Chapter

Inductive Power Transfer: Past, Current, and Future Research

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Abstract

Electric vehicle (EV) technology has proven to be a propulsion technology of the future but urgently needs to address challenges such as lower-priced, reasonably sized EV for higher market penetration, higher life cycle efficiency, and increased power density. Range extension, in particular, in urban scenarios is critical. Inductive power transfer (IPT) technology solves simultaneously the electric hazard risks of conventional power cord battery chargers, but specially EV limited autonomy and related anxiety and even security. In this context, this chapter presents the past, current, and future research areas of IPT systems. A review of the main resonant compensation networks and prominent geometries of magnetic couplers is presented. Then, future research areas namely dynamic IPT and in-wheel IPT solutions are introduced along with their main challenges.

Keywords: wireless power transfer, inductive power transfer, magnetic coupler, electric vehicle

1. Introduction

Electric vehicles (EVs) have clear advantages over internal combustion engine (ICE) vehicles like reduced noise, full torque capability of the motor from a standstill position, and smaller carbon footprint. However, they are still limited in range by the batteries storage capacity. The current state of EV lithium-ion battery technology has a specific energy (energy per unit mass) that placed them behind that of gasoline by a factor of almost 100. Manufacturers workaround this limitation using larger battery packs, a costlier and bulkier solution to a limitation that follows EVs since their first appearance. In addition, lithium-ion batteries can take up to several hours to charge which will undoubtedly affect the driving habits of the users. **Table 1** identifies some EVs and EV truck models and their corresponding battery storage capacities. On average, an EV requires 185 Wh per kilometer, whereas EV trucks requires 1250 Wh to travel the same distance. These values together with the battery capacity define the EVs range.

All commercial available hybrid and battery EV models have in-built sockets that can charge the battery pack from a few kilowatts, in domestic chargers, up to 250 kW

Model	Battery capacity	Range	Energy consumption
	(kWh)	(km)	(kWh/km)
BMW i3	33	200	0.165
VW Golf-e	35.8	190	0.188
Nissan Leak	39.5	240	0.165
Tesla Model 3	55	310	0.177
Chevy Bolt	65	417	0.156
Ford Transit	68	315	0.216
Toyota bZ4X	71.4	380	0.188
Cupra Born	77	450	0.171
Audi e-tron	95	360	0.264
Ford Mustang	99	539	0.184
Tesla Model S	100	510	0.196
Lucid Air	105	630	0.167
Mercedes EQS	107.8	640	0.168
Trucks			
Freightliner eM2	315	370	0.851
eCascadia	475	402	1.18
Tesla Semi	500	482	0.829
Volvo VNR	565	443	1.275
Nikola Tre	753	563	1.337

Table 1.
Battery specifications of different BEVs.

Operating level	Input voltage	Maximum current	Output power	Charging time
	(V)	(A)	(kW)	(h)
AC Level 1	120	12–16	1.08–19	6–24
AC Level 2	208–240	16–80	3.3–19.2	1–3
AC Level 3	208/480/600	150–400	≥19.2	0.5–1.5
DC Level 1	200–450	80	36	0.5–1.3
DC Level 2	200–450	200	90	0.3–1.3
DC Level 3	200–600	400	240	0.25–1

Table 2.
Power levels of EV chargers.

in supercharging stations. The vehicles can be charged from AC or DC power supply with different voltage and current values. According to Society of Automotive Engineers (SAE) standards, AC chargers can be divided into three different power levels, as depicted in **Table 2**. The AC levels 1 and 2 are intended for domestic use. The AC level 3 is directly supplied from the grid, and they are usually found in commercial locations. The DC charging systems require a dedicated infrastructure, and they are usually mounted at parking area or public charging stations. DC chargers regulate the voltage ratings according to the battery packs. Moreover, they bypass the vehicle on-board controller and charger the batteries at a higher current rate than AC chargers. The supercharger of Tesla is one example where this strategy is adopted, allowing a maximum charging power of 250 kW.

The high power rating of level 3 AC/DC chargers require large power demands from the grid simultaneously. Current grid infrastructures are not prepared for a wide-scale installation of theses chargers. As a consequence, the increase of EVs will create longer queues in existing charging areas. Additionally, the need of human intervention in the charging process increases the risk of shock hazard and electrocution. New wireless charging technologies are then being studied as viable replacements to conductive chargers.

