive coupling addresses these limitations by introducing resonant compensation networks on both the primary and secondary sides. By adding capacitors to form resonant circuits, the system is tuned to operate at a specific resonant frequency, typically in the range of 20–100 kHz for EV charging applications. At resonance, the reactive components cancel each other, resulting in higher circulating currents and improved power transfer efficiency even under weak coupling conditions.

One of the key advantages of resonant inductive coupling is its improved tolerance to coil misalignment and variations in air gap distance. This characteristic is particularly important for autonomous EV charging, where precise vehicle positioning may not always be guaranteed.

Resonant WPT systems can maintain acceptable efficiency over a wider range of operating conditions compared to non-resonant inductive systems.

Wireless power converters play a critical role in resonant WPT systems. On the primary side, high-frequency inverters generate the required alternating excitation for the transmitting coil. On the secondary side, rectifiers and DC–DC converters condition the received high-frequency power into a stable DC voltage suitable for battery charging. Proper design of these converters is essential to achieve soft-switching operation, reduce losses, and ensure reliable performance.

2. System Power Levels and Standards

Wireless EV charging systems are typically classified based on their rated power levels, which directly influence converter design, coil dimensions, and thermal management requirements. Low-power systems, usually rated around 3.3 kW, are suitable for light-duty vehicles and overnight residential charging. These systems prioritize simplicity and cost-effectiveness, often using single-phase grid input and relatively compact power electronics.

Medium-power wireless charging systems, in the range of 7 to 11 kW, are commonly targeted for public and workplace charging infrastructure. At these power levels, efficiency, electromagnetic compatibility, and thermal performance become more critical. Resonant full-bridge inverter topologies and advanced control techniques are often employed to meet performance requirements.

High-power wireless charging systems, typically above 20 kW, are intended for fast charging applications such as commercial fleets, buses, and autonomous taxis. These systems demand robust converter designs capable of handling high currents and voltages while maintaining high efficiency. Multi-level inverters, wide bandgap semiconductor devices, and advanced cooling methods are increasingly used in such applications.

To ensure interoperability, safety, and regulatory compliance, international standards have been developed for wireless EV charging. The SAE J2954 standard specifies operating frequency bands, power classes, alignment tolerances, and electromagnetic field limits for light-duty EVs. It also defines communication protocols between the vehicle and the charging station to ensure safe initiation and termination of power transfer.

Wireless power converter design must strictly adhere to these standards while also achieving high efficiency and reliability. This requires careful optimization of switching frequency, resonant components, control algorithms, and protection mechanisms. As wireless charging technology continues to mature, standards are expected to evolve to support higher power levels and broader applications within renewable energy-based charging hubs.

WIRELESS POWER CONVERTER TOPOLOGIES

Wireless power converters form the backbone of EV charging systems, enabling efficient energy transfer from a power source—either the electrical grid or renewable energy hub—to the vehicle battery. Their primary function is twofold: on the primary (transmitting) side, they convert DC power into high-frequency AC suitable for wireless transmission; on the secondary (receiving) side, they rectify the received AC and regulate it to the desired DC voltage for battery charging. Proper selection and design of these converters directly influence system efficiency, thermal performance, and overall reliability.

PRIMARY-SIDE CONVERTER TOPOLOGIES

The primary-side converter, often called the inverter stage, drives the transmitting coil with high-frequency AC. Operating frequencies usually range from 20 kHz to 100 kHz in resonant WPT systems for EVs, although some research explores frequencies up to 200 kHz to reduce magnetic component size. The most commonly used primary-side topologies include:

1. Full-Bridge Inverter

A full-bridge inverter consists of four switching devices arranged in an H-bridge configuration. By alternating the conduction of diagonal switches, a bipolar high-frequency voltage waveform is applied to the primary coil. Full-bridge inverters are widely preferred in medium- to high-power EV charging applications due to several advantages:

- **Maximum utilization of DC bus voltage**, which allows higher output power for the same input voltage.
- **Lower current stress on individual switches**, reducing conduction losses and thermal load.
- Compatibility with **resonant circuits** for soft-switching, minimizing switching losses.

Full-bridge designs can easily be adapted for bidirectional operation, enabling advance applications like vehicle-to-grid (V2G) energy flow.

2. Half-Bridge Inverter

Half-bridge inverters use only two active switches and two capacitors to generate a high-frequency AC output. They are simpler and less costly than full-bridge designs, making them suitable for low- to medium-power applications (typically up to 7–10 kW). However, they have certain limitations:

- **Reduced voltage swing** across the primary coil compared to a full-bridge inverter.
- Higher current stress on switches, potentially requiring more robust devices.

