AUIQ Technical Engineering Science

Manuscript 1061

A Comprehensive Review of Wireless Charging Technologies: Inductive, Capacitive and Hybrid Power Transfer

Zahraa M.Y. Islam

Yasir M. Y. Ameen

AUIQ TECHNICAL ENGINEERING SCIENCE 2026;3:1–24

REVIEW

A Comprehensive Review of Wireless Charging Technologies: Inductive, Capacitive and Hybrid Power Transfer

Zahraa M.Y. Islam *, **Yasir M. Y. Ameen**

Electrical Engineering Department, College of Engineering, University of Mosul, Mosul, Iraq

ABSTRACT

Wireless power transfer has attracted more and more attention as a potential solution to electric vehicle charging due to its safety, convenience and the potential to automate this process. This review paper gives an overview of inductive and capacitive wireless power transfer technologies, especially focusing on hybrid wireless power transfer systems that integrate both approaches. The basic operating principles in both inductive and capacitive power transfer are covered with an emphasis on their advantages and inherent limitations with respect to efficiency, voltage and current stress, the tolerance of misalignment and the power capability. Building upon this background, the paper is limited to hybrid systems as an effective mechanism for taking advantage of both the advantages of inductive and capacitive coupling and reducing the respective disadvantages. Special attention is paid to compensation networks used in HWPT systems. Different compensation topologies are reviewed and analyzed in terms of the role they play in improving the power transfer capability, improving operating conditions to the favor of the system and improving the system stability. In addition, various losses mechanisms related to the hybrid systems such as copper losses, magnetic losses, dielectric losses, and power electronic losses are analysed in order to check its effect on the overall system efficiency. This review is aimed to give a clear and structured understanding of HWPT systems and to bring out their potential as a possible solution for high-efficiency wireless charging applications, especially in the field of electric vehicle systems.

Keywords: Wireless power transfer (WPT), Inductive power transfer (IPT), Capacitive power transfer (CPT), Hybrid wireless power transfer (HWPT)

1. Introduction

Over the past few decades, the world has been dealing with growing environmental and economic problems, most notably climate changes and global warming which are mainly contributed to the ever increasing levels of greenhouse gas emissions. The transportation sector is one of the biggest contributors of these emissions as it heavily depends on the use of internal combustion engine (ICE) vehicles that are powered by fossil fuels. This dependence has led not only to an increase in emissions of carbon dioxide (CO_2), but also to serious air pollution and to environmental degradation and especially to increasing public health concerns. Consequently, sustainability has become a key global goal which focuses on the minimization of environmental impacts, the improvement of energy efficiency and the conservation of resources to progress in a manner that future generations can meet their mobility and energy demands [1–3].

Within this context, electric vehicles (EVs) have come into prominence as one of the versatile solutions for sustainability and a healthier alternative to the traditional fossil fuel-based transportation systems. Battery electric vehicles in particular have no tailpipe emissions while they are operating, and have an overall reduced environmental footprint if the

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Received 25 January 2026; revised 21 February 2026; accepted 21 February 2026.
Available online 3 April 2026

* Corresponding author.
E-mail addresses: Zahraa.m.y@uomosul.edu.iq (Z. M. Y. Islam), Yasir_752000@uomosul.edu.iq (Y. M. Y. Ameen).

https://doi.org/10.70645/3078-3437.1061

power used for charging is generated from renewable energy sources. As a result, EVs are an important contribution to global efforts towards decarbonization, climate neutrality, and sustainability development. In addition to their environmental benefits, EVs are characterized by the following features: high energy efficiency, low maintenance requirements and better performance compared to ICE vehicles [3, 4]. The adoption of electric vehicles worldwide is rapidly increasing in the recent years, with the number of EVs reaching tens of millions worldwide. Forecasts show that there could be more than 250 million electric vehicles could be in operation in the coming decades. This swift growth has the potential to make a substantial contribution to the reduction of greenhouse gas emissions; however, the widespread success of electric mobility depends not only on developments in vehicle and battery technology, but also on the provision of a reliable, efficient and user-friendly charging infrastructure that can keep pace with the growing power demand [5].

Electric vehicle charging technologies can be roughly grouped by their charging mechanism, either into conductive (wired) charging systems and wireless charging systems. Conductive charging is the most widely deployed charging method at the moment and provides relatively high transfer efficiency of power. However, it is subject to a number of practical and operational disadvantages, including manual plug-in and unplug-out of the device, safety hazards in terms of electrical shock and tripping hazard, mechanical wear of connectors due to the high current stresses, security against vandalism and flexibility in harsh or wet environments. Furthermore, wired charging systems are not suitable for fully automated or dynamic charging applications which limits their use in future smart transportation systems [6, 7].

Wireless power transfer (WPT) technology has emerged as a promising solution to these constraints to be used in EVs charging. Wireless charging does not require physical cables and connectors, which makes wireless charging technology more safe to operate and more convenient for users, as well as supports full automated operation. In addition, WPT systems can be applied in harsh environmental conditions, and are suitable for stationary and dynamic charging applications. These advantages make wireless charging an attractive solution with the continued adoption of electric vehicles continuing to increase throughout the world [8, 9]. Despite its benefits, conventional wireless charging technologies such as inductive power transfer (IPT) and capacitive power transfer (CPT) still suffer from a number of challenges. These include the low power transfer efficiency, the sensitivity to the misalignment of the transmitter and receiver and the limitations in the amount of power that can be transferred and the degradation of performance under real world operating conditions. Solving these problems are very important for the development of a high-power efficient and robust wireless charging systems for electric vehicles [1, 6]. In view of these limitations, lately an advanced wireless charging technique has emerged which is called hybrid wireless power transfer (HWPT) which include inductive and capacitive coupling within a single system. By combining the coils and capacitive plates, HWPT tries to make use of the two complementary strengths of IPT and CPT resulting in higher power transfer efficiency, higher power density, a misalignment of alignment, robustness under various operating conditions. The above characteristics make the hybrid power transfer particularly interesting for high power electric vehicle charging applications for both stationary and dynamic (in-motion) charging applications [10, 11]. This paper gives a comprehensive review about WPT systems. It first presents the historical development of the WPT technologies and then introduces a general classification of the various WPT approaches. The paper further discusses inductive, capacitive, and HWPT systems in detail, with respect to their operating principles, circuit design, coupling characteristics and compensation networks, system losses, and practical considerations. In addition, the study examines different compensation circuit topologies for HWPT systems and analyses the performance, losses, and practical aspects of the hybrid systems themselves. These topics have not been addressed fully in previous studies.

2. Wireless power transfer

WPT has been defined as transmission of electrical energy from source to the load without using physical electrical connections through the use of electromagnetic fields instead of conducting wires. This concept makes it possible to contactlessly deliver an energy together ensuring a galvanic isolation between the transmitter and the receiver, which increases the operational safety and reliability of the system. The motivation for WPT comes from the limitations of conventional wired charging systems such as mechanical wear of connectors, corrosion, safety risks and limited automation capabilities, to name a few. These drawbacks are especially important in EV charging systems, biomedical implants and in harsh industrial environments where the conductors can become exposed and cause failures, or even be a safety hazard. From an engineering perspective, WPT systems have a number of advantages including electrical isolation, reduced maintenance and greater durability. The elimination of physical connectors enables wireless charging systems to perform in adverse environmental conditions such as humidity, dust and vibration making them suitable for applications in transportation and industrial automation [12–15].

In the application area of electric mobility WPT has become a promising alternative to conductive charging. Wireless charging enables the automatic and user-independent energy transfer of the EV, and that is static, quasi-dynamic and dynamic charging situations. However, achieving high power levels at acceptable efficiency and misalignment tolerance is currently a major technical problem, which provides a motivation for the design of advanced WPT architectures [16, 17]. Beyond EVs, WPT technologies have a huge use in the biomedical devices as well, where the wired devices can be risky for infection and uncomfortable things for the patient.

Wireless charging is also increasingly being implemented in consumer electronics, e.g. smartphones and wearable devices, as well as in Internet of Things (IoT) systems, where sealed and maintenance-free power delivery is desirable [18].Despite all these advantages, WPT systems have several technical challenges such as limited transfer distance, sensitivity to misalignment between coupling elements, electromagnetic interference (EMI), efficiency degradation, and electromagnetic field exposure regulation compliance. As a consequence, there has been a great deal of research effort put into enhancing the performance of WPTs through optimized coupling structures, resonant compensation circuits, advanced power electronic converters and intelligent control strategies [19, 20].

3. Historical development of WPT

The history of WPT can be traced back to the late nineteenth century, when Nikola Tesla conducted groundbreaking experiments on the transmission of electrical energy without any wires using high frequency alternating currents. Building on Faraday's electromagnetic induction principle, Tesla demonstrated contactless power transfer by using resonant electromagnetic fields. Most notably through use of Tesla coil operating at frequencies of around 150 kHz [12, 21].

The theoretical basis for WPT was also laid with the work of James Clerk Maxwell and Heinrich Hertz. Maxwell's equations united electricity and magnetism in one theory and Hertz experimentally verified the propagation of electromagnetic waves in free space. These contributions formed the science for both wireless communication and wireless energy transmission [12, 22, 23]. In the mid-twentieth century, the research efforts were focused on the long-distance WPT using radiative electromagnetic waves. Although far-field WPT enabled long-distance energy transmission, its low efficiency and strict safety constraints limited its widespread adoption. Consequently, there was a gradual shift in research towards near field WPT methods, which rely on non-radiative methods of electromagnetic coupling and can only operate at distances much smaller than the wavelength of the frequency of operation. A major milestone in terms of near-field WPT occurred in 2007, when researchers at the Massachusetts Institute of Technology (MIT) demonstrated resonant inductive coupling in the field of wireless power transmission. This breakthrough had a direct impact on subsequent studies of high-power wireless charging systems, especially for EV applications, for which efficiency, transfer distance and misalignment tolerance are important requirements in WPT [12, 22, 24, 25]. Following this breakthrough, fast progress in power electronics, magnetic materials and semiconductor devices spurred the development of practical WPT systems. The appearance of wide bandgap semiconductor technologies, such as silicon carbide (SiC) and gallium nitride (GaN), enabled high frequency, high efficiency converters possible which are essential for modern WPT systems [26–29]. In recent years, WPT technologies have transitioned from experimental demonstrations to commercial applications. Inductive charging standards for consumer electronics have been widely adopted, while the automotive industry has invested heavily in wireless charging systems for EVs. More recently, CPT and hybrid systems have been proposed to overcome limitations in terms of magnetic field exposure, misalignment tolerance and system integration [10]. Understanding the history of WPT is of great value to understand the design principles, technological limitations and research issues that still affect the design of modern WPT systems. The high growth rate of EVs in the past decade further stimulated the research on WPT technologies. Researchers started paying attention to the customization of WPT systems to satisfy the unique needs of EV charging such as higher power levels, enhanced misalignment tolerance, and auto safety requirements. More recently, work has moved on beyond conventional static wireless charging to quasi-dynamic and dynamic wireless charging concepts. These approaches make it possible to transfer energy when vehicles are temporarily stopped or moving, and promise to lower the battery power capacity needs on board, and ease the range anxiety linked to EVs.