Wireless power transfer (WPT) technology enables the energy transfer between two systems without any contact. The concept dates from the late nineteenth century where Prof. Heinrich Hertz demonstrated for the first-time electromagnetic wave propagation in free space using a spark to generate high-frequency (HF) power and to detect it in the receiving end. Nikola Tesla, in 1899, conducted a series of experiments in Colorado Springs where he devised the best approach for WPT. During its stay in Colorado Springs, Tesla reported power transfer capabilities over distances superior to 18 m between the transmitter and receiver coils. Tesla accomplishments in Colorado Springs mark the beginning of WPT technology.

WPT systems can be classified as far-field and near-field technologies [1, 2]. The first group includes radio frequency/microwave techniques that radiate energy isotropically or toward some direction through beam-forming. However, the high-frequency spectrum (300 MHz to 300 GHz) makes them undesired for EVs application due to the effects of electric fields in the human body. The near-field group includes the techniques that use variable magnetic or electric fields to accomplish power transfer between two coupled sides. Electric field coupling, also referred as capacitive power transfer, uses a pair of plates to form a capacitor with air as a medium. In this way, the electric field created between the two plates enables the energy transfer between both plates. One advantage of electric field coupling is the possibility of energy transfer through metallic materials, since a capacitor is formed between each conductor plate and the metallic surface. Moreover, they are less sensitive to lateral displacements as the electric field between the plates “bends” with the displacement value. However, the low capacitance between two plates at high air gap values limits the power transfer capabilities to a few kilowatts.

Magnetic field coupling techniques use a varying magnetic field to achieve power transfer, and it includes inductive coupling and magnetic resonance coupling (MRC) techniques. The second technique is based on evanescent-wave coupling that accomplishes energy transfer between two resonant coils through varying or oscillating magnetic fields. The two resonant coils are strongly coupled and operate at the same resonant frequency; thus high-power throughput is achieved with small leakage to nonresonant externalities. Several studies demonstrated the capabilities of power transfer over larger distances while charging multiple devices using MRC technique [3]. However, the high operating frequency (range of MHz) and the complex tuning of both sides are unsuitable for EVs charging applications.

Inductive coupling, also referred as inductive power transfer (IPT) system, transfers energy between two coupled coils. The transmitter coil generates a varying magnetic field which induces a voltage across the receiver coil, according to Faraday’s law. To boost the quality factors of the coils at low operating frequencies (from 10 kHz to 250 kHz), compensation capacitors are added to the circuit. IPT systems gain popularity and its applicability in EVs are being investigated by the scientific community since the early twenty-first century. Since then, a lot of works present efficiency values as high as 97% and in line to conductive chargers [1, 4].

This chapter reviews IPT technology and its applicability to EVs. The use of electric propulsion systems in vehicles has formulated its construction methods and opened new opportunities. The shift of the powertrain into the wheels, the inclusion autonomous guiding systems is changing the dynamic of vehicles. IPT technology also plays an important role in the massification of EVs. Therefore, this chapters discusses the main research fields of IPT systems including past trends of research. Then, recent developments are reviewed along with future research areas.

2. IPT system and main development areas

This section explores the main constituents of IPT systems and main development areas. These areas are related to the electrical configuration of the compensation networks, power converters topology, and design optimization of the magnetic coupling structure.

2.1 Basic IPT system configuration

An IPT system, in its simplest form, uses two magnetically coupled coils, also known as power pads, to transfer energy between the off-board and on-board sides, as illustrated in **Figure 1**. The off-board side usually comprises a high-frequency power supply, a resonant compensation network, and the transmitter (Trm) power pad of a magnetic coupler (MC). The on-board side includes the receiver (Rec) power pad of the MC, a resonant compensation network, the on-board converter, and battery pack. An intrinsic characteristic of EV IPT systems is movement of Rec pad in relation to

