World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Review Article)

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Wireless Power Transfer for the Next Generation: Challenges, Opportunities and Applications: A Review

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World Journal of Advanced Engineering Technology and Sciences, 2025, 17(02), 238-251

Publication history: Received on 16 September 2025; revised on 08 November 2025; accepted on 11 November 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.17.2.1478

Abstract

Wireless power transfer (WPT) is moving quickly from theory to reality, thanks to a series of smart design improvements. Innovations like the Resonant Regulating Rectifier (3R), multi-frequency operation, optimized coil designs, impedance matching, and adaptive frequency control now make it possible to deliver power efficiently even when conditions aren't perfect. Whether using capacitive coupling for short distances, magnetic resonance for mid-range, or multi-coil setups for broader coverage, these systems work reliably in many different situations. From tiny medical implants and underwater robots to electric vehicles and high-speed trains, WPT is proving it can power devices both small and large. The strong agreement between lab results and real-world tests shows that these designs aren't just theoretical anymore, they're practical, reliable, and ready to power everyday life. They're compact, efficient, and versatile enough to fit into consumer gadgets, industrial machines, and even transportation systems.

Keywords: Wireless Power Transfer (WPT); Inductive and Capacitive Coupling; Magnetic Resonance; Impedance Matching; Adaptive Frequency Control; Electric Vehicle Charging; Medical Implants; Underwater Power Transfer

1. Introduction

The way we power our world is changing. Concerns about air pollution and the limits of fossil fuels are driving the search for cleaner, smarter solutions and wireless power transfer (WPT) is stepping up as a game-changer. Once a niche lab experiment, WPT is now proving it can deliver energy reliably to everything from tiny medical implants to massive trains, without a single plug or cable.

One of the most exciting applications is electric cars that recharge while driving, with coils under the road sending power directly to the vehicle, eliminating charging stops, enabling smaller batteries, and saving time. This isn't just an idea on paper: UC Berkeley has shown it works with 60% efficiency over an 8 cm gap, and Korea Advanced Institute of Science and Technology (KAIST's) "Online Electric Vehicle" in South Korea has already delivered 100 kW at 80% efficiency over a much larger 26 cm gap. In fact, OLEV is already running in Seoul Grand Park, with more pilot projects underway.

The same core technology is also powering phones, home electronics, robots, and even underwater drones. Engineers are constantly finding ways to make it better, using smarter coil designs, multiple operating frequencies, intermediate resonators, and adaptive tuning so efficiency stays high even when things aren't perfectly lined up. Some EV prototypes using these techniques have hit up to 95% efficiency in real-world conditions.

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A practical WPT system was developed using a large rectangular transmitter coil and a smaller square receiver coil with a parasitic helical element. By combining detailed computer simulations with real-world testing, the design was fine-tuned, with performance evaluated under different loads, coil positions, and environmental conditions. The results show it can deliver stable, high-efficiency power in real-life scenarios, especially for EVs charging on the move.

2. Resonant rectifiers and circuit design

Advances in wireless power transfer (WPT) are coming together in a compact, highly efficient system that blends several clever design ideas. At its core is the Resonant Regulating Rectifier (3R) a small but capable circuit tuned for 6.78 MHz operation, delivering up to 6 W of power without the need for extra bulky parts. Instead of adding more hardware, it cleverly reuses the inductance already present in the system's coils to control voltage. It can operate in both Continuous and Discontinuous Conduction Modes as shown in fig.1, reaching efficiencies as high as 86%, while its 0.35 µm BCD chip design and intelligent switching approach keep components cool and under less stress [1].

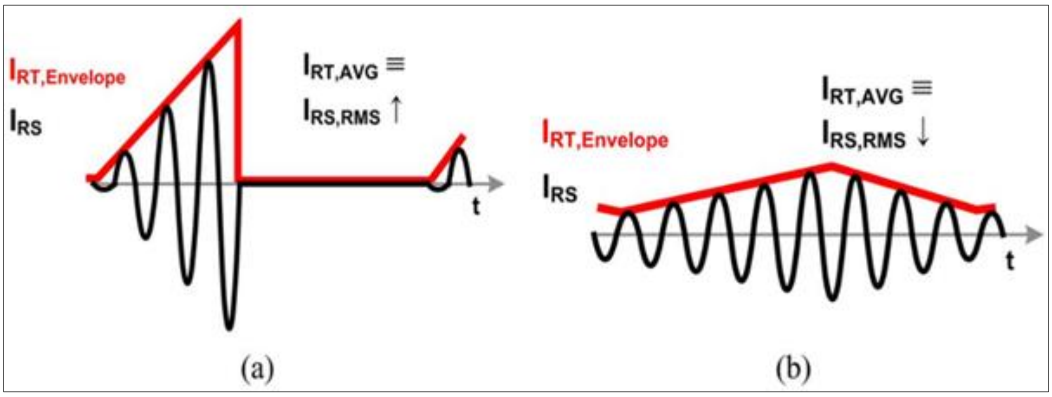


Figure 1 Current control mechanisms in (a) the Discontinuous Conduction Mode (DCM) (b) Continuous Conduction Mode (CCM) [1].

An improved three-switch version as shown in fig.2, takes these benefits further handling more power, reducing heat losses, and keeping voltage steady even as loads change. It performs reliably at the challenging high frequency of 6.78 MHz, where many designs struggle due to parasitic effects.