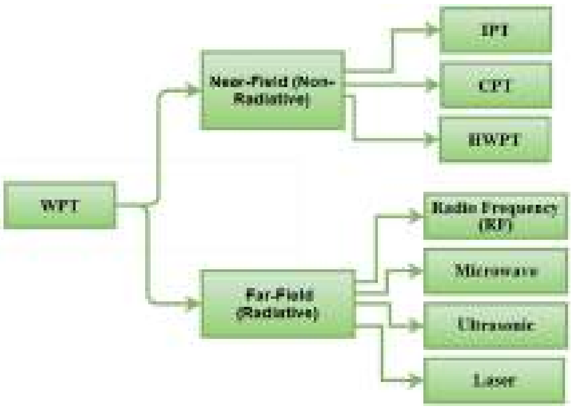

Fig. 1. Classification of WPT technologies.

4. Classification of WPT technologies

WPT technologies can be broadly classified based on the physical mechanism used to convey energy between the transmitter and the receiver. The most widely accepted classification divides WPT systems into far-field (radiative) and near-field (non-radiative) methods, depending on the operating distance relative to the wavelength of the electromagnetic field as indicated in Fig. 1 [30–33].

4.1. Far-Field (Radiative) WPT

Far-field WPT relies on the propagation of electromagnetic waves through free space, where energy is transmitted over distances significantly larger than the wavelength of operation. Typical far-field WPT techniques include radiofrequency (RF), microwave, laser, and ultrasonic power transfer systems.

In these systems, power is radiated omnidirectionally or directionally using antennas, and the receiver captures a small portion of the transmitted energy, which is then converted into electrical power using rectifying circuits. Although far-field WPT enables long-distance power transmission, its overall efficiency is inherently low due to beam spreading, atmospheric attenuation, and strict regulatory limits on electromagnetic radiation exposure [12, 18]. Consequently, far-field WPT is mainly used in low-power applications such as Radio-frequency identification (RFID) systems, wireless sensor networks, and space-based power concepts.

4.2. Near-Field (Non-radiative) WPT

Near-field WPT operates at distances much smaller than the wavelength of the operating frequency and relies on non-radiative electromagnetic coupling mechanisms. In contrast to far-field methods, near-field WPT systems achieve significantly higher efficiency and improved safety, making them suitable for medium- and high-power applications [30, 33]. Near-field WPT technologies can be further classified into:((1) Inductive Power Transfer (IPT), (2) Capacitive Power Transfer (CPT), (3) Hybrid Inductive–Capacitive Power Transfer). This classification is based on whether magnetic fields, electric fields, or a combination of both are used as the primary energy transfer medium [10, 11].

5. Inductive power transfer and magnetic coupling model

IPT systems operate by generating a time-varying magnetic field through an alternating current flowing in the transmitter coil. According to Faraday's law of electromagnetic induction, the variation of this magnetic field induces a voltage in the receiver coil, enabling contactless power transfer between the transmitting and receiving sides [34]. IPT is a near-field wireless charging technique based on magnetic coupling between a transmitter (Tx) coil and a receiver (Rx) coil across an air gap, causing the system to behave as a loosely coupled transformer. A practical IPT system typically consists of a high-frequency inverter feeding a resonant tank on the transmitter side, a magnetic coupler including coils, ferrite materials, and shielding, a resonant tank on the receiver side, and rectification and regulation stages supplying the load [35]. The overall configuration of the IPT circuit and its main components is illustrated in Fig. 2 [34]. The coupled coils are commonly modeled using self-inductances Lp and Ls, equivalent AC resistances Rp and Rs, and the mutual inductance M, which represents the portion of magnetic flux linking both coils. The strength of magnetic coupling is quantified by the coupling coefficient k, which is related to the mutual inductance by [36]:

$$K = \frac{M}{\sqrt{L_P L_S}} \left(0 \le \mathrm{k} \le 1\right) \tag{1}$$

The value of k depends primarily on coil geometry, air-gap distance, and lateral or angular alignment between the transmitter and receiver coils. To characterize AC losses in the coils, the unloaded quality factor Q is commonly used. The quality factors of the transmitter and receiver coils are defined as [37, 38]:

$$Q_P = \frac{\omega L_P}{R_P}, Q_S = \frac{\omega L_S}{R_S} \tag{2}$$

where $\omega = 2\pi \mathrm{f}$ denotes the angular frequency and f is the operating frequency.

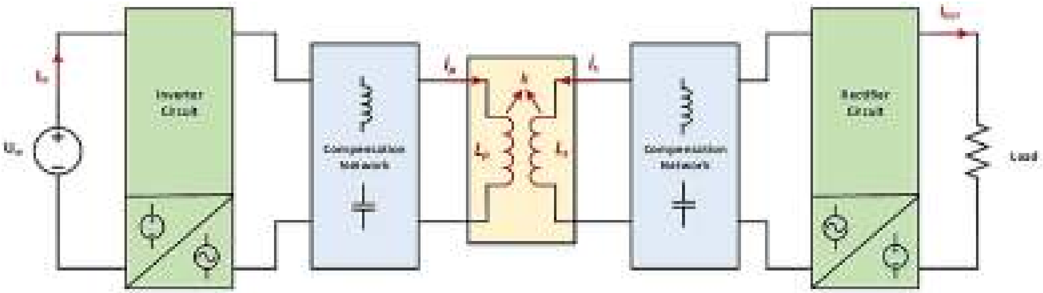

Fig. 2. Block diagram of a general architecture of an IPT system.

The k-Q product is a widely used indicator for assessing the performance of the magnetic link in IPT systems. It shows that improving the coupling coefficient k and the quality factors of the transmitter and receiver coils can significantly enhance power transfer efficiency, even when magnetic coupling is relatively weak. An increase in air-gap distance or coil misalignment reduces magnetic coupling, which directly affects the transferred power and system stability. To address these variations, compensation networks and suitable control strategies are commonly employed to keep the system operating close to resonance and to maintain conditions such as zero-phase angle (ZPA) or zero-voltage switching (ZVS) [34].

5.1. Classification of inductive coupler structures for IPT systems

In IPT systems for electric vehicle (EV) applications, the inductive coupler has a decisive influence on the system performance. Its geometry influences its strength of magnetic coupling, misalignment tolerance, power density and stability. Because of the great dependence of the magnetic field distribution on the shape and arrangement of the coils, many pad and coil structures have been reported in the literature with an eye towards facilitating improvement in power transfer efficiency and insensitivity to lateral and angular misalignment. Based on the dominant elements of the coupled magnetic flux, IPT pads are often divided into non polarized pads (NPP) and polarized pads (PP). In addition, from a structural perspective, IPT pads may take on single-coil, multi-coil, and multi-path configurations, which can be polarized or non-polarized depending on their magnetic field distribution. This classification provides a practical means by which it is possible to have some relation between the geometry of the coil and the system behaviour in the case of realistic operating conditions, especially when there are air gaps and misalignmets between the transmitter and the receiver. Recent studies further emphasize that pad selection cannot be treated in isolation; it must be considered alongside the compensation scheme, safety requirements, and magnetic field exposure limits. Consequently, no single pad geometry can be regarded as universally optimal. Instead, the most appropriate structure depends on the application requirements, including whether charging is static or dynamic, the available installation space, the air-gap distance, and the required level of misalignment tolerance [1, 14, 17].

- Non-Polarized Pads (NPP): NPP generally uses a single planar coil in the shape of circles, squares or rectangles. In these designs, good magnetic coupling is primarily related to the vertical component of the magnetic field. Their simplicity of structure, low interconnections, and ease of manufacture makes them attractive for low- to medium-power applications where reliability and mechanical simplicity are important. However, one of the drawbacks of NPP structures is well known as their sensitivity to lateral misalignment that causes a noticeable reduction in coupling coefficient and transferred power. Addressing this problem often requires the increase of the pad dimensions or the use of compensation networks and control strategies that can account for the variation of the coupling coefficient during operation [1, 39, 40]. Representative examples of circular, square and rectangular NPP are shown in Fig. 3.
- Polarized Pads (PP): PP are specially designed to shape the magnetic field so that both vertical and horizontal flux components contribute to the coupling process. This design approach offers better tolerance to lateral displacement and angular misalignment than non-polarized structures, and thus, PP are more suitable for high power EV charging systems. The most popular polarized structure is the Double-D (DD) and Bipolar (BP) coil structures [1, 41]. The Double-D pad,

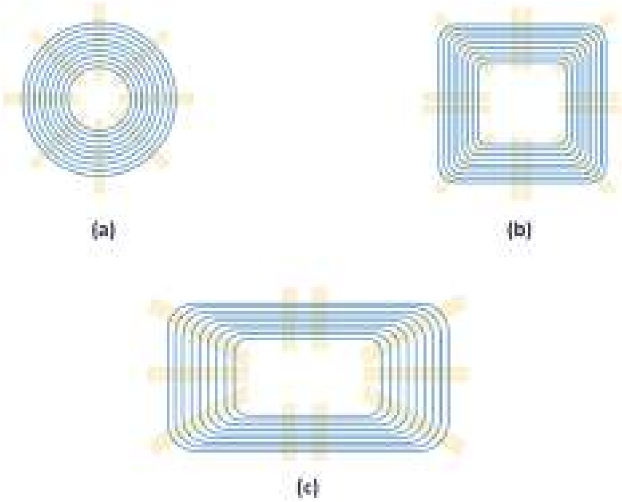

Fig. 3. Non-Polarized Pads shapes (a) circular, (b) square, (c) rectangular.

shown in Fig. 4, consists of two D-shaped coils that are designed to generate a more uniform distribution of magnetic field and therefore provide better tolerance for misalignment and more stable power transfer. Further improvements in advanced design such as the Double-D Quadrature (DDQ) coupler in which another orthogonal coil is introduced to maintain the stable coupling under severe misalignment conditions is shown in Fig. 4 [14, 28, 42].

- Multi-Coil and Multi-Path Pads: Beyond single-coil pad structures, some IPT systems have multi-coil or multi-path structures. These include the use of intermediate repeater coils, multiple transmitter coils in the form of segmented tracks for dynamic charging or the use of multiple receiver coils within the same system itself. Such approaches are intended to increase the coupling region and to increase power transfer for greater areas and low sensitivity to misalignment as shown in Fig. 5. Nevertheless, these advantages come at the expense of higher system complexity including more demanding control requirements and additional cross-coupling effects that must be carefully addressed during modeling and design [22, 43].