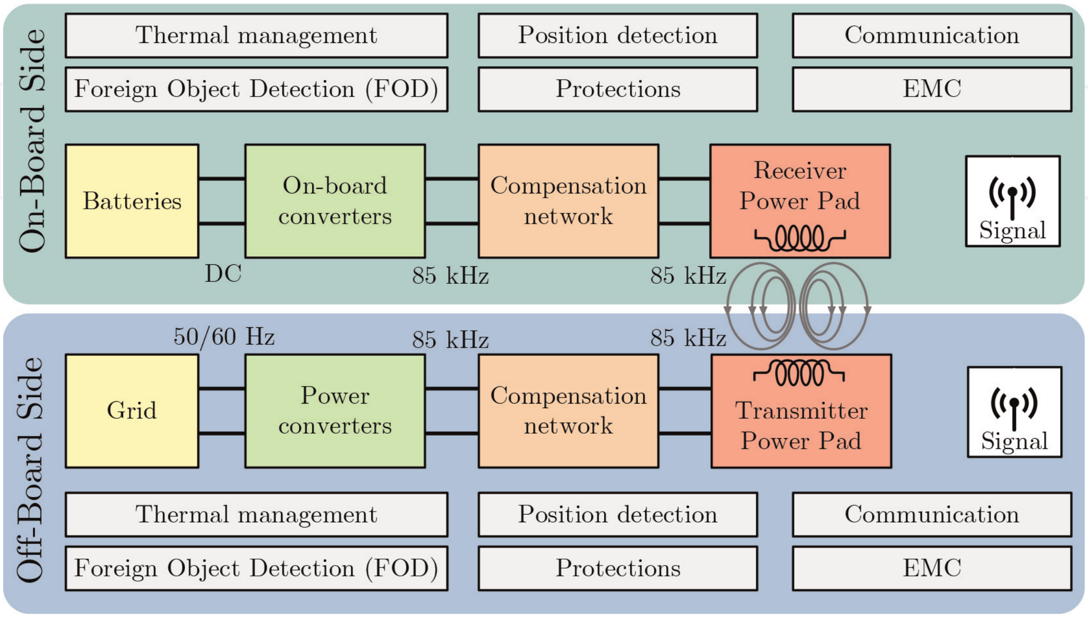


Figure 1.
Overview of a typical IPT system with its main components.

Trm pad due to the vehicle's movement. As a consequence, the coupling factor has a high variability which directly impacts the system power transfer capabilities. High operating frequencies together with resonant compensation networks are used to increase power transfer capabilities minimizing, at the same time, the volt-ampere rating and commutation losses of the power supply. The free-movement of the Rec pad together with the high operating frequency creates new challenges like vehicle position detection, stray magnetic fields compliance, and foreign object detection between the Trm and Rec pads. **Figure 1** summarizes the main concerns in both off-board and on-board sides.

IPT systems are divided into static (SIPT) and dynamic charging (DIPT) modes. In the first mode, the vehicle is charger in a fixed position whereas in second mode, the charging process occurs with the vehicle moving along the roadway. Nevertheless, four main research areas are found for IPT systems: magnetic couplers, resonant configurations, circuit analysis, and controllers and control. **Figure 2** illustrates the main research areas and subcategories of IPT systems. The first advancements in EV IPT occurred for static IPT mode. The energy transfer from a still position eliminates the variable coupling effect during the charging process and simplifies the analysis. Electrical circuit analysis for classical IPT systems is already well defined in the literature [5]. Controllers and control research areas have also well-established solutions. On the other hand, the study of new resonant network configurations and MC geometries were object of research over the last decades with new findings being reported in the literature on a weekly basis. The following subsections detail the main findings in resonant configurations and MC research areas.

