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Wireless Power Transfer Technologies for Electric Vehicle Charging: A Review

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Abstract

Wireless power transfer (WPT) offers a contactless method of charging electric vehicles (EVs) by transferring energy across an air gap between a ground-side transmitter and a vehicle-mounted receiver. The technology has attracted attention because it can simplify charging, support automated operation, and reduce dependence on exposed electrical connectors. This review examines the operating principles, system components, charging configurations, and practical challenges associated with wireless EV charging. Particular attention is given to inductive and resonant inductive power transfer, magnetic coupler design, compensation networks, power electronic converters, and static and dynamic charging applications. The review also discusses efficiency, electromagnetic safety, interoperability, cost, and integration with renewable energy and smart grids. Although laboratory and demonstration systems have shown the technical feasibility of wireless charging, performance depends on factors such as coil alignment, air-gap distance, load conditions, and system design. Wider deployment will require reliable operation, common standards, appropriate safety testing, and favorable economic performance. Future research should focus on improved misalignment tolerance, lower system losses, coordinated grid operation, and practical evaluation of dynamic charging infrastructure.

Keywords

Wireless power transfer, electric vehicle charging, inductive charging, resonant coupling, dynamic wireless charging

INTRODUCTION

The growing use of electric vehicles has increased the need for charging systems that are convenient, reliable, and compatible with different vehicle types and operating environments. Conventional conductive charging uses a physical cable and connector to transfer electricity to the vehicle. Although this approach is established, it requires users or automated equipment to

connect and disconnect the vehicle. In some applications, including public transport, commercial fleets, and autonomous vehicles, a contactless alternative may offer operational advantages.

Wireless power transfer enables electricity to be transmitted without a direct electrical connection between the supply and the vehicle. Most wireless EV charging research focuses on inductive power transfer, in which an alternating magnetic field couples a transmitting coil in or near the ground to a receiving coil mounted on the vehicle. Resonant circuits improve the ability to transfer energy across the air gap and help manage the electrical characteristics of the system [1, 2]. Wireless charging can be used while a vehicle is parked, briefly stopped, or moving along a specially equipped road. Each application has different requirements for power delivery, alignment, control, and infrastructure. This article is a **narrative review** of selected literature and standards; it is not a systematic review or a report of new experimental measurements. chrismi.sdsu.edu

Overview of Wireless Power Transfer Principles

A wireless EV charging system generally includes a grid connection, a power conversion unit, a transmitting coil, a receiving coil, and a vehicle-side converter connected to the battery. Grid electricity is processed by power electronics to produce a high-frequency alternating current in the transmitting coil. This current creates an alternating magnetic field, which induces a voltage in the receiving coil. The induced alternating current is then rectified and controlled to provide power suitable for the vehicle battery. Compensation components, commonly capacitors and sometimes additional inductors, are used to manage reactive power and establish the desired operating characteristics [1, 3]. The amount of power transferred depends on the electrical properties of the coils and the degree of magnetic coupling between them. Coil separation and misalignment can reduce coupling, making control and mechanical positioning important aspects of system design. Wireless transfer therefore requires coordinated electrical, magnetic, thermal, and mechanical engineering.

Inductive and Resonant Inductive Charging

Inductive charging transfers energy through magnetic coupling between two coils. In an EV application, the coils are separated by an air gap that accommodates the vehicle's ground clearance. Unlike a tightly coupled transformer, the charging system must operate efficiently despite a comparatively large separation and possible movement of the vehicle. Resonant inductive charging uses compensation networks to tune the electrical behavior of the coupled coils. Resonance can help support power transfer across a loosely coupled magnetic link, although system efficiency depends on the complete design rather than resonance alone [1, 2]. Resonant inductive charging is the principal approach considered in many EV wireless charging standards and deployment programs. Other approaches, including capacitive power transfer, have also been studied. Capacitive systems transfer energy through an electric field between conductive plates. They offer a different set of design trade-offs, but inductive systems have received greater attention for practical EV charging. Comparisons must consider the full system, including insulation, shielding, power electronics, and safety requirements. Wiley Online Library