5.2. Compensation networks in IPT systems

In IPT systems, compensation networks are needed to eliminate the reactive component of the system impedance as well as to bring the transmitter and receiver coils to resonance at the operating frequency. Without appropriate compensation, the loosely coupled coils present high reactive impedance and large circulating currents, which reduce efficiency and increase stress on power electronic components. By using resonant LC compensation networks, leakage inductance can be effectively compensated and results in a high power transfer efficiency, an enhanced voltage gain, a better load regulation and a reduced inverter VA rating [1]. The most widely used compensation topologies in IPT systems are obtained by connecting resonant capacitors in series or in parallel with the transmitter and receiver coils. This leads to four basic types: Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP) [44, 45]. Due to their simplicity and simple analysis, these configurations are the basis of most of the IPT system designs. Among them, the SS topology is more popular in EV charging applications because its resonant condition is relatively insensitive to load and coupling coefficient variation and provides stable output current characteristics naturally [46, 47]. The basic structures of the SS, SP, PS and PP compensation networks are shown in Fig. 6. To address the limitations of these basic topologies under conditions such as coil misalignment, wide load variation, and high-power operation, more advanced multi-element compensation networks have been developed. In particular, LCL and LCC topologies introduce additional design flexibility, allowing better control of voltage gain, input impedance phase, and overall system robustness. These compensation networks are commonly used to achieve constant-current (CC) or constant-voltage (CV) operation, reduce sensitivity to changes in load and coupling coefficient, and enable soft-switching in high power IPT systems [10, 46–50]. Ultimately, the choice of compensation topology depends on application-specific requirements, including power level, operating frequency, efficiency targets,

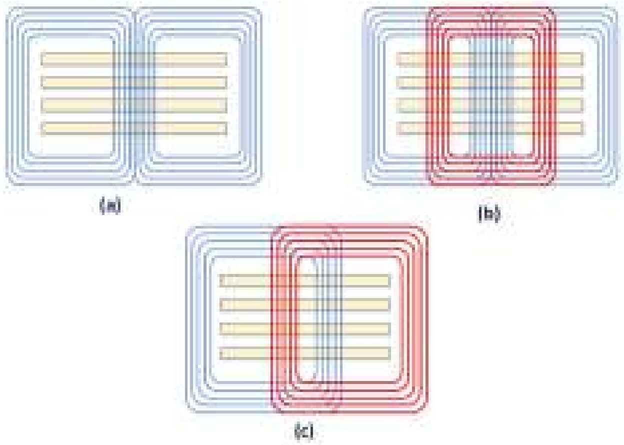

Fig. 4. Polarized Pads shapes (a) Double-D coil. (b) Double-D quadrature coil (c) Bipolar coil.

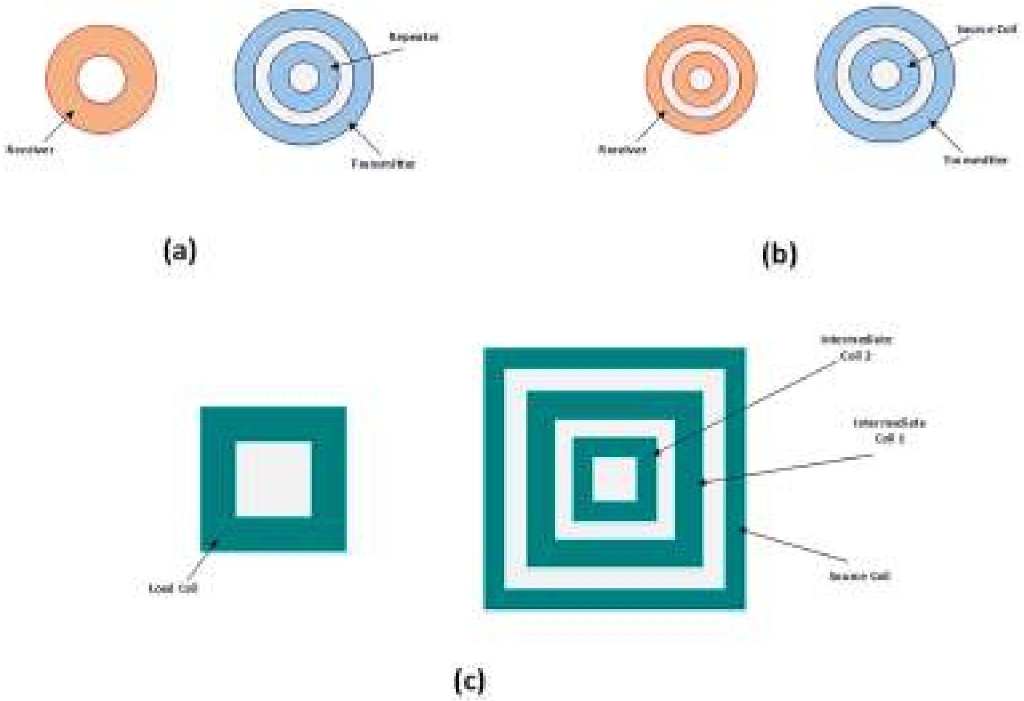

Fig. 5. Multi-Coil and Multi-Path coils (a) three coils(b) Four coils (c) asymmetric four coil system.

allowable misalignment, and overall system constraints.

At the end of this part on IPT, a complete comparative analysis is presented as summarized in Table 1 which shows representative past studies in recognition of transmitter and receiver pad configurations, compensation topologies, output power, power transfer efficiency and distance between air-gaps. The comparison shows that the system performance is highly dependent on the pad design as well as the compensation topology chosen and proper compensation methods are also essential in improving the efficiency and power transferred, especially when the air gaps are large. Despite the high efficiencies that have been reported in most studies, the overall system performance is usually limited by constraints associated with transfer distance limitations and pad geometry. This underscores the ongoing challenge in inductive WPT system design of achieving an optimal trade-off between efficiency, transferred power, and air-gap distance.

6. Capacitive WPT (CPT)

CPT is a WPT technique that relies on the electric field established between facing metallic plates separated by an air gap or a dielectric medium. These plates function as capacitor electrodes, and power transfer is achieved through the displacement current generated by the periodic charging and discharging process at high operating frequencies. Unlike IPT, CPT primarily utilizes electric-field coupling, which can offer advantages such as reduced magnetic-field emissions, lower weight, and simpler mechanical integration in certain applications [10, 11].

In most practical CPT implementations, the coupling plates are manufactured from aluminum due to its low density, low cost, and ease of fabrication. In applications where lower electrical resistance or enhanced thermal performance is required, copper plates may also be employed. The selection of plate material, along with plate dimensions and separation distance, directly influences the coupling capacitance and electric-field distribution [12, 58–60]. Fig. 7 illustrates the general architecture of a CPT system. On the transmitter side, a DC power source feeds a high-frequency inverter, which is connected to a resonant compensation network before energizing the transmitting plates. The high-frequency alternating voltage applied to the plates generates a time-varying electric field across the coupling gap, enabling power transfer through capacitive coupling. On the receiver side, a corresponding compensation network is used to achieve resonance and reduce the effective impedance of the capacitive interface, followed by rectification and delivery of power to the load or battery [10, 61].

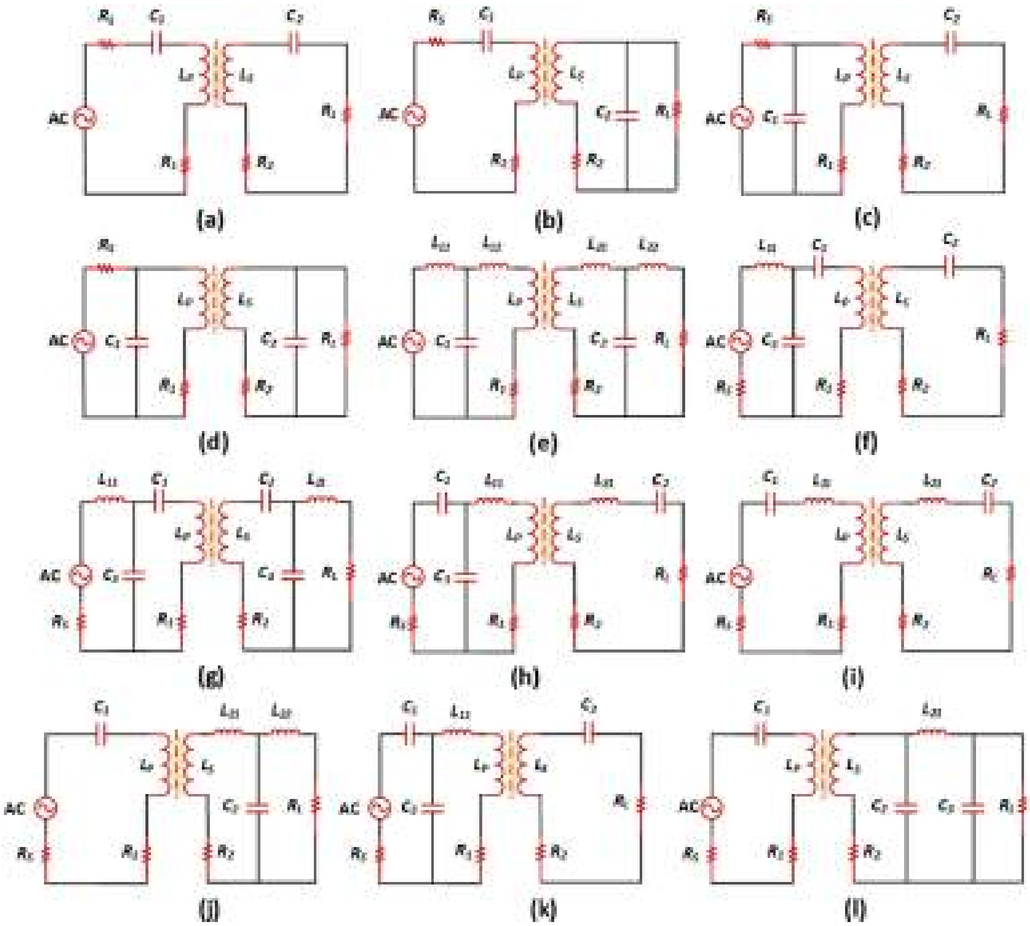

Fig. 6. Common compensation topologies for IPT systems (a) S–S (b) S–P (c) P–S (d)P–P (e) LCL–LCL, (f) LCC–S, (g)LCC–LCC, (h) CCL–LC, (i) LC–LC, (j) S–LCL, (k) CCL–S, and (l) S–CL.

Table 1. Comparison of representative IPT systems.