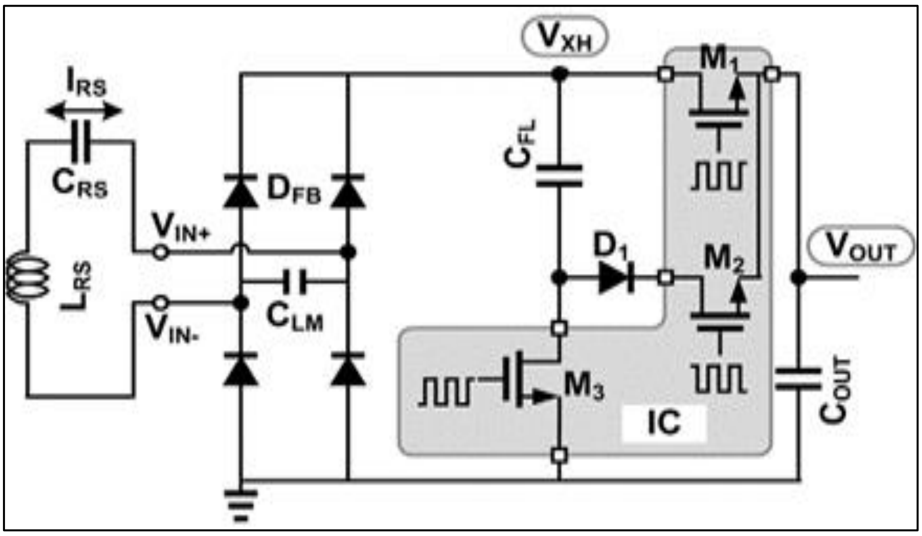


Figure 2 The proposed three-switch 3R [1]

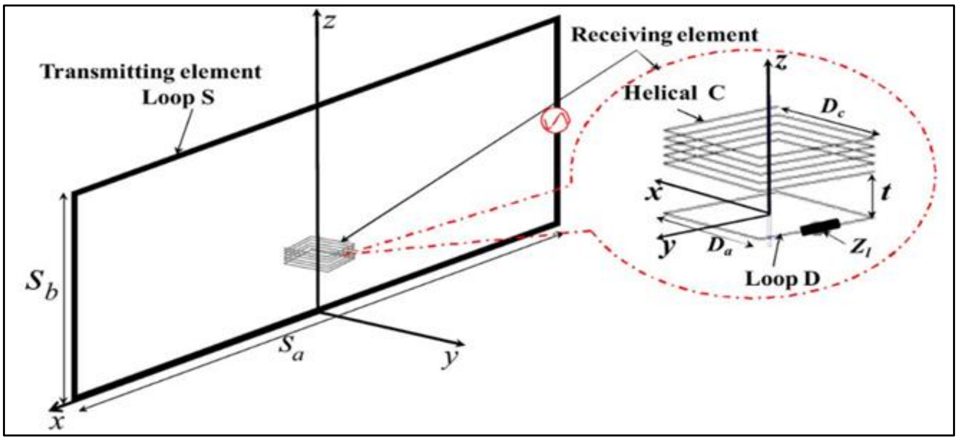
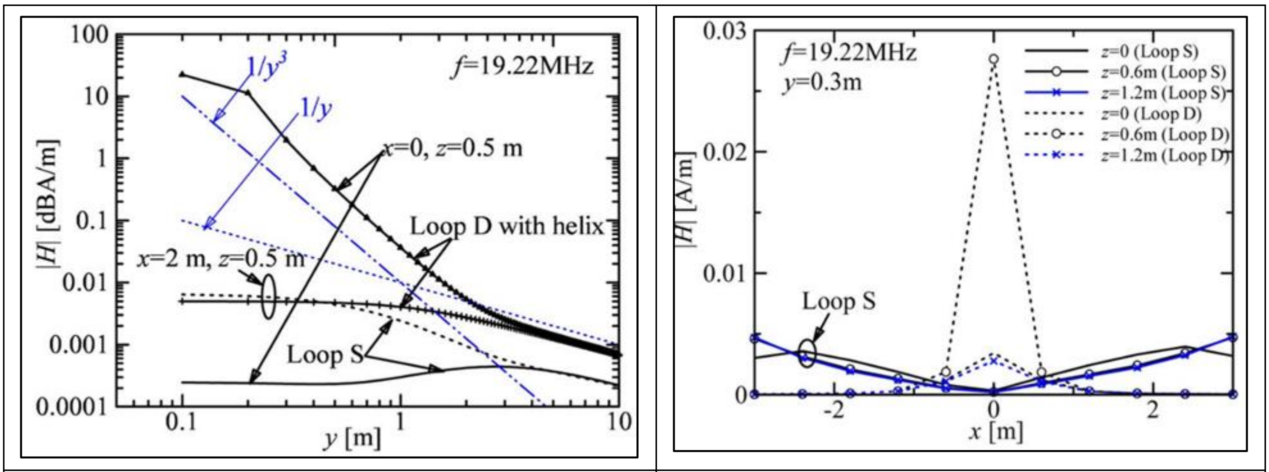


Figure 3 A schematic model of WPT system [2]



A	B

Figure 4 Magnetic field distribution along lines which are (a) parallel to y axis, (b) parallel to x axis [2]

To expand the charging area, the design incorporates a two-dimensional resonator array that creates a broad, evenly powered surface. Devices can be placed almost anywhere within this zone and still charge efficiently [2]. Careful placement and tuning of the resonators eliminate the short range and uneven coverage typical of single-resonator systems.