Half-bridge inverters are commonly used in residential EV charging pads or light-duty vehicles.

3. Push-Pull Converter

Push-pull converters employ a center-tapped transformer and two switches to alternate current through the primary winding. While compact and cost-effective, push-pull converters are generally limited to medium-power applications due to uneven transformer utilization and higher core losses at high frequencies. They are occasionally used in experimental WPT setups or low-cost urban EV charging solutions.

2. Secondary-Side Converter Topologies

The secondary-side converter processes the high-frequency AC received by the vehicle coil and delivers regulated DC power to the battery. Depending on system requirements, different topologies are used:

1. Diode Bridge Rectifier with DC–DC Converter

The simplest and most widely used approach is a diode bridge rectifier followed by a DC–DC converter (buck, boost, or buck-boost).

- **Diode Bridge Rectifier:** Converts AC from the receiving coil to unregulated DC.
- **DC–DC Converter:** Adjusts voltage to match battery requirements and ensures stable charging current.

This topology is reliable and relatively low-cost, though efficiency may be slightly lower due to diode conduction losses, especially at higher power levels.

2. Synchronous Rectifier

Synchronous rectifiers replace diodes with actively controlled switches (typically MOSFETs). This reduces conduction losses significantly, especially at high currents, and improves overall efficiency of the secondary-side converter. Synchronous rectification is particularly beneficial for high-power wireless charging systems (>20 kW).

3. Isolated DC–DC Converters

Isolated DC–DC converters, such as full-bridge or half-bridge isolated topologies, provide galvanic isolation between the high-voltage vehicle battery and the high-frequency AC input. Isolation enhances safety and allows voltage adaptation to different battery chemistries or architectures. These converters are essential for V2G-enabled vehicles or renewable energy hubs supplying multiple EVs with varying voltage requirements.

4. Bidirectional Converters

Bidirectional converters enable energy flow in both directions: from the charging pad to the vehicle battery (normal charging) and from the vehicle battery back to the grid or renewable hub (V2G or vehicle-to-hub operation). Bidirectional operation requires carefully coordinated control algorithms to ensure safety, prevent overvoltage, and maintain stable communication between the vehicle and charging infrastructure.

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Table 1: Comparison of Wireless Power Converter Topologies

Converter Type	Power Capability	Efficiency	Complexity	Typical Application
Half-Bridge Resonant	Low–Medium	Moderate	Low	Small EVs, scooters
Full-Bridge Resonant	Medium–High	High	Medium	Passenger EVs
Multi-Level Inverter	High	Very High	High	Fast wireless charging
Bidirectional DC–DC	Medium	High	High	V2G-enabled systems

RESONANT CONVERTER DESIGN FOR WIRELESS CHARGING

Resonant converters are essential in WPT systems because they enable soft switching, reduced losses, and improved efficiency.

1. Series–Series and Series–Parallel Compensation

Different compensation topologies are used to tune the primary and secondary coils. The most common are:

- Series–Series (SS)
- Series–Parallel (SP)
- Parallel–Series (PS)
- Parallel–Parallel (PP)

Series–Series compensation is widely used due to its simplicity and constant current characteristics. It also provides good performance under varying load conditions.

2. Soft-Switching Operation

By operating at or near resonance, resonant converters achieve zero-voltage switching (ZVS) or zero-current switching (ZCS). This significantly reduces switching losses and electromagnetic interference, making the system suitable for high-power EV charging.

AUTONOMOUS EV CHARGING USING WIRELESS POWER CONVERTERS

Autonomous EV charging refers to charging systems that require minimal or no human intervention. Wireless power converters enable this by removing physical connectors and enabling automatic alignment and power transfer.

1. Stationary Autonomous Charging

In stationary charging, the EV parks over a ground-mounted charging pad. Sensors and control algorithms ensure proper alignment before power transfer begins. Wireless converters adjust frequency and power levels based on coupling conditions.

2. Dynamic Wireless Charging

Dynamic charging allows EVs to charge while in motion, using embedded coils in roads. This concept reduces battery size requirements and range anxiety. However, it requires complex converter coordination and grid-side power management.