Ref	Type of pads	Compensation Topology	Out Power	Efficiency	Airgap (mm)	Frequency
[51]	Circular pad	SS	500 W	90%	125	85 kHz
[52]	Circular pad	SS	3.7 kW	90.02	120	85 kHz
[53]	Circular pad	SS	1.011 kW	74.84	200	85 kHz
[54]	Square pad	LCC-LCC	10 kW	92%	200	85 kHz
[55]	DD pad	LCC - LCC	20 kW	96.2%	280	22 kHz
[56]	DD pad	LCC-LCC	12.82 kW	89.08%	100	22 kHz
[57]	Square pad	SS	3.7 kW	91.6%	100	85 kHz

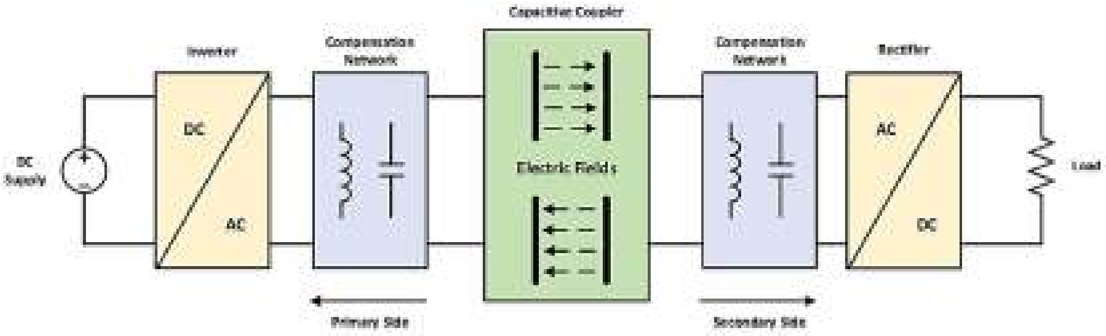

Fig. 7. Block diagram of a general architecture of a CPT system.

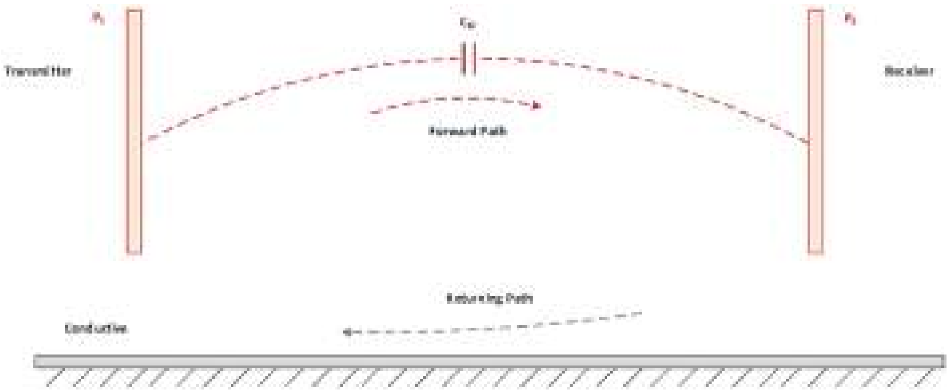

Fig. 8. Structure of a two-plate capacitive coupler.

6.1. Electrical modeling of capacitive couplers

Due to the diversity of CPT coupler structures and their varying electrical and geometrical characteristics, CPT couplers are commonly classified according to the number of plates and their geometric arrangement. From an electrical perspective, a CPT coupler cannot be accurately represented as a single ideal capacitor. Instead, it must be modeled as a network of parasitic capacitances, including mutual capacitances between opposing plates, cross-coupling capacitances between non-facing plates, and self-capacitances associated with plates on the same side of the coupler, in addition to capacitances to ground or the surrounding structure [60].

The values of these parasitic capacitances depend strongly on the number of plates, their dimensions, separation distance, alignment conditions, and the dielectric properties of the medium between the plates. Consequently, the geometric design of the coupler plays a decisive role in the overall performance of a CPT system. Because the equivalent mutual capacitance is typically very small often in the picofarad range the capacitive interface exhibits a high impedance at practical operating frequencies. As a result, efficient power transfer cannot be achieved without resonant operation. Furthermore, since different coupler structures lead to different parasitic capacitance networks, a universal electrical model cannot be applied to all CPT configurations. Each coupler topology therefore requires a dedicated equivalent model tailored to its specific geometry [58, 61].

6.2. Classification of CPT coupler structures

- **Two-Plate Coupler:** The two-plate coupler, shown in Fig. 8, represents the simplest capacitive coupling structure. It consists of a single transmitting plate facing a single receiving plate. In this configuration, no explicit return path exists for the displacement current, and circuit closure relies on parasitic capacitances to ground or the surrounding structure. Although this structure is mechanically simple and can tolerate certain misalignment conditions, its strong dependence on environmental factors reduces modeling accuracy and severely limits the transferable power. Consequently, two-plate couplers are generally restricted to low-power applications [62–64].
- **Four-Plate Coupler:** The four-plate coupler, illustrated in Fig. 9, is the most widely used structure in medium- and high-power CPT systems. It comprises two transmitting plates and two receiving plates, providing a well-defined forward and return path for the displacement current. This configuration enables more accurate electrical modeling and improved power transfer capability. Four-plate couplers can be implemented in a lateral (horizontal) arrangement, which offers high efficiency and simplified analysis, or in a vertical stacked arrangement that reduces system footprint and improves rotational misalignment tolerance. However, the stacked configuration typically requires enhanced insulation due to increased voltage stress on the plates [63, 65–67].
- **Six-Plate Coupler:** To enhance safety and reduce electric-field leakage into the surrounding environment, six-plate coupler structures have been proposed, as shown in Fig. 10. In these configurations, two additional shielding plates are introduced, often with one connected to ground. This approach effectively confines the electric field between the transmitting and receiving plates, reducing unwanted exposure and improving compliance with safety regulations. Nevertheless, the inclusion of additional plates increases the number of parasitic capacitances, resulting in a more complex electrical model that must be carefully considered during system design [63, 68].

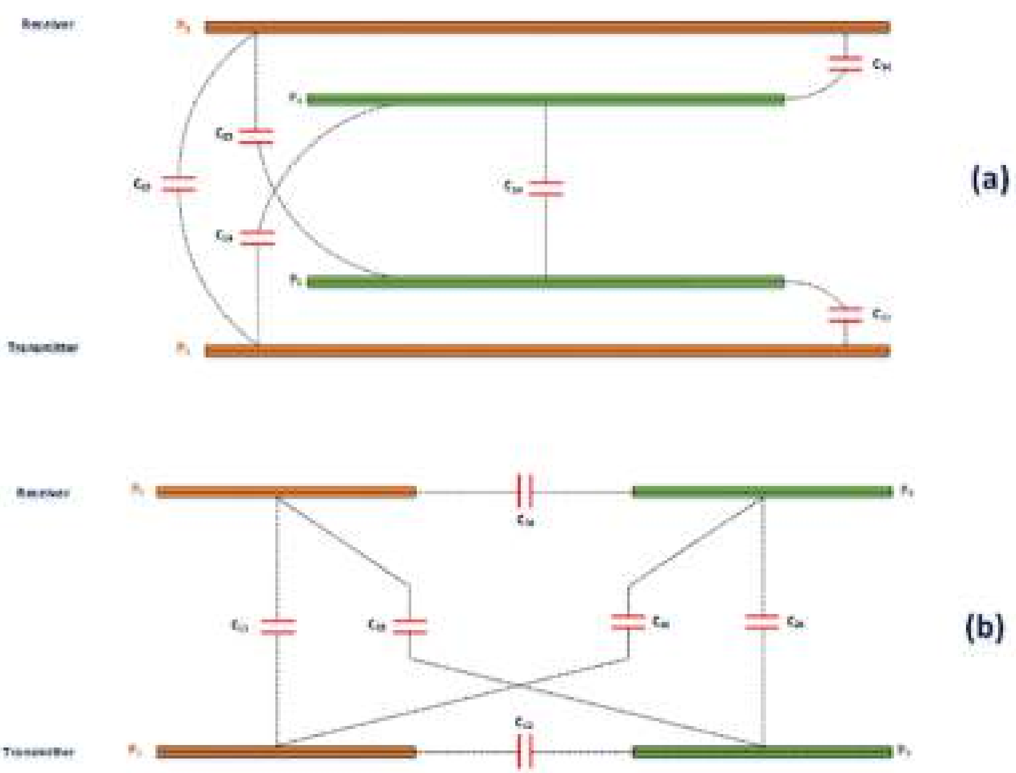

Fig. 9. Structure of a four-plate (a) parallel capacitive coupler (b) stacked capacitive coupler.

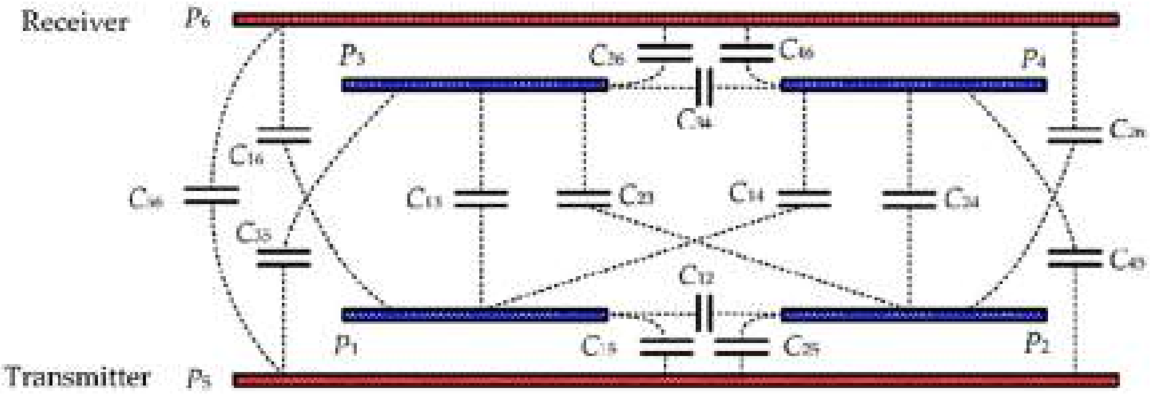

Fig. 10. Structure of a six-plate capacitive coupler [59].

6.3. Compensation networks in CPT systems

In CPT systems, because the coupling capacitance is small in nature, the capacitive interface has a high impedance at low and moderate frequencies, which is a severe limitation to power transfer if not compensated. Therefore, resonant compensation networks are necessary to remove the capacitive reactance, create resonance at the operating frequency and increase the plate voltage to enable sufficient displacement current flow [69].