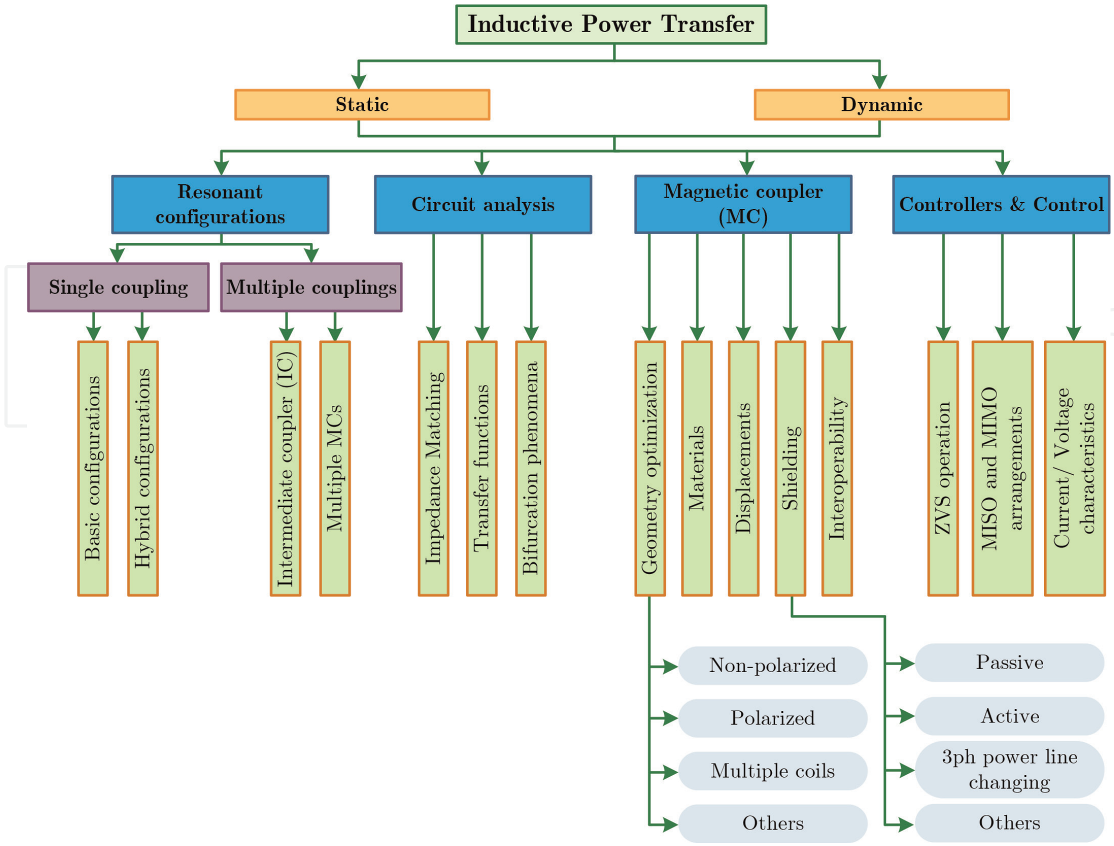


Figure 2.
Main research areas of IPT systems.

2.2 Research areas

2.2.1 Resonant configurations

Early single-coupling IPT systems had limited power transfer capabilities caused by the poor coupling between the transmitter and receiver power pads of the MC coupler [1]. The simplest way to compensate the self-inductance of the power pad coils is to place a capacitor in each side, either in series or parallel. Four classical resonant configurations can then be derived: Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP), as illustrated in **Figure 3**. The positioning of the capacitor changes the intrinsic characteristics of the circuit and their response to coupling, load, and frequency variations [6, 7]. The SS configuration offers output current independence of load and resonant frequency, and it is preferable for high-power applications. PS and PP configurations, on the other hand, limit the input current in the event of total absence of the vehicle, and they are ideal for dynamic applications [8, 9].

Hybrid configurations use multiple reactive components to form high-order resonant configurations like the LCL-LCL, LCL-S, S-SP, and SP-S, as depicted in **Figure 3**. These new compensation networks offer power transfer capabilities over wider coupling range, load-independent zero-voltage switching (ZVS), zero-phase angle (ZPA), and voltage/current source characteristics. One of the first hybrid configurations used in IPT systems was the LCL configuration [10–12]. When applied in the off-board side, the LCL configuration offers load-independent current source characteristics in the second L, if both values of L are the same [10]. Therefore, this configuration is often used in dynamic applications, since the vehicle's absence does not compromise the integrity of the power supply [4]. The LCL configuration is also employed in the on-board side to provide a smooth power transition between fully-on and fully-off [13] or to keep an unitary power factor in the transmitter side [14]. The S-SP configuration offers mutual coupling and load-independent voltage gain. In addition, it can realize good output voltage stability and low circulating losses under the condition of wide parameters variations [15]. The SP/S configuration was proposed in [16]. This configuration combines the characteristics of SS and PS configurations and allows higher displacement tolerances. The studies [17–19] evaluate high-order