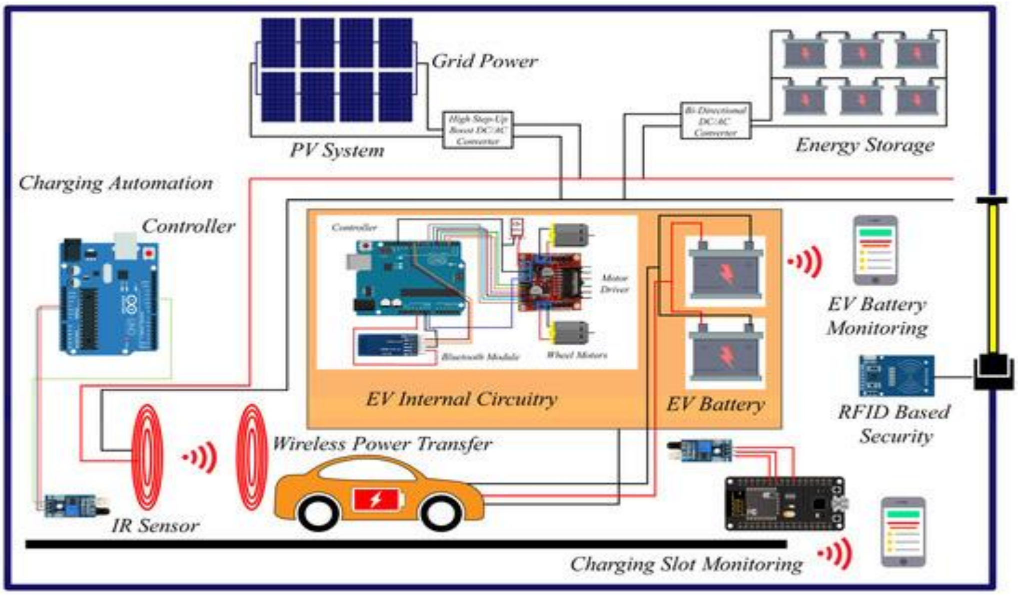

Figure 1: Block Diagram of Wireless EV Charging Integrated with Renewable Hub

INTEGRATION WITH RENEWABLE ENERGY HUBS

Renewable energy hubs combine multiple distributed energy resources, storage systems, and loads. Wireless EV charging can be effectively integrated into such hubs.

1. Role of DC Microgrids

DC microgrids are well suited for wireless charging integration because they eliminate unnecessary AC–DC conversions. Renewable sources like PV naturally produce DC power, which can directly feed wireless inverters.

2. Energy Management Strategies

Energy management systems (EMS) coordinate power flow between renewable sources, storage, grid, and EV chargers. Wireless power converters must respond dynamically to changing power availability and EV demand.

CONTROL STRATEGIES FOR WIRELESS POWER CONVERTERS

Advanced control techniques are required to ensure stable and efficient wireless power transfer.

1. Frequency and Phase Control

Power transfer in resonant WPT systems is often controlled by varying switching frequency or phase shift. Frequency control is simple but may reduce efficiency under misalignment.

2. Model Predictive and Adaptive Control

Model predictive control (MPC) allows the converter to anticipate changes in load or coupling and adjust switching parameters accordingly. Adaptive control compensates for coil misalignment and parameter variation due to temperature or aging.

CHALLENGES AND PRACTICAL LIMITATIONS

Despite significant progress, several challenges remain in wireless power converters for EV charging.

- Reduced efficiency under misalignment conditions
- High cost of power electronics and magnetic components
- Electromagnetic interference and safety concerns
- Limited standardization across manufacturers

Thermal management is also critical, especially for high-power converters operating continuously in outdoor environments.

RECENT RESEARCH TRENDS AND FUTURE DIRECTIONS

Recent studies focus on high-power density converters, wide bandgap semiconductor devices (SiC and GaN), and AI-based control techniques. Integration of wireless charging with smart grids and renewable hubs is also an active research area.

Future systems are expected to support bidirectional power flow, dynamic pricing, and seamless integration with autonomous transportation networks.

CONCLUSION

Wireless power converters play a vital role in enabling autonomous EV charging and its integration with renewable energy hubs. By eliminating physical connectors, wireless charging improves safety, reliability, and user convenience, particularly for autonomous and unmanned systems. Resonant converter topologies and high-frequency power electronics are key enablers of efficient wireless power transfer. Although challenges related to efficiency, cost, and standardization remain, ongoing advancements in power semiconductor devices, control strategies, and system integration are expected to accelerate adoption. The combination of wireless charging and renewable energy hubs represents a promising pathway toward sustainable and intelligent transportation infrastructure.

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