As shown in Fig. 11, various compensation topologies have been proposed for CPT systems which include L, LC, LCL, LCLC and CLLC networks. The most basic is L-type network, which uses a single series inductor to resonate with the coupling capacitance, and is appropriate for small air gap and low power applications. However, with increasing air gap and decreasing coupling capacitance, the required inductance will be impractically large and thus the losses will be higher [63, 70–72]. To address this issue, LC and LCL compensation networks introduce additional reactive elements, enabling higher-order resonance and greater flexibility in frequency tuning and power regulation. Among them, LCL compensation offers improved tolerance to variations in

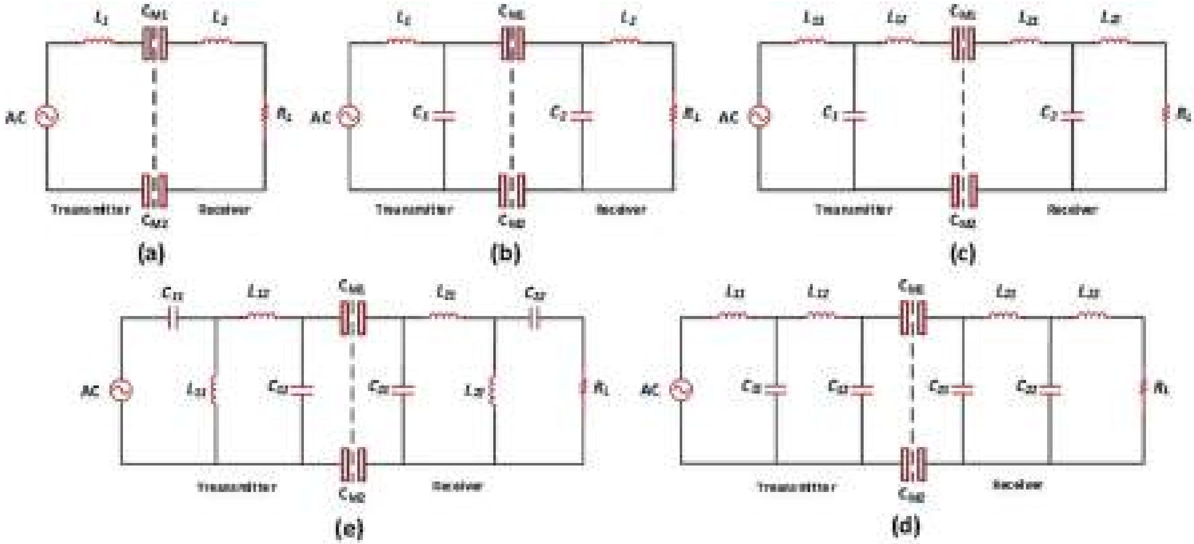

Fig. 11. Common compensation techniques in CPT system: (a) L (b) LC (c) LCL (d) LCLC (e) CLLC [10].

coupling and load conditions. For larger air gaps and higher power levels, double-sided LCLC and CLLC networks are commonly used, as they provide effective voltage amplification, enhanced stability under misalignment and load changes, and reduced electrical stress on components. Consequently, the choice of compensation topology directly affects voltage stress, component sizing, system stability, and overall safety [63, 73, 74]. Therefore, the capacitive coupler and its compensation network should be jointly designed and optimized as a single integrated system to ensure high performance while meeting safety and electromagnetic compatibility requirements.

At the end of this part on CPT, Table 2, shows a comparative overview of representative past research with regard to their important system attributes, such as the total number of coupling plates, compensation topology, power output, transmission efficiency, distance to air, and operating frequency. The comparison suggests that the performance of the system in CPT is highly influenced by the coupling structure, especially the plate numbers and arrangement and the compensation topology chosen. Some of the appropriate methods of compensation come in handy to enhance power transfer abilities and effectiveness, particularly in larger air-gap circumstances. Although significant progress has been claimed in the literature, the maximum attainable power output and transmission range are still small in comparison with the inductive schemes, pointing out at inevitable trade-offs in CPT systems. It is a comparative analysis that highlights the ongoing issue of efficiency improvement and power transferred through enhanced efficiency whilst keeping practical air-gap distances in CPT systems.

7. Hybrid WPT

HWPT is a new concept in the near-field WPT systems, where the electrical power is transferred over a short air gap by electromagnetic fields. Unlike in conventional systems, which use one specific power transfer mechanism, HWPT operates in the near-field region, and at the same time, combines more than one specific coupling mechanism within one integrated structure. This places HWPT in the company of other near-field WPT technologies, but with better

Table 2. Comparison of representative CPT systems.

Ref	No. of plates	Compensation Topology	Out Power	Efficiency	Airgap (mm)	Frequency
[75]	6	SS	100W	87.4%	30	13.56 MHz
[76]	6	LCL	1.97 kW	91.6%	150	1 MHz
[77]	2	SS	0.35 Kw	74.1	110	1 MHz
[78]	4	SS	0.112	70.6	180	1.5 MHz
[79]	4	PP	3.55kW	94.2	8	2.5 MHz
[80]	4	LCL- LCL	0.50 kW	90	50	1 MHz
[81]	5	N/A	5kW	96.5%	N/A	N/A

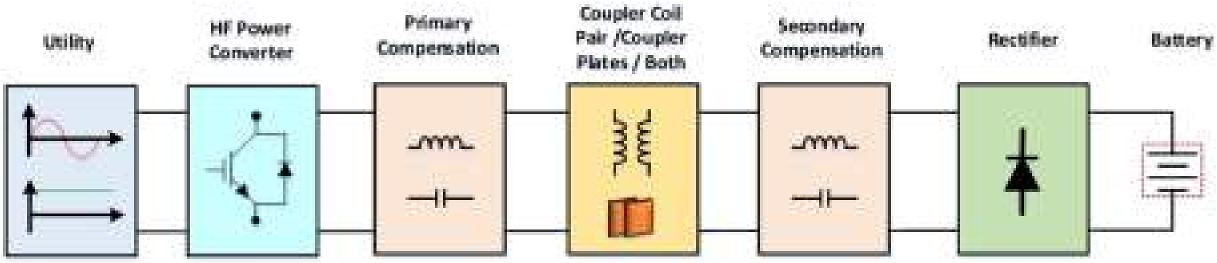

Fig. 12. Block diagram of a general architecture of an HWPT system.

flexibility and performance that comes with its hybrid operating principle.

The basic idea of HWPT is to combine the inductive (based on magnetic field) and capacitive (based on an electrical field) power transfer mechanisms so that both contribute to the total delivered power. Instead of relying on a single transmission path, HWPT creates a dual-channel power transfer architecture whereby the energy is fed to the same load via two complementary coupling paths as shown in Fig. 12. Recent studies have shown that it is possible to greatly improve the system performance by means of this combined approach, especially in applications with different operating conditions or where single-mechanism WPT systems have practical limitations [10, 11, 82].

HWPT is benefited by the strengths of both the mechanisms. The magnetic coupling path allows for efficient transfer of relatively high levels of power and has wide applications in industrial and transportation applications. In contrast to the magnetic coupling path, the electric coupling path has lighter structures, planar interfaces, is less sensitive to the effect of nearby metallic objects, and is less affected by lateral misalignment. By combining both mechanisms in a single hybrid circuit, HWPT uses the complementary benefits and addresses the individual shortcomings of the two methods [83–85]. A key motivation for HWPT development is its improved robustness under non-ideal conditions. Variations in air-gap distance, lateral misalignment between transmitter and receiver, or load changes can severely degrade the performance of single-channel WPT systems. In HWPT systems, when one transfer path becomes less effective due to misalignment or environmental influences, the second path can still deliver part of the required power. This shared contribution enhances reliability and ensures more stable power delivery, which is particularly important for demanding applications such as electric vehicle charging and moving platforms [86, 87].

Another important characteristic of HWPT is the flexible of power distribution between the two channels. The contribution of the different paths is not fixed but depends on parameters of the system design such as resonant components, coupling characteristics, operating frequency and the selection of the hybrid connection topology. This is a flexible way for designers to optimize for efficiency, power density, electromagnetic emissions and thermal performance as required by their specific application. Several studies refer to this controllable power sharing capability as one of the big benefits of HWPT compared to traditional near-field WPT systems [86, 87]. Despite the merits associated with it, the integration of two power transfer paths presents other design challenges. Issues such as reactive power management, mutual interaction between the inductive and capacitive channels and stable resonance under varying conditions need to be carefully addressed. Consequently, recent research has concentrated on developing appropriate hybrid circuit structures, advanced compensation method and precise analytical models to achieve reliable and efficient HWPT operation in practical environments [82, 85, 87].

7.1. Literature review of hybrid WPT

HWPT systems that combine inductive and capacitive coupling have been shown to achieve significant performance enhancements due to the complementary advantages of magnetic and electric field channels. For instance, in electric vehicle charging applications, adding a CPT channel to an IPT charger can increase power throughput and improve misalignment tolerance. In one early-stage development, a CPT channel integrated into an IPT charger achieved a power transfer of 2.84 kW with an efficiency of approximately 94.45% at 1 MHz, while also exhibiting superior misalignment performance compared to IPT alone [82].

Subsequent EV-oriented designs contributed to improving and optimizing the coupler integration and compensation networks - Badwey et al [86]. designed a spiral/helical coil plus four-plate hybrid coupler whose performance resulted in ∼10 kW transfer with ∼99.37% simulated coupler-to-coupler efficiency over large air gaps, and Li et al [85]. came up with the concept of a compact "comb shape" coupler that interleaved metal plates between coils in an attempt to minimize the impact of the eddy current shielding; their prototype achieved 2.2 kW output at 92.6% dc-dc efficiency, thus demonstrating the HWPT has also been used in transport infrastructure and robotics: an IPT-CPT railway charger achieved 653W at 87.7% efficiency with only ∼8% output drop at only ∼270mm lateral misalignment (a huge improvement from single coupler IPT or CPT system) [88], and a multi-channel based "Tri-SS" architecture also achieved ∼81% efficiency under 60% coil displacement by coordinating power flow via both magnetic and electric pathways [87].

A number of researchers focus on output stability at different loads or alignment. The 200 W HWPT prototype by Qing et al [84]. gave the inherent advantage of having a constant output current for load changes (20–40 Ω) and for coil offsets (0–100 mm), which corresponds to about doubling the current capacity of an equivalent CPT-only system. In case of underwater scenario, Zhang et al.[89] introduced double-D coils with C-shaped capacitor plates (backed by ferrite) in an integrated coupler and used an S/LCL-S compensation network to achieve easy CC/CV mode switching, where the developed system achieved stable constant-current or constant-voltage output (power variation $<15\%$) under 50% misalignment, with a maximum efficiency of ∼88.2% at 255W output power. More generally, hybrid IPT-CPT designs in water have demonstrated the utility of a common power resource among the channels to minimize extreme operating stresses - an underwater HWPT prototype achieved ∼87.8% efficiency with mitigation of ∼39% and 31% reduction in the required coil current and plate voltage, respectively, to the same conventional IPT or CPT systems, mitigating eddy current losses and dielectric stress in conductive seawater [90].