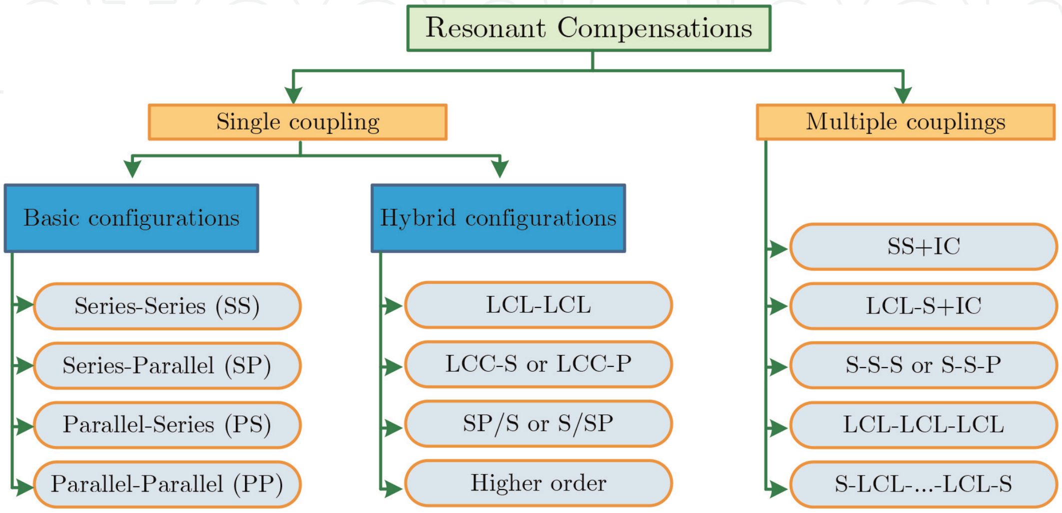


Figure 3.
Classification of resonant configurations in IPT systems.

configurations with different L and C arrangements in terms of soft-switching, system efficiency, and zero-phase angle. The S-CLC compensation network was proposed in [20]. The proposed configuration offers easier achievement of ZPA and ZVS. In addition, it offers CC and CV modes and simplifies the control circuit design.

Both classical and hybrid configurations have limited power transfer capabilities in charging scenarios where the vehicle has large ground clearances and is lateral displaced from the transmitted power pad. The low mutual coupling value requires high current values on the off-board side and as a consequence, higher magnetic fields which may lead to adverse problems in the human body. Intermediate coil (IC) systems, also known as multi-coil resonators or relay coil IPT systems, place resonators between the transmitter and receiver pads to enhance the magnetic link [21–24]. The resonators are formed by a magnetic coupled coil and a capacitor, usually tuned at a higher frequency than the operating frequency. Several studies show that ICs offer better efficiency values, less component stress, and better flux leakage control [25, 26]. The mid-air positioning of an IC is, however, incompatible with an EV IPT charger. Therefore, they are placed in proximity or even in a coplanar fashion with the Trm coil. In this configuration, ICs are often used as a replacement to the ferromagnetic core of the Trm pad, making them suitable for dynamic applications. The inclusion of IC with a classic or hybrid resonant configuration modifies its intrinsic characteristics altogether. As an example, the SS configuration with an IC exhibits both load-independent voltage and current source characteristics in different operating frequencies, while the Trm current is shifted to the intermediate circuit, thus reducing the commutation losses. Recent works use several ICs to increase robustness of EV IPT systems against the unavoidable lateral displacements [27]. This means the total number of admissible configurations increases drastically each time a new IC or a variant of a hybrid resonant configuration is proposed, meaning that multiple resonant configurations can satisfy a specific EV IPT application. Therefore, the selection of the most adequate resonant configuration can be decided in the smallest detail like voltage stress across the capacitors or even the configuration with the minimum number of components.

The use of multiple couplers connected with one another is also investigated for delivering power to multiple loads or for dynamic applications. **Figure 4** exemplifies a multicoupler configuration. The authors in [28] use a LCL-LCL-LCL configuration as a contactless interface for multiple Trms and Rec sides. The use of a parallel compensation in the intermediate circuit minimizes the VAr requirements. A n-coupler S-LCL- … -LCL-S configuration is investigated in [29] to power multiple loads. The proposed configuration ensures constant load current values regardless of load variations. The double coupling S-S-P and S-S-S configurations are analyzed in [30]. The S-S-S exhibits load-independent CV mode if all natural resonant frequencies match the switching frequency. On the other hand, CC mode is achieved in the same conditions for the S-S-P configuration. In addition, both configurations exhibit ZPA during CC or CV modes. Moreover, S-S-X double coupling systems limit the Trm current in the absence of the receiver, making them ideal for dynamic IPT applications.

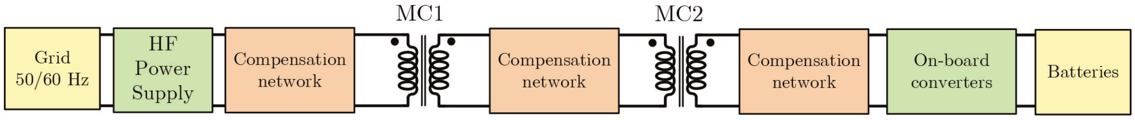


Figure 4.
Equivalent circuit of a double coupling system.