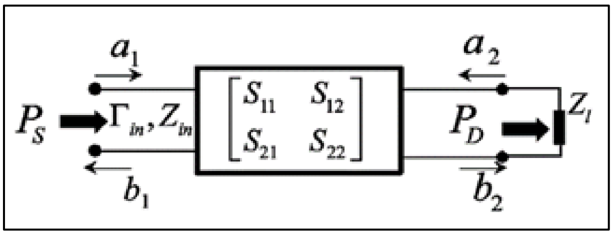


Figure 5 Power transmission efficiency versus receiving location [2]

Performance is further enhanced by fine-tuning the way the transmitter and receiver coils interact. Adjusting coil shape, alignment, and spacing significantly improves efficiency especially for mid-range charging and keeps performance stable across varying distances [3]. The close match between simulations and real-world results shows the approach is practical and ready for deployment.

Together, these elements create a wireless charging system that is compact, efficient, flexible, and capable of reliably powering multiple devices in both day-to-day life and industrial settings.

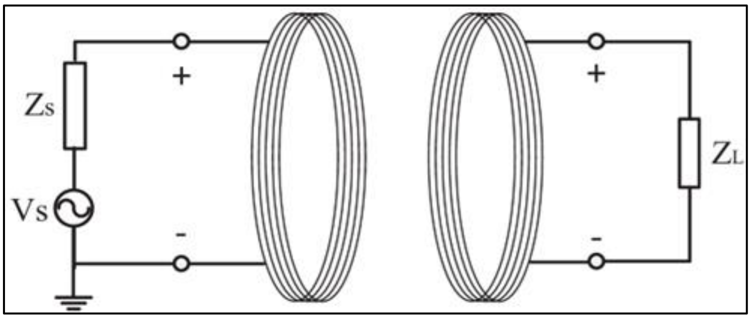


Figure 6 A simplified system configuration of a wireless power transfer system [3]

Together, these elements create a wireless charging system that is compact, efficient, flexible, and capable of reliably powering multiple devices in both day-to-day life and industrial settings.

Table 1 PARAMETERS OF THE TWO RESONANCE COILS

Coil diameter	**320 mm**
Coils gap	150 mm
Resonant frequency	13.56 MHz
Inductance *L*	7.8 µH
Capacitance *C*	17.6 pF
Internal resistance *R*	3.4 Ω
Mutual Inductance L_m	0.7 µH

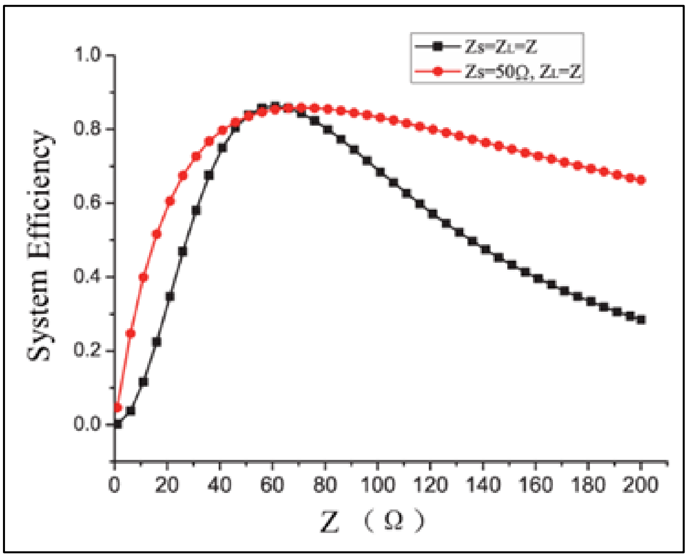


Figure 7 System efficiency with variable source impedance (black) and fixed source impedance (red) [3]

3. Frequency and resonance analysis

WPT is no longer limited to gadgets on a desk it's now being designed to power devices deep inside the human body. Using inductive coupling, energy can be sent safely through tissue, with coil shapes and operating frequencies carefully tuned so the system runs efficiently without crossing any safety limits. Tests and simulations both show it can deliver steady power at the needed depth, making it a realistic and safe option for medical implants [4].

Digging deeper into how these systems work reveals an interesting effect in resonant WPT called frequency splitting. In a two-coil setup, when the coils are very close, voltage and power don't peak at a single frequency instead, they form two peaks, one slightly above and one slightly below the natural resonance. Efficiency, however, behaves differently, staying highest exactly at resonance. The math and the lab results agree, clearing up confusion and helping designers choose the right operating point [5].

The same design principles can be applied outside the medical field. For example, one indoor WPT setup uses a large rectangular transmitter loop paired with a small square receiver loop and a parasitic helical coil. By testing different load resistances, receiver positions, and even the effect of nearby objects like people or metal boxes, the system was fine-tuned for real-world conditions. With a load of around 1–2 Ω, it can hit close to 50% efficiency over most of its range, and obstacles cause only small drops if they're more than half a meter away. Matching coil dimensions to align their resonant frequencies boosts performance, and adding conductor losses to the simulations makes the predictions line up almost perfectly with actual results [6].

All of this reinforces the earlier ideas about optimizing coils, tuning resonators, and controlling frequency. Whether it's delivering power to life-saving implants or wirelessly running devices across a room, WPT can be shaped to meet the needs of each application while staying efficient, safe, and practical.

4. System performance optimization in wireless power transfer

4.1. Multi-Load, Multi-Receiver and Selective WPT

WPT is moving beyond small electronics and into larger, more demanding applications like charging EVs and powering several devices at once. For EVs, a key challenge is keeping efficiency high when the transmitter and receiver coils aren't perfectly aligned. A redesigned coil layout, paired with a clever compensation method, makes it possible to handle both sideways and angled misalignments. That means the system can still deliver steady, efficient power even if a car isn't parked exactly over the charger [7]. Testing and simulations show it consistently outperforms traditional setups, with results matching closely between the lab and the models.