Other innovations have included the application of parity-time (PT) symmetric circuit theory for extending the range of constant power and high efficiency operation in a hybrid resonant topology and lightweight combined couplers for aerial vehicles, such as a UAV charger using ferrite cores with L-shaped cores and coils embedded within plus foil electrodes, which was shown to deliver 130 W at ∼81% efficiency in order to contactlessly recharge its battery without the use of heavy hardware onboard [91]. Collectively, these works show how inductive-capacitive HWPT can achieve improved efficiencies, power density, misalignment tolerance, and load invariable output power compared to single technology WPT with successful implementations across a variety of applications that include railroads, underwater vehicles, electric cars, drones and even small e-mobility devices.

7.2. Transmission channels in hybrid WPT systems

Unlike conventional single-mode WPT systems, HWPT uses a design philosophy whereby the power transmission channel itself is hybrid in nature as shown in Fig. 13. Rather than depending on one path coupling, energy is applied through various complementary transmission mechanisms which operate at the same time in the same system. Depending on the way these transmission paths are organised and

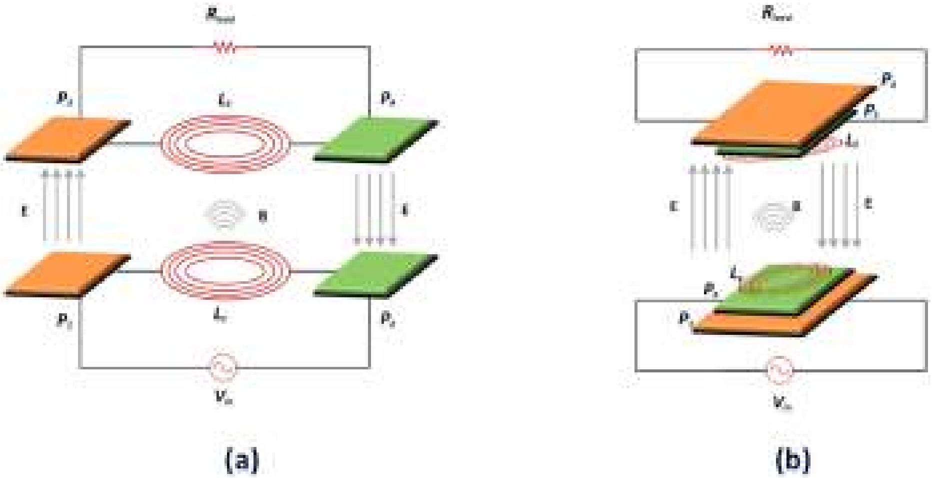

Fig. 13. Coupling Structures in Hybrid WPT Systems: (a) Independent Hybrid Coupler, (b) Integrated Hybrid Coupler.

integrated, HWPT systems can be divided into two main categories.

- Independent Hybrid Channels (Series/Parallel Hybrid): In this approach, hybrid power transfer is achieved by combining two independently designed transmission paths within a single system. Each path follows a distinct coupling mechanism, and the hybrid operation is realized using series or parallel interconnection at system level. This configuration has high design flexibility and easy control strategies because each transmission path can be analyzed and optimized separately. In addition, the functional separation between paths contributes to improved system reliability [82, 90, 91]. However, the use of independent hybrid channels usually leads to a larger system size and a greater number of compensation components, which may limit its applicability in space-constrained or compact designs.
- Integrated Hybrid Channels: Integrated hybrid channels are a more advanced and compact implementation of HWPT. In this structure, a single physical structure is used to simultaneously implement several coupling mechanisms, wherein the same elements can be used for both magnetic and electric field coupling-based power transfer. By combining transmission paths from the structural level, this method can greatly reduce the volume and weight of the system, and the number of compensation parts [84–86]. In addition to compactness, integrated hybrid channels offer improved electromagnetic field distribution and reduced field leakage, contributing to enhanced electromagnetic safety. Owing to these advantages, integrated hybrid architectures have become the dominant research trend in modern HWPT systems, particularly for applications that demand high power density under strict spatial constraints.

7.3. Compensation networks in hybrid WPT systems

Compensation networks play a central role in the operation of HWPT systems, as they regulate resonance conditions, reactive power and power sharing between the simultaneous inductive and capacitive pathways. This multi-path nature makes the system behaviour more complicated than in conventional WPT systems and the compensation design becomes a critical factor to achieve stable system operation, high efficiency, and reliable performance in changing coupling and load conditions. Beyond the basic tuning of resonance, good compensation network design is useful to keep excessive reactive power in check, dash out circulating currents, stabilize power distribution and eliminate sensitivity to coupling and load variations. Different compensation topologies have thus been proposed in the literature and each one is suited to a particular system architecture, operating frequency and performance goals.

- LC Compensation in Hybrid WPT Systems: LC compensation is one of the most fundamental and widely adopted resonant compensation approaches in hybrid WPT (HWPT) systems. In this topology, inductive and capacitive elements are combined to form resonant networks on both the transmitter and receiver sides, enabling the hybrid inductive–capacitive link to operate at or near resonance, as illustrated in Fig. 14, which presents a typical LC-compensated HWPT circuit structure. By effectively minimizing reactive impedance, LC compensation contributes to improved power transfer efficiency, enhanced operational stability, and provides a solid analytical basis for system modeling and design [82, 85, 90].

In some HWPT architectures [84], LC compensation networks are integrated directly into the overall system structure rather than implemented as

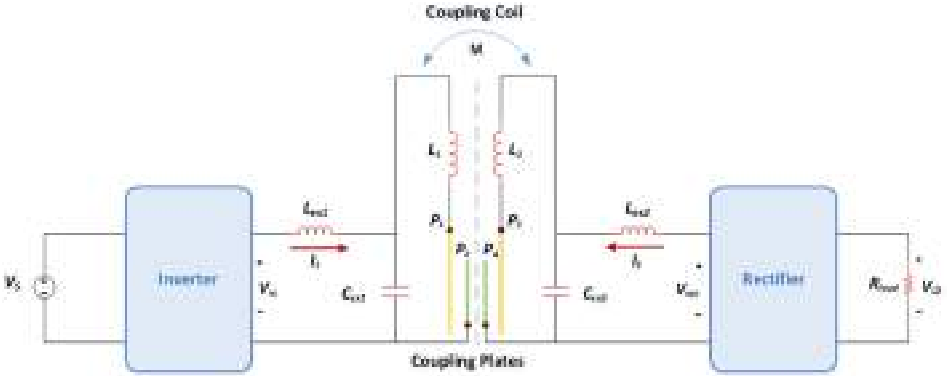

Fig. 14. HWPT system with LC compensation topology.

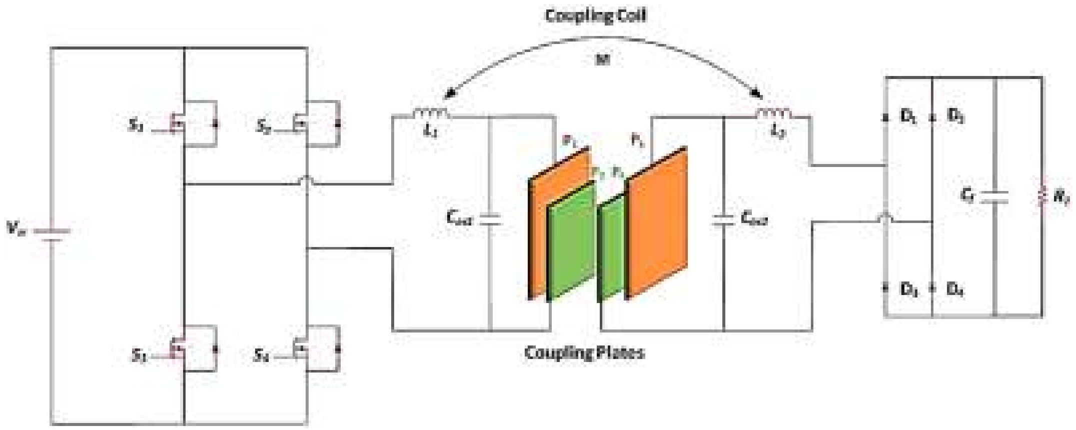

Fig. 15. HWPT system with LC compensation topology.

isolated resonant stages. This integrated realization, illustrated in Fig. 15, shows how LC elements are embedded within the hybrid coupler to achieve coordinated resonance at a common operating frequency. Such an approach simplifies system design and reduces the number of discrete compensation components while maintaining stable performance. When the inductance and capacitance values are properly selected, the system can preserve near-resonant operation even under variations in coupling conditions, misalignment, or load changes. Furthermore, LC-based equivalent circuit models are widely employed to analyze transferred power, determine optimal operating conditions, and assess system sensitivity to parameter variations, with analytical predictions showing good agreement with simulation and experimental results reported in the literature.

- LCL Compensation in Hybrid WPT Systems: As HWPT systems evolve toward higher performance and increased robustness, more advanced compensation structures such as LCL compensation have been introduced. Compared to conventional LC compensation, the LCL topology incorporates an additional inductor, providing greater flexibility in shaping the equivalent impedance seen by the power converter, as illustrated in Fig. 16. In hybrid systems, LCL compensation is particularly effective in parallel-connected configurations, where interactions between transmission paths may otherwise lead to instability. The additional filtering effect of the LCL network improves current quality, suppresses circulating reactive currents, and reduces voltage and current stresses on system components. Experimental studies have shown that double-sided LCL compensation enables stable operation and high efficiency under varying load and coupling conditions, making it well suited for HWPT applications with dynamic operating environments [92, 93].
- Series–Series and Tri-SS Compensation in Multi-Channel Hybrid Systems: Series-Series (SS) compensation is usually used in HWPT systems for transmission paths which require

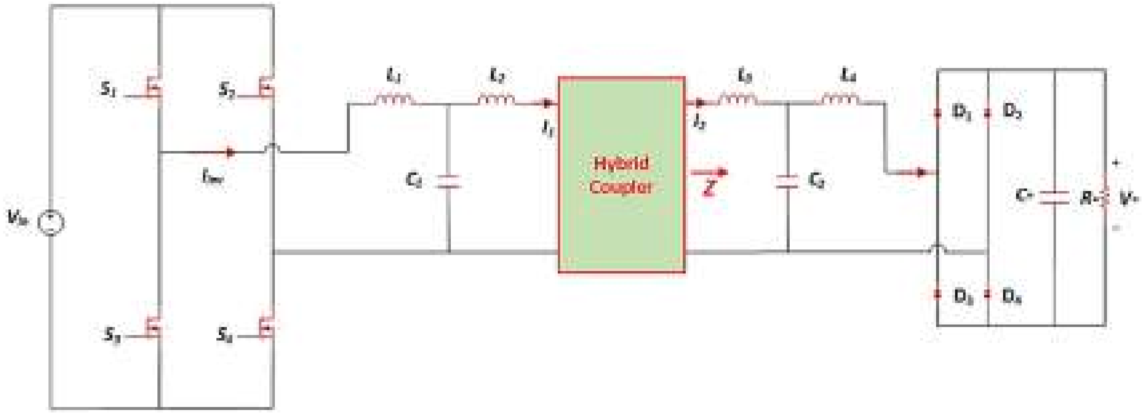

Fig. 16. HWPT system with LCL compensation topology.