Static, Quasi-Dynamic, and Dynamic Charging

Static wireless charging occurs while the vehicle is parked over a charging pad. Suitable locations include homes, office car parks, taxi ranks, and fleet depots. Because the vehicle remains in one position, the system can establish alignment and maintain a relatively stable transfer condition during charging. Quasi-dynamic charging takes place during short, predictable stops, such as at bus stops or taxi waiting areas. It may provide useful additional energy during normal operation, but its effectiveness depends on stopping duration, charging power, and the frequency of stops. Dynamic wireless charging transfers energy while a vehicle travels over transmitter infrastructure installed in the roadway. It could potentially reduce the amount of

energy a vehicle must carry for a given route, especially for vehicles operating repeatedly along the same corridor. However, the potential benefit must be assessed against roadway installation, maintenance, control, metering, and infrastructure costs. Dynamic charging also requires the system to manage rapidly changing alignment between the moving receiver and roadway transmitters [4, 5]. IEEE Xplore

Magnetic Coupler Design and Alignment

The magnetic coupler consists of the transmitting and receiving coil assemblies and their associated magnetic and shielding materials. Common coil geometries include circular, rectangular, and double-D configurations. Each design presents different characteristics in terms of coupling, size, magnetic field distribution, and tolerance to misalignment. Ferrite materials can guide magnetic flux and improve coupling, while shielding can help control unwanted fields and reduce heating in nearby conductive structures. These materials add weight and cost, so their use must be balanced against performance requirements [6]. Alignment is particularly important in parked-vehicle charging. A vehicle positioned away from the intended location may experience lower power transfer or efficiency. Driver guidance, sensors, and automated positioning can help improve alignment. Designers should also consider variation in vehicle ground clearance, parking accuracy, and suspension height. Testing over a range of operating positions is more informative than reporting only the best aligned result. bip.imsi.athenarc.gr

Compensation Networks and Power Electronics

Compensation networks are used on the transmitting side, receiving side, or both sides of the magnetic coupler. Frequently discussed arrangements include series–series, series–parallel, parallel–series, and parallel–parallel compensation. More complex networks, such as LCC arrangements, can provide additional control over current and voltage characteristics. No single topology is best for every application. Selection depends on charging power, changes in battery voltage, coil coupling, component ratings, and the intended control method [3]. For example, a design that performs well at nominal alignment may require additional control or protection when coupling changes. Power electronic converters also affect overall performance. The system commonly includes an inverter to energize the transmitting coil and a rectifier on the vehicle side. Converter losses, switching behavior, thermal management, and component cost all influence the final design. Efficient control must account for changing battery conditions and ensure that power transfer remains stable throughout the charging process.

Charging Efficiency and Energy Losses

Charging efficiency describes the proportion of input energy that reaches a defined output point. In EV applications, researchers may report coil-to-coil, DC-to-DC, or grid-to-battery efficiency. These values are not directly interchangeable because they include different parts of the charging system. Losses occur in the power converters, coil conductors, magnetic materials, shielding, and auxiliary equipment. Efficiency can change with charging power, coil alignment, air gap, temperature, and battery operating conditions. Therefore, a meaningful comparison should state the measurement boundaries and test conditions [2, 3]. The graph below illustrates how overall efficiency affects the grid energy needed to deliver a fixed amount of energy to a battery. It uses a simple calculation rather than measurements from a particular charger.

Safety, Electromagnetic Compatibility, and Standards

Wireless chargers must be designed to address electrical safety, electromagnetic exposure, equipment protection, and interference with other devices. Foreign metallic objects placed near an energized charging pad may heat because of induced currents, making detection and appropriate shutdown mechanisms important. Systems should also consider the presence of people or animals near the charging area. Electromagnetic compatibility testing helps determine whether charging equipment operates appropriately alongside other electrical and electronic