For mid-range charging, combining magnetic resonance coupling with improved coil shapes and finely tuned compensation circuits helps maintain high efficiency even when the spacing between coils changes as shown in fig.8. This flexibility makes it ideal for situations where the transmitter and receiver can't always be placed in a fixed position but reliable performance is still needed [8].

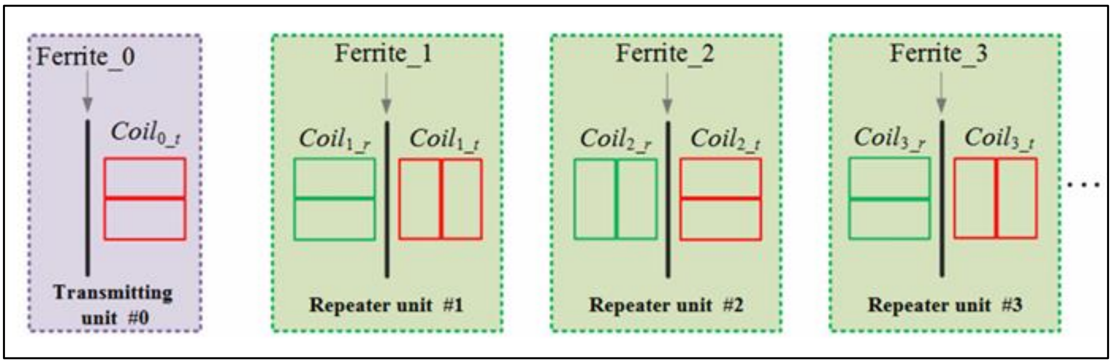


Figure 8 Coil structure of the proposed WPT repeater system [8]

When powering multiple devices, giving each coil both transmitter and receiver its own resonant frequency allows energy to be directed to one specific device just by matching the operating frequency to its resonance as shown in fig.9. This cuts down on interference between devices, and even when two receivers have similar resonances and share a small amount of power, overall performance stays strong [9]. It's a simple yet effective way to deliver targeted power in multi-device systems.

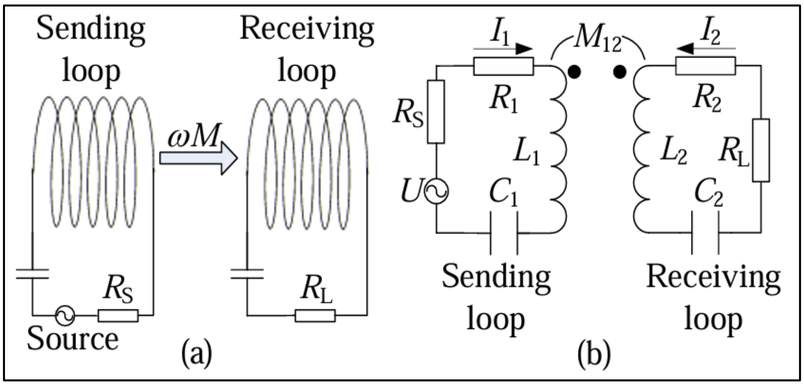


Figure 9 (a) Abstract model and (b) equivalent circuit of two-coil structure [9]

Together, these innovations take WPT beyond fixed, perfectly aligned arrangements, making it versatile enough for EV charging, adaptable for mid-range use, and precise enough to power multiple devices at once all while building on the same core ideas of coil optimization and resonance tuning developed in earlier designs.

4.2. Efficiency Enhancement and Coil Configurations

WPT can get a big performance boost by placing an extra resonant coil between the transmitter and receiver. Tests with both helical and spiral coil designs arranged either in a straight line (coaxial) or at right angles (perpendicular) showed clear gains in both efficiency and range compared to setups without the extra coil. Using temporal coupled mode theory, formulas were worked out to predict performance and find the best impedance match, and real-world tests closely matched those predictions. While coaxial designs achieved the highest efficiency, perpendicular setups are often easier to fit into tight spaces, making them a practical choice for products like wall-mounted electronics or built-in appliances [10].

Another proven way to improve performance is through a “matching condition” based on a simple circuit model, which involves fine-tuning how strongly the source or load connects to the resonator. With this approach, efficiency improved by more than 46% at 60 cm and nearly 30% at 1 meter, with a peak of 92.5% at shorter distances as shown in fig.10. Adding variable coupling adjusting the connection strength based on distance helped maintain high efficiency across a much wider range, making the system far more adaptable in real-world use [11].

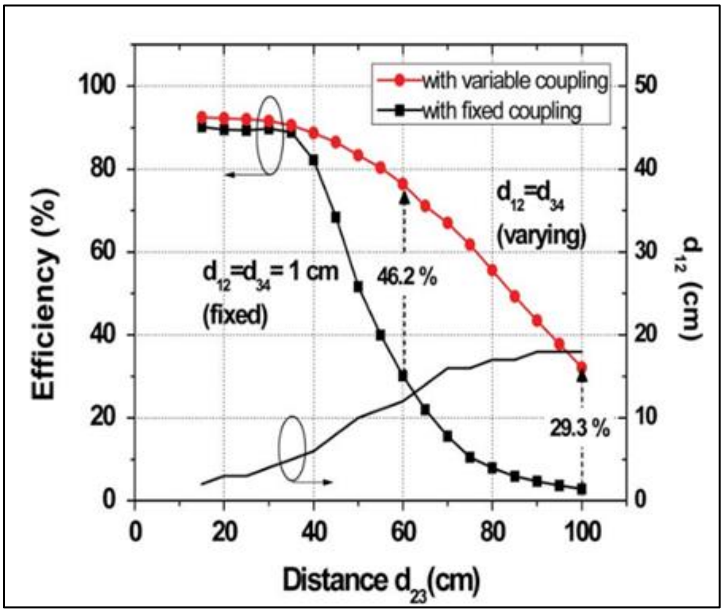


Figure 10 Measured efficiency comparison of the wireless power transfer system with fixed and variable coupling methods [11]

For midrange wireless power, a predictive model that considers coil coupling, coil quality, and resonant frequency proved to be a reliable design guide [12]. By carefully shaping the coils and fine-tuning system settings, performance in tests lined up closely with simulation results, confirming that the approach works just as well outside the lab.