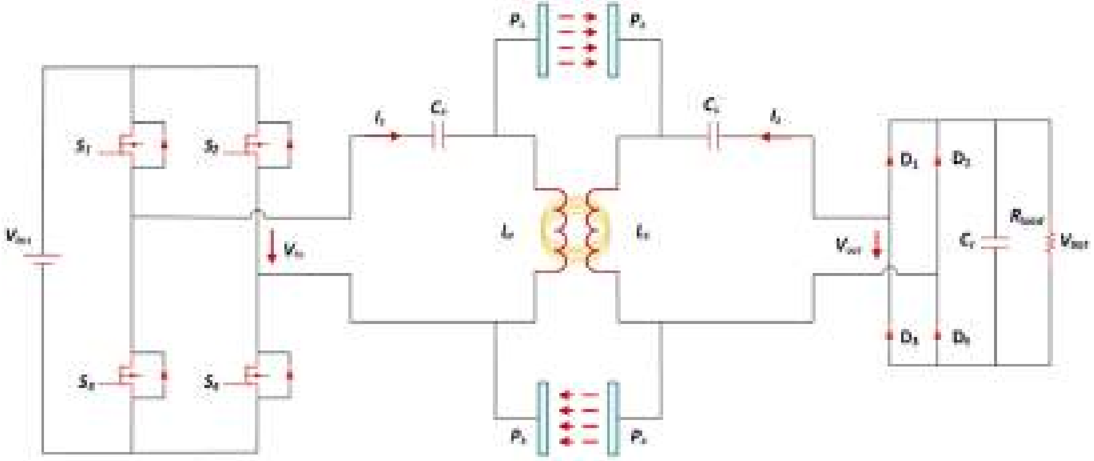

Fig. 17. HWPT system with SS compensation topology.

stable current characteristics and high efficiency. In such topology, series capacitors are inserted on both transmitter and receiver ends of a particular transmission path and hence form low impedance condition with resonating frequency, as shown in Fig. 17. In the case of hybrid systems, SS compensation is generally only used selectively instead of uniformly across all transmission paths, which makes efficient power delivery possible, while the reactive power remains limited [94].

For advanced HWPT systems with more than one active resonant channel, Tri-SS (Triple Series-Series) compensation has been introduced which is a further development of conventional SS compensation. In Tri-SS systems 3 resonant paths are simultaneously contributing to power transfer and coordinated resonance control is required as shown in Fig. 18. Each resonant channel is provided with series capacitors on the transmitter and receiver end, which ensures that all the channels are near resonance even in the presence of coupling variations. This multi-channel approach improves power density, power balance, and tolerance to misalignment to a great extent, stating a shift towards cooperative power transfer strategies in modern HWPT designs [87].

- Independent Compensation for Parallel Hybrid Paths: In parallel-connected hybrid WPT systems, independent compensation of each transmission path is essential to prevent circulating currents and unstable power sharing, as illustrated in Fig. 19. When multiple paths share a common compensation network, reactive currents may circulate between paths, leading to increased losses and degraded efficiency. Independent compensation allows each hybrid path to maintain its own resonant condition without interference from other paths. This approach is often combined with isolated rectification, further enhancing system stability and reliability, particularly under

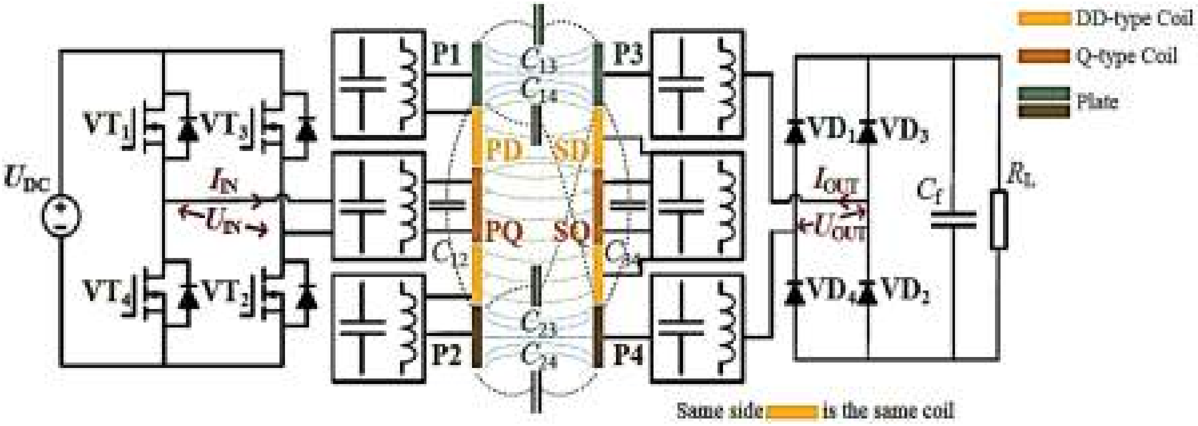

Fig. 18. HWPT system with Tri-SS compensation topology HWPT System [73].

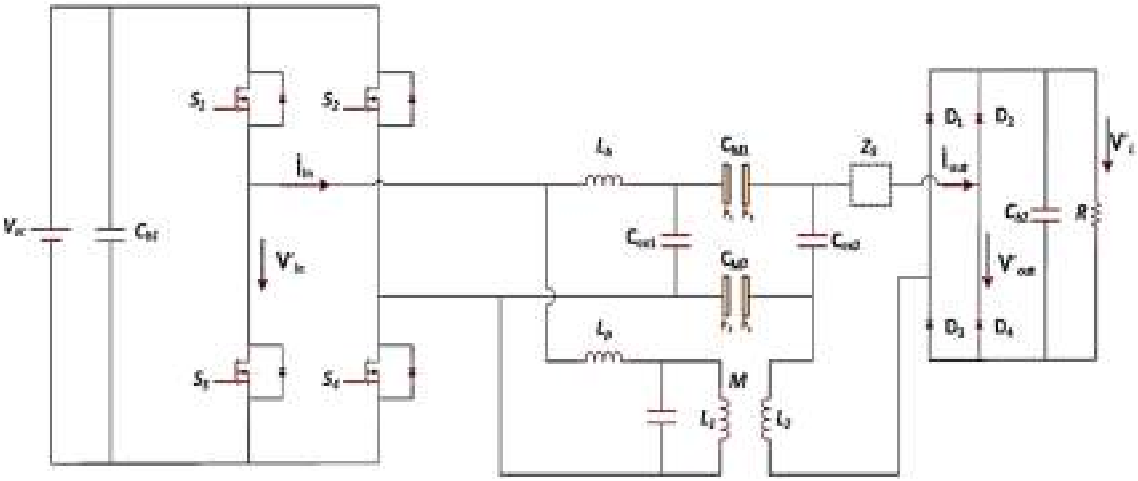

Fig. 19. HWPT system with Double-LC-S compensation topology.

Table 3. Comparative analysis of HWPT systems.

Ref	Coupler	Frequency	Compensation Topology	Out Power	Efficiency	Airgap (mm)
[82]	Series	1MHz	LC -LC	2.84 kW	94.45%	150
[88]	Series	1MHz	LC -LC	653W	87.7	60
[94]	Parallel	1MHz	SS	1.1kW	91.9%	150
[93]	Series	1.1MHz	LCL- LCL	100W	77.8%	N/A
[90]	Integrated	800kHz	LC -LC	278W	87.8%	120
[83]	Parallel	800kHz	LC -LC	1kW	90.97%	100
[85]	Integrated	1MHz	LC -LC	2.2 kW	92.6%	150
[87]	Integrated	800kHz	Tri-SS	550W	81.4%	100

dynamic operating conditions such as misalignment or load variation [83, 88, 91, 95].

To summarize this part on HWPT systems, Table 3 has given a comparative summary of the previous studies that have been done especially on the hybrid coupler configuration and the mechanism of integrating the inductive coils and capacitive plates. These consist of various coupling and connection methods like series, parallel and integrated structure, operating frequency, compensation topology, output power, efficiency and air-gap distance. The comparison shows that the approach to implement the inductive and capacitive coupling is a significant factor that affects the overall system performance since it directly influences the ability to transfer power, efficiency, and the ability to tolerate air-gap variations. Further, the relevant integration approaches allow the better use of magnetic and electric coupling paths. These findings indicate the persistence of the problem of the HWPT system design in attaining efficient and stable power transfer by optimized coordination of both inductive and capacitive coupling mechanisms.

7.4. Losses in hybrid WPT systems

HWPT systems are inevitably plagued by multiple types of losses due to more power transfer paths and multiple types of electromagnetic coupling mechanisms in a single structure. These losses have a noticeable effect in the system efficiency, thermal performance and long-term reliability. Compared to the conventional single path WPT systems, the hybrid system presents additional loss sources caused by the use of multiple resonant components, the operation at broader frequency ranges, and the stronger electromagnetic field interaction [82, 86]. The losses are due to the electromagnetic, electrical and material effects and are highly influenced by the operating frequency, magnitude of the voltage and current, coupling conditions, compensation network design, and the surrounding environment. Therefore, to reach high efficiency levels in HWPT systems, careful loss reduction is needed on as many levels as the component and the overall system [84].

7.4.1. Copper losses in hybrid WPT systems

Copper losses are some of the dominating loss mechanisms in HWPT systems. They are originating from the ohmic resistance of transmitting and receiving coils, interconnections and compensation networks and increase with the square of the current. In hybrid architectures, these losses are typically greater than in single path WPT systems because of the existence of multiple resonant channels and the

Table 4. Recommended strand gauge for a variety of frequency ranges.

Frequency range	AWG	Strand diameter in (mm)
100 kHz to 200 kHz	40	0.0799
200 kHz to 350 kHz	42	0.0635
350 kHz to 850 kHz	44	0.0508
850 kHz to 1.4 MHz	46	0.0398
1.4 MHz to 2.8 MHz	48	0.0316

circulations of higher currents in inductive and capacitive paths.

At high operating frequencies, copper losses are greatly aggravated by the skin effect as well as the proximity effect. The skin effect causes alternating current to be concentrated near the surface of the conductor and thereby decreases the effective cross-sectional area and increases AC resistance [16, 86]. The skin depth is given by [18]:

$$\delta = \sqrt{\frac{\rho_{copper}}{\pi \ f_{sw}\mu_0\mu_r}} \tag{3}$$

where ρ_{copper} is the electrical resistivity of copper, f is the working frequency, μ_r is the relative permeability of conductor and μ_0 is the permeability of free space, which is equal to $(4\pi \times 10{-}7\,\mathrm{H/m})$.

The proximity effect further increases to copper losses because of the magnetic field interactions between adjacent conductors such as closely spaced coil turns that cause eddy currents and current distribution distortions. Both effects are particularly severe in the case of compact coil geometries and high frequency HWPT systems.