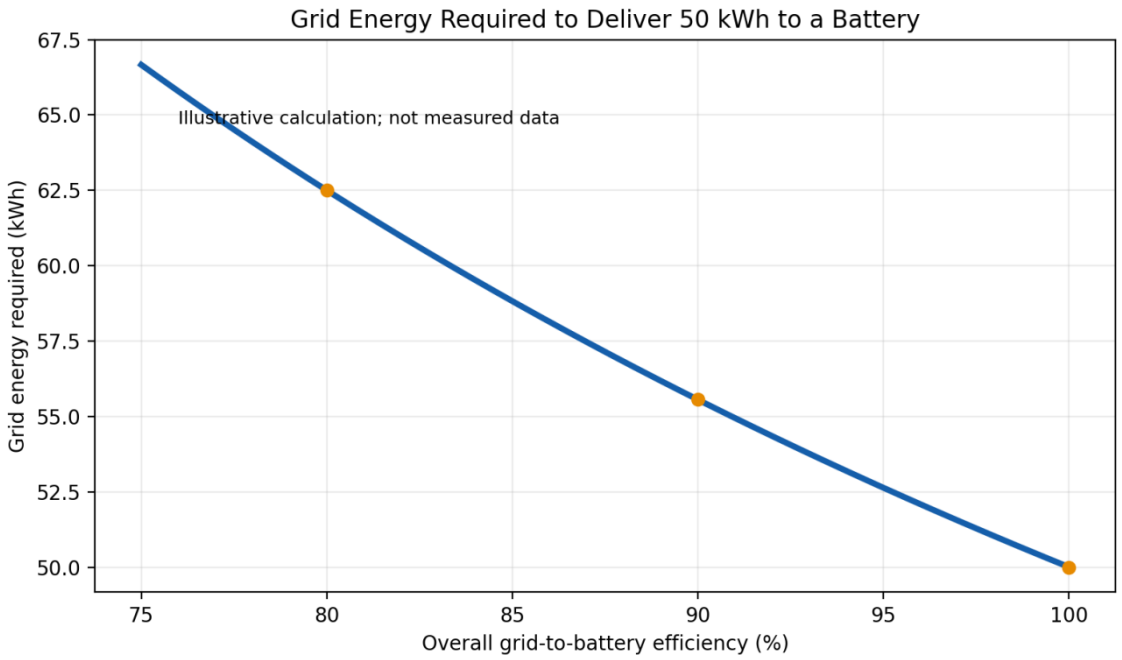
systems. Exposure assessment must be performed using the applicable limits and test methods for the jurisdiction and product. SAE J2954 provides criteria and test methods for wireless charging of light-duty plug-in EVs, including interoperability, electromagnetic compatibility, performance, safety, and alignment. Other relevant international work includes IEC and ISO standards for wireless EV power transfer [7–9]. A manufacturer must verify the applicable edition and complete conformity assessment; mentioning a standard alone does not establish compliance. Technical Standard

Integration with Renewable Energy and Smart Grids

Wireless chargers can be integrated into energy management systems that coordinate charging with electricity demand, renewable generation, and tariff periods. For example, a workplace charging system could schedule charging during periods of strong solar generation, subject to vehicle departure times and available power. Smart charging may also help reduce peak demand by controlling when and how quickly vehicles charge. In a fleet depot, centralized scheduling can distribute available power among several vehicles according to their required departure times and state of charge. Bidirectional wireless power transfer is a research area in which energy could potentially flow between a vehicle and an external electrical system. However, bidirectional operation requires suitable converters, communication, battery management, and applicable standards. The 2022 edition of SAE J2954 addresses unidirectional charging; it should not be treated as proof that a system supports wireless vehicle-to-grid operation [7]. The environmental benefit of wireless charging depends on the electricity source, charging efficiency, equipment manufacture, and actual usage. A full life-cycle assessment is therefore needed when comparing it with conductive charging.

Challenges and Future Research Directions

The principal challenge for wireless charging is achieving an attractive balance among convenience, efficiency, cost, and compatibility. Additional ground and vehicle components can increase system cost and vehicle weight. Performance may also decline under unfavorable alignment or when a charger operates away from its design conditions. Future research should investigate magnetic couplers that maintain acceptable performance across a wider range of parking positions and vehicle heights. Improved control systems could adjust to changing coupling and battery requirements while maintaining safe temperatures and electromagnetic performance. Dynamic charging requires further evaluation under realistic traffic, weather, and roadway conditions. Research should address infrastructure reliability, road maintenance, payment and metering, grid connection, and the distribution of costs among vehicle owners and infrastructure operators. Comparative studies should report consistent system boundaries and include installation and operating costs. Interoperability remains important for public deployment. A charging system is more useful when vehicles and infrastructure from different manufacturers can operate together safely under defined conditions. Independent field trials and transparent performance reporting can help determine where wireless charging provides the greatest practical value.



Summary

Wireless power transfer provides a contactless approach to EV charging and can support convenient and automated operation. Resonant inductive systems are the leading focus for many vehicle applications, with static charging currently presenting a more contained infrastructure challenge than charging vehicles while they are moving. The effectiveness of a wireless charger depends on the magnetic coupler, compensation network, power electronics, control strategy, alignment, and safety mechanisms. Meaningful evaluation requires clearly defined efficiency measurements and consideration of the complete charging system. Continued work on interoperability, cost, safety, and real-world operation will determine the extent to which wireless charging complements conventional conductive charging.

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