Bringing these ideas together intermediate coils, impedance matching, adjustable coupling, and optimized coil design creates a set of strategies that make magnetic resonance wireless power systems more efficient, flexible, and ready for everyday applications [13].

5. Hybrid systems, communication and special environments.

WPT has steadily moved from lab experiments into dependable, real-world systems by rethinking how coils are built, tuned, and controlled. One promising approach uses multiple coils working together to create a stronger magnetic link between transmitter and receiver while keeping stray electromagnetic fields low. Tests in both simulations and physical prototypes showed that this setup not only delivers more power but also reduces interference compared to traditional designs [14].

Different applications call for different design tricks. For example, autonomous underwater vehicles often rotate during charging, which can disrupt the magnetic link. Using two receiver coils wound in opposite directions and placed at right angles keeps that link steady, as shown in fig.11, holding efficiency above 92% even in the most challenging orientations [15].

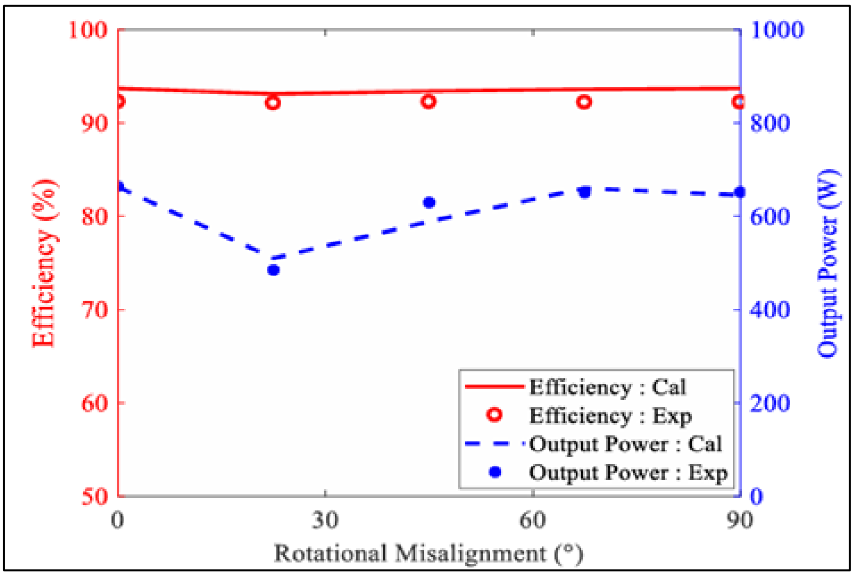


Figure 11 DC-DC efficiency and output power versus rotational misalignments [15]

When coil alignment isn't perfect as is often the case with electric vehicle charging a double-sided LCC compensation design can step in as shown in fig.12 [16]. It provides either a stable current or voltage without complex control systems and maintains high efficiency even when the coils shift or the coupling changes.

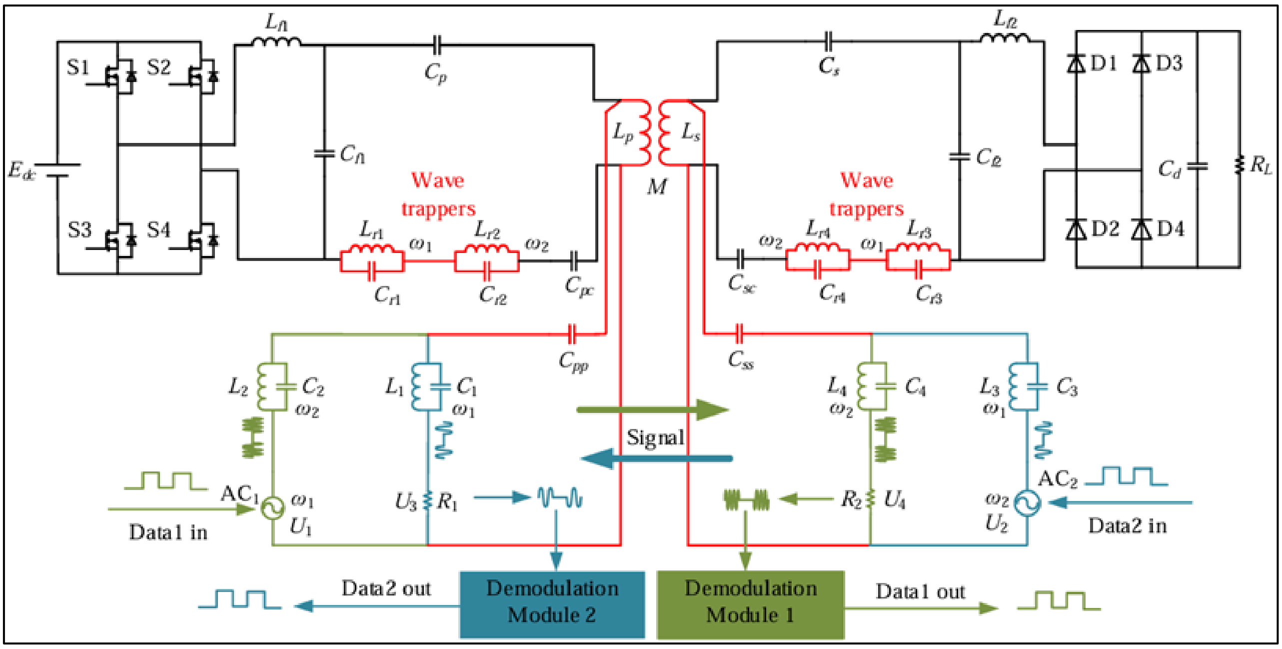


Figure 12 Topology of wireless power transfer with full-duplex communication [16]

Some systems need to do more than just deliver power. In setups where a device must first charge itself before sending data, timing is everything [17]. An adaptive scheduling method can decide in real time how to split time between charging and transmitting, adjusting automatically as network or signal conditions change, which makes it far more efficient than fixed-time approaches.