To reduce these frequency dependent losses is the reason that Litz wire is used extensively for HWPT applications. Its structure of many thin, individually insulated strands allows current to be distributed more uniformly and greatly reduce skin and proximity effects (hence, AC resistance will be lower and efficiency will be improved) [16]. The recommended values of strand diameter and strand count, according to the American Wire Gauge (AWG) standard, for different frequency ranges are summarized in Table 4 in order to ensure minimum AC resistance and optimum high-frequency performance [96].

The effectiveness of Litz wire in reducing copper losses is further illustrated in Fig. 20, which compares the current density distribution in a solid copper conductor and a Litz wire. As shown, the solid conductor exhibits strong surface current concentration due to the skin effect, whereas the Litz wire demonstrates a much more uniform current distribution across its cross-section, confirming its superior performance for high-frequency operation [97].

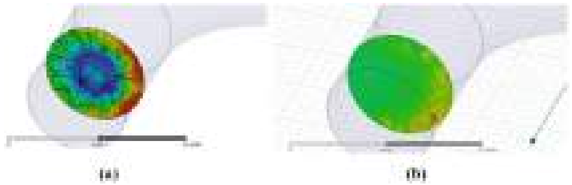

Fig. 20. Skin effect in terms of current density for copper cable versus Litz wire (a) Current density in a copper cable (b) Current density in litz wire.

Overall, optimizing copper losses in HWPT systems needs carefully weighing of the hardware factors of operating frequency, conductor geometry and material selection. The use of appropriately designed Litz wire along with optimized coil winding geometry and appropriate compensation network design plays a critical part in ensuring high efficiency, as well as thermal stress and reliable operation for HWPT applications.

7.4.2. Ferrite losses in hybrid WPT systems

Ferrite materials are popularly used in HWPT systems because of their good magnetic characteristics, which allow for good magnetic flux guidance, increased coupling between transmitter and receiver coils, and reduced electromagnetic leakage. Ferrites are the ferrimagnetic materials consisting of fine magnetic particles, which are glued together to attain solid form, have high magnetic responsiveness and are easily shaped, making them well suited for practical WPT applications [20, 34].

In HWPT systems ferrites are especially compatible with inductive coils. Their high relative permeability ($\mu r > 1000$) allows for low reluctance paths for magnetic flux and their very low electrical conductivity allows for low formation of eddy currents. As a result ferrite cores or backing layers are widely used for improving coupling coefficients and mutual inductance and often used behind coils as magnetic shielding for reducing stray flux and improving electromagnetic compatibility [22, 82, 98]. Despite these advantages, ferrites cause magnetic losses, mainly hysteresis losses and eddy current losses, although the influence of this loss is not too high when ferrite materials with narrow hysteresis loops are chosen [98].

In hybrid configurations, such losses might be affected by interactions between several electromagnetic fields in composite inductive-capacitive structures, thus making the careful material choice and magnetic design of such structures important. Studies show the use of high-performance ferrites with low coercivity and low loss factors in combination with optimized geometries enable the advantages of ferrites to be fully exploited with low losses even under strong magnetic fields in HWPT systems [89, 91, 94].

7.4.3. Eddy current losses in conductive plates

In HWPT systems, time-varying magnetic fields near conductive plates or grids induce eddy currents due to the alternating magnetic flux associated with inductive coupling. These currents circulate within conductive structures such as capacitive plates, shielding layers, or metallic supports, generating opposing magnetic fields in accordance with Lenz's law and dissipating energy as heat because of the material's finite electrical resistance. Consequently, eddy currents represent an additional loss mechanism that can degrade system efficiency if not properly mitigated [84, 85].

The power dissipated by eddy currents in a conductive body is given by

$$P_{eddy} = \rho \int_{V} J^2 dV \tag{4}$$

where ρ is the electrical resistivity of the material and J is the induced current density over the volume V, indicating that higher-resistivity materials generally lead to lower eddy current losses. These losses strongly depend on the magnetic field variation and the properties of the conductive structures, including geometry, thickness, electrical conductivity, magnetic permeability, operating frequency, and field magnitude. While large continuous metallic plates promote extensive eddy current loops and higher losses, segmented or slotted designs interrupt current paths and effectively reduce induced currents [84, 85].

7.4.4. Losses in compensation network elements (ESR losses)

In HWPT systems, resonant compensation networks based on inductors and capacitors are essential for efficient power transfer and resonant operation; however, their non-ideal nature introduces losses due to equivalent series resistance (ESR), which appear as heat dissipation and reduce system efficiency. In inductors, ESR results from winding resistance and frequency-dependent skin and proximity effects, and remains non-negligible even in air-core inductors due to finite conductor resistivity. In capacitors, ESR arises from dielectric losses and resistive effects of electrodes and internal connections. Owing to the large circulating reactive currents in compensation networks, even small ESR values can cause significant I^2R losses [84, 87].

The impact of ESR is commonly quantified using the quality factor Q, defined for inductors and capacitors as

$$Q_L = \frac{\omega L}{R_L}, Q_C = \frac{1}{\omega C R_C} \tag{5}$$

Where ω is the angular operating frequency, L and C denote the inductance and capacitance values, and RL and RC represent the ESR of the inductor and capacitor, respectively. By rearranging these expressions, the corresponding ESR values can be obtained as

$$R_L = \frac{\omega L}{Q_L}, \quad R_C = \frac{1}{Q_C \omega C} \tag{6}$$

It is well established that high quality factor (Q) components are crucial for minimizing ESR-related losses, particularly at high frequencies where reactive currents are large and quality factors degrade, often causing discrepancies between theoretical and experimental efficiencies. Therefore, selecting high-Q inductors and capacitors and designing compensation networks that limit excessive circulating reactive power are key to achieving high-efficiency hybrid WPT systems [84].

7.4.5. Switching losses in hybrid WPT systems

In HWPT systems, switching losses mainly result from the high-frequency operation of power converters that simultaneously excite the inductive and capacitive coupling paths at a single operating frequency. These losses occur during the turn-on and turn-off transitions of semiconductor devices, when voltage and current overlap across the switch and cause instantaneous power dissipation. As the operating frequency increases, the number of switching events rises accordingly, leading to higher cumulative switching losses and placing practical limits on overall system efficiency [82, 89].

To minimize these losses many HWPT architectures are based on well designed resonant compensation networks that provide near soft switching operation, especially zero voltage switching (ZVS). Under properly tuned resonant conditions, the inverter switches are commutated when drain-source is close to zero and thus the amount of energy dissipated in each switching process is reduced significantly. Both experimental measurements and simulation results reported in the literature confirm the effectiveness of appropriate resonance shaping in order to reduce switching losses while, at the same time, reducing voltage stress on power devices also at relatively high operating frequencies [84, 93, 95].

The selection of semiconductor technology also has an impact on switching associated losses in single frequency HWPT systems. Several studies emphasize the implementation of wide-bandgap devices,

Table 5. Comparison of near-field wireless power transfer techniques.

WPT Type	Transmission channel	Frequency	Distance	Ability to pass through obstacles	Efficiency (%)	Misalignment Tolerance
IPT	Magnetic Fields	kHz	Well (cm -m)	Low	good	Low
CPT	Electric Fields	MHz	Poor (mm)	Medium	Medium	High
HWPT	Magnetic and Electric Fields	(kHz ∼ MHz)	Better	High	good	Better

e.g., gallium nitride (GaN), and silicon carbide (SiC) transistors, because of their ability to achieve fast switching capability and low parasitic capacitances and switching energy compared with conventional silicon devices. These features make wide-bandgap devices especially suitable for high frequency HWPT operation, where switching losses would be the major efficiency-degrading factor [85, 99].

8. Comparison of inductive, capacitive, and hybrid WPT systems

Concluding on this review study, a full comparison of the three major methods of near-field WPT in terms of inductive, capacitive, and hybrid methods has been made, and is as is shown in Table 5. The comparison reveals that IPT systems tend to be most applicable in the areas where the transfer of power and high efficiency are necessary, but those systems are also likely to be affected by misalignment and conductive conditions. By contrast, the CPT systems provide a simpler overall coupling arrangement and superior compatibility with metallic environments, but are generally restricted in terms of transfer distance and power output this can be reached. The HWPT systems combine the two inductive and capacitive coupling methods into a common transmission system in which the magnetic and electric field coupling may interactions. This combination allows the hybrid systems to overcome a number of the drawbacks of single-mode methods, leading to a higher level of robustness, increase in misalignment tolerance and a broader operating range. In general, this review finds that HWPT is an opportunity in the future development of WPT systems, especially when efficiency, transferred power, air-gap distance, and system adaptability are to be balanced.

9. Conclusion

The review presents an in-depth analysis of inductive, capacitive and HWPT technologies, together with a special focus on hybrid technologies as these are becoming increasingly relevant in current wireless charging applications. While inductive and capacitive methods both have their own unique advantages, their actual implementation is frequently limited by factors concerning efficiency, voltage and current stress and sensitivity to misalignment. HWPT systems solve these issues by allowing power to be shared between inductive and capacitive power paths which can solve the problem of excessive current in inductive components and high voltage stress across capacitive interfaces. This is a balanced operation, which helps to contribute to an improved overall efficiency as well as improved system reliability. The success of hybrid systems is greatly affected by the design of compensation networks which are central to the specification of the resonance behavior, power transfer capability and robustness under different coupling and load conditions. Despite these advantages, the results of the loss mechanisms analysis suggest that the copper, magnetic, dielectric and power electronic losses are the main factors impacting the system performance. As a result, high efficiency in HWPT systems requires carefully and cooperatively developed couplers, compensation circuits and operating conditions. Overall, HWPT is an exciting and viable direction to take for the future of wireless charging technologies, especially in the electric vehicle applications. Continued research that targets optimized compensation strategies, reduction of losses and integrations of the systems at the system level are likely to further advance the efficiency, reliability and feasibility of these systems in real-world deployment environments.

Conflicts of interest

I/We hereby declare that there is no conflict of interest of any kind, whether financial, personal, professional, or institutional, that could have influenced or be perceived to influence the results, interpretation, or conclusions of the submitted manuscript. The research was conducted objectively and independently, without any external influence that could compromise its scientific integrity.

Funding

I/We confirm that this research did not receive any specific funding or financial support from any public, commercial, or not-for-profit funding agencies. The study was conducted using the authors' own resources, without any external sponsorship or financial assistance.

Author contributions

This paper provides a clear and structured review of WPT systems, covering their historical development and main classifications. It also gives a focused overview of inductive, capacitive, and hybrid systems, explaining how they work, how their circuits are designed, and the key factors that affect their performance and losses. In addition, the paper highlights and discusses different compensation circuit topologies used in HWPT systems, offering insights into their performance and practical challenges an area that has not been fully addressed in previous studies.

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