Dynamic EV charging pushes things even further. By refining coil shapes, tuning circuit parameters, and improving alignment control, engineers have managed to reduce energy losses and keep power delivery smooth even when the coils aren't perfectly lined up. These refinements bring wireless charging on the move closer to everyday use.

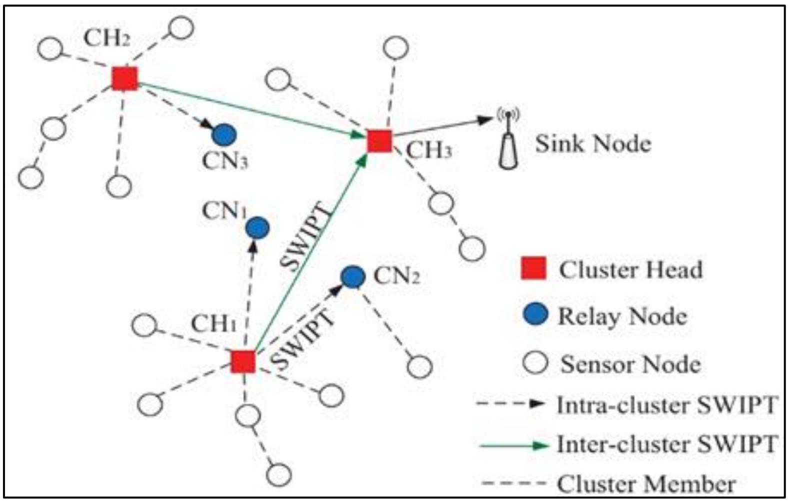


Figure 13 A clustered wireless sensor network with SWIPT consisting of 3 clusters [18]

All of these advances point in the same direction: smart coil engineering, precise tuning, and adaptive control can make wireless power transfer reliable and efficient across a wide range of scenarios from powering underwater robots to keeping EVs topped up on the road, and even running self-powered devices that can send data without ever being plugged in [17][18].

6. Applications

6.1. Electric Vehicle and Transportation

WPT is quickly evolving from a niche lab technology into a practical, everyday solution driven by a wave of clever engineering improvements. One major leap forward comes from a coil design that can operate at two different frequencies, 13.56 MHz and 6.78 MHz, using the exact same hardware. This means a single charging system can adapt to different distances and power needs without swapping out components.[19] Both simulations and hands-on tests showed it could deliver steady, efficient power in either mode, making it far more versatile than traditional setups.

On a much larger scale, engineers have created a 1 MW inductive power transfer system capable of supplying energy to a high-speed train while it's moving completely removing the need for heavy onboard batteries as shown in fig.14. With a resonant inverter, a 128 m transmitter, multiple pickup units, and a wireless feedback loop to keep the voltage stable, it maintained smooth, efficient operation even across a 5 cm air gap. Field trials confirmed it met safety standards and could deliver over 800 kW reliably, pointing to a future where railways could run battery-free [20].

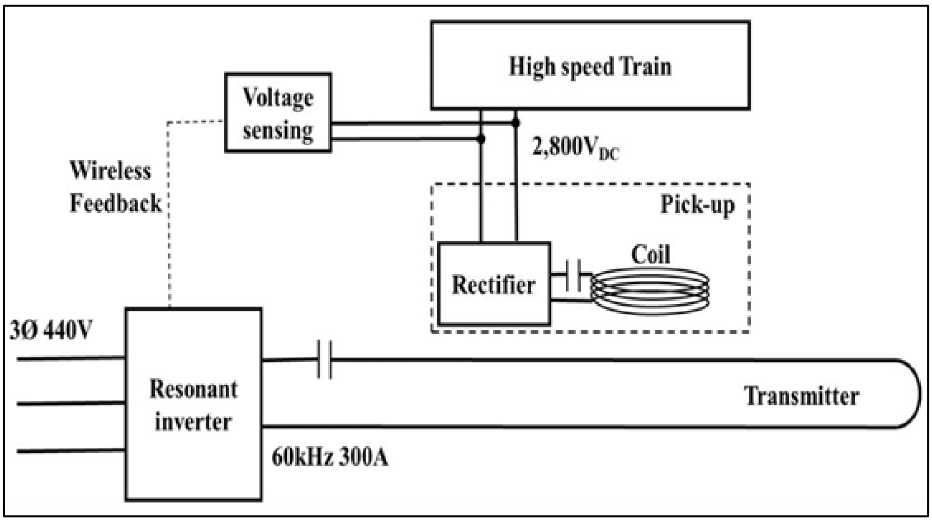


Figure 14 Configuration of the IPT system for a high-speed train [20]

When it comes to sending power over longer distances without losing efficiency, a four-coil magnetic resonance design has proven far more capable than the standard two-coil approach. Detailed modelling and real-world trials confirmed its ability to push power farther while keeping losses low, making it a strong candidate for applications where range is critical.

But efficiency doesn't just depend on hardware it also depends on adapting to real-world changes. A smart frequency-tracking method now allows WPT systems to automatically tune themselves to the optimal operating point, even when coil alignment or spacing changes [21]. In testing, it consistently beat fixed-frequency designs, keeping performance high in situations where movement or misalignment would normally cause big drops in efficiency.

Even large-gap charging often a major challenge has seen a breakthrough. Using a self-resonant pulse-width modulation (SR-PWM) approach, engineers developed an EV charger as shown in fig.15, that holds a steady operating frequency without extra control electronics [22]. A 6.6 kW prototype handled gaps of 12–20 cm with efficiency reaching up to 95%, and it stayed stable even when the coils weren't perfectly aligned.

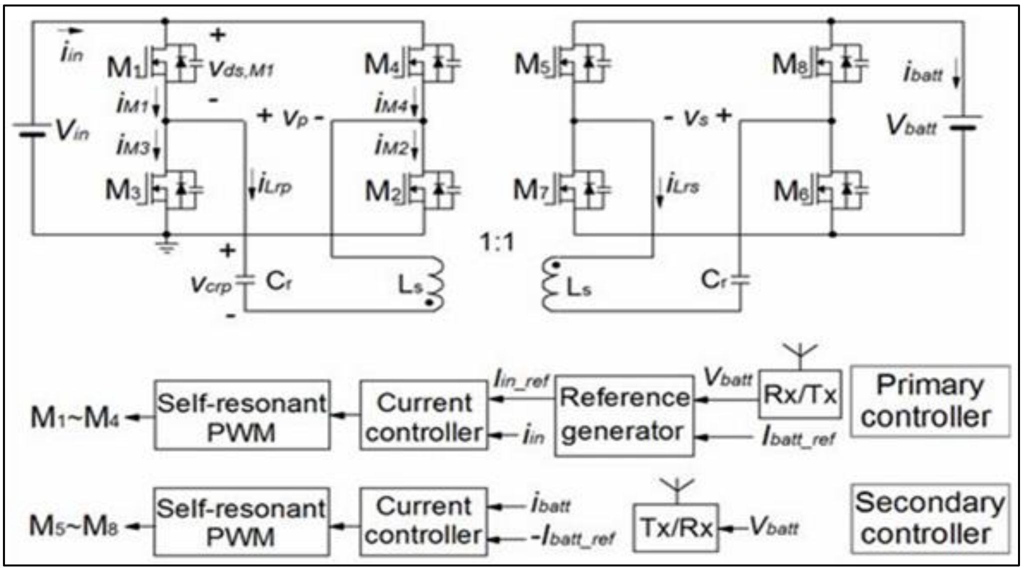


Figure 15 Proposed WPT charger [22]

Together, these innovations multi-frequency coils, megawatt-scale rail charging, extended-range four-coil systems, adaptive frequency tracking, and high-efficiency large-gap chargers paint a clear picture of WPT's future [23]. The technology is becoming not only more powerful and efficient, but also more flexible and resilient, paving the way for a world where everything from smartphones to high-speed trains can be charged seamlessly, without plugs, cables, or interruptions.

6.2. Omnidirectional and Spatial WPT

A WPT system has been purpose-built for underwater environments ideal for situations where running electrical cables would be too risky, too costly, or simply impossible. Instead of relying on metal connectors that can corrode or fail, it uses inductive coupling to send power safely through water, no physical contact needed.

At the core is a finely tuned coil, designed to keep a strong magnetic link even in challenging seawater conditions [24]. It's sealed inside a rugged, corrosion-proof housing that can handle deep-water pressure, constant motion, and even the slow buildup of marine growth. In short, it's built to last where most hardware wouldn't survive.

Extensive lab testing and computer simulations told the same story steady, efficient power delivery, even when coil spacing, alignment, or water temperature changed. And because the real-world results matched the simulations, there's solid proof the design is not just a clever concept, but a field-ready solution.

With this reliability, it opens up new possibilities: powering underwater drones for longer missions, running deep-sea research instruments without constant battery swaps, or keeping ocean monitoring stations online for years at a time. The design can be scaled for both small, low-power devices and large, energy-hungry submersibles, making it as flexible as it is dependable.

6.3. General

Wireless power transfer (WPT) is quickly moving from the lab into the real world, powering everything from tiny wearable gadgets to large industrial machines. One clever approach, capacitive coupling, uses a Class-E power amplifier with precisely tuned plates to send power across small gaps. This setup keeps energy loss low, delivers stable output, and stays efficient even when the load changes perfect for compact electronics, medical devices, and sensors where wires simply won't do. Lab tests and simulations lined up closely, proving the system works exactly as intended.

For situations that require more distance, magnetic resonance offers a reliable solution. By carefully shaping the coils and matching impedance, mid-range WPT systems can transfer power efficiently over longer gaps. Even when distances or loads shift, these systems maintain steady performance, making them ideal for autonomous robots, charging stations, and industrial equipment where cables would be cumbersome [25].

To keep efficiency high when things aren't perfectly aligned, adaptive frequency control comes into play. Instead of a fixed frequency, the system constantly "listens" to its environment and adjusts on the fly. That means it keeps delivering power efficiently even when coils move or conditions change something fixed-frequency setups can't match [26].

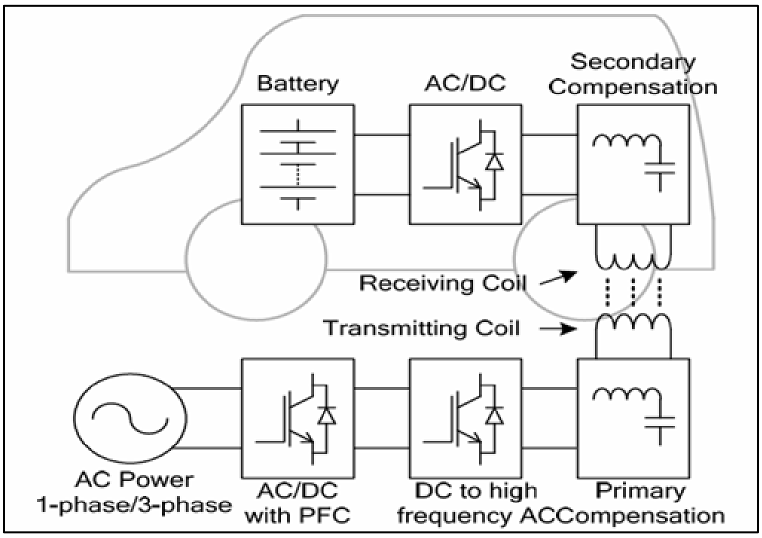


Figure 16 Typical wireless EV charging system [27]

By combining these techniques capacitive coupling for short gaps, magnetic resonance for mid-range distances, and adaptive tuning to handle dynamic conditions WPT becomes versatile, dependable, and practical as shown in fig.16. It can charge electric vehicles without perfect alignment, keep warehouse robots running smoothly, and power remote or hidden sensors. Altogether, it's bringing us closer to a future where electricity flows as freely and seamlessly as Wi-Fi [27].

6.4. Matching and Optimization

WPT has come a long way, evolving from small lab experiments into practical solutions capable of powering everything from compact devices to large industrial systems. For short distances, capacitive coupling with a Class-E amplifier and carefully tuned resonant plates delivers energy efficiently across small gaps. This approach keeps losses low, maintains stable output even when loads fluctuate, and works perfectly for devices like medical implants, smart sensors, and other electronics where wires just aren't practical.

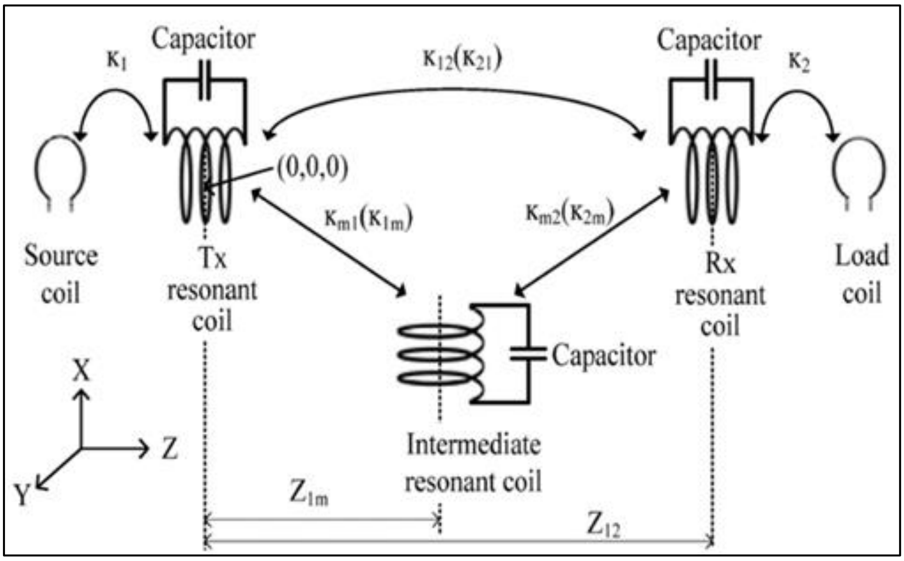


Figure 17 Configuration of a magnetic resonance WPT system with an intermediate resonant coil [28]

For intermediate-distance applications, magnetic resonance provides a reliable way to transfer power as shown in fig.17. By optimizing coil design and carefully matching impedance, these systems maintain consistent performance even as distances or loads change. Adaptive frequency control enhances this further by adjusting the operating frequency in real time, keeping efficiency high even if coils shift or environmental conditions vary. This makes it ideal for applications like charging electric vehicles, keeping industrial robots running smoothly, or powering remote and embedded sensors.

One of the key challenges is maintaining efficiency as the distance between coils changes. Traditional techniques, like simultaneous conjugate matching, achieve great efficiency but are difficult to implement in real-world setups. Fixed-frequency tracking works at close range but loses effectiveness over longer gaps. A smarter solution adjusts the load according to the distance, keeping efficiency high across a wider range. Experiments have shown that this approach works in practice, closely matching theoretical predictions. Careful attention to coil placement and mounting is also important, as these factors can introduce additional energy losses [28].

By combining short-range capacitive coupling, intermediate-distance magnetic resonance, adaptive frequency control, and distance-aware load matching, WPT systems have become flexible, robust, and highly efficient. They can charge electric vehicles without requiring perfect alignment, keep industrial robots running reliably, and power underwater or remote sensors. Together, these innovations are bringing us closer to a future where electricity flows as seamlessly and effortlessly as wireless data, turning the vision of untethered power into a practical reality.

7. Conclusion

WPT has grown into a dependable way to send power without cables, combining efficiency, flexibility, and safety in one package. Careful coil design, smarter compensation methods, automatic frequency tuning, and adaptive control have solved long-standing issues like short range, alignment sensitivity, and interference. These improvements are already powering everything from medical implants to large-scale transport systems while keeping energy losses low. Together, they point toward a future where getting electricity is as easy and seamless as connecting to Wi-Fi. With continued refinement, WPT is set to become a key part of daily life and the backbone of next-generation industrial and transportation infrastructure

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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