2.2.2 Magnetic couplers

Magnetic couplers (MCs) are considered the key element in IPT systems as they enable the energy transfer without physical contacts using a variable magnetic field. The MC resembles a conventional 50 Hz transformer with a Trm and Rec pads. A clear characteristic of IPT systems is the spatial freedom of the Rec pad toward the Trm pad due the vehicle's movement. The relative positioning of the Rec pad has a direct impact on the coupling factor, and it ranges between 0.05 and 0.3. The degrees of freedom that the receiver pad may be subject to are as follows:

- *Vertical Displacement*—corresponds to the ground clearance of the vehicle.
- *Lateral displacement*—corresponds to the lateral distance between the transmitter and receiver pad center points.
- *Tilt*—corresponds to the inclination angle of the receiver pad.
- *Rotation*—corresponds to the rotational angle between the transmitter and receiver pads along the horizontal plane (only applicable to in-wheel IPT system).

Figure 5 illustrates the different degrees of freedom in different perspectives. The vertical displacement and tilt degrees of freedom depend on the vehicle's type (Sedan, SUV, etc) and, in normal operation, these values remain approximately constant. The lateral displacement and rotation degrees of freedom, on the other hand, depend on the drivers ability to park the vehicle or driving it in a straight line. The guideline SAEJ 2954 suggests that a minimum lateral tolerance of ±150 mm is sufficient for an average driver to drive/park the vehicle correctly. Extreme charging positions with large vertical and lateral displacements reduce the coupling factor of the MC and increase the leakage magnetic fields. Over the years, many researchers have address these issues by proposing new coil and core arrangements with better materials and shield techniques.

2.2.3 Transmitter coil: track versus pad

MCs commonly have a unitary size ratio between the Trm and Rec pads, especially in SIPT. DIPT systems, on the other hand, require longer charging areas and elongated

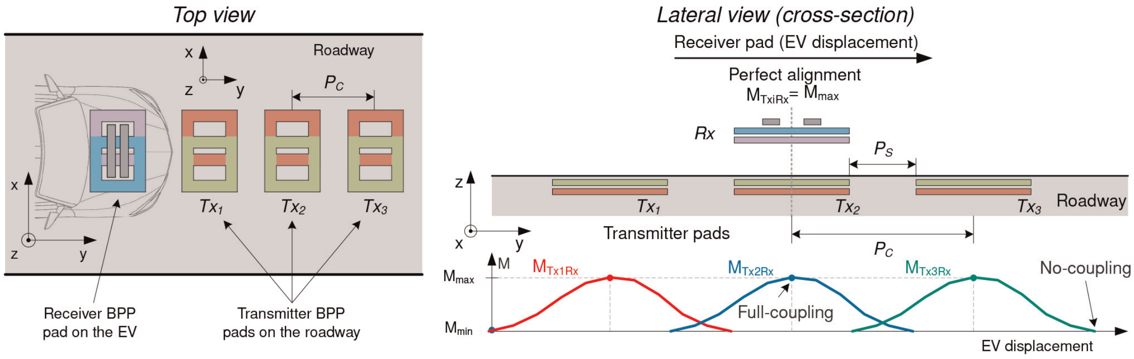


Figure 5.
DIPT system, top view (left side), and lateral cross-sectional view (right side).

tracks can be applied instead of a set of smaller Trm pads. The first option offers a continuous power transfer with constant coupling factor. The large inductance of the track, however, reduces the overall coupling factor and requires higher voltage levels to drive the necessary Trm current. Additionally, most power track systems prototypes operate with frequencies around 20 kHz instead of the 85 kHz recommended by the SAEJ 2954 standard. Furthermore, compliance with the ICNIRP guidelines to human exposure leakage magnetic field levels is only achieved at wider distances. The second option places several discrete transmitter pads along the roadway where the power transfer to the vehicle occurs, as illustrated in **Figure 5**. Since both approaches exhibit merits, there is still an open discussion on the appropriate solution for EV charging applications. However, the segmented solution is gaining terrain [4].

The impact of the EV movement in the mutual inductance (M_{12}) profile between the Trm and Rec pads in DIPT systems is visible in **Figure 5**. The bell-shaped pattern of M_{12} is caused by the lateral displacements between both pads. This behavior occurs for both static and dynamic IPT systems, and the difference resides in the range variation of M_{12}. For SIPT systems, M_{12} varies between a perfect aligned charging position, which corresponds to the peak of the bell shape curve, and a minimum M_{12} in the worst charging position in terms of vertical and lateral displacements. This minimum value also ensures that the rated characteristics of the overall system are not exceeded. Likewise, DIPT systems exhibit the same maximum value as static systems, but the minimum value is zero. This no-coupling charging position M_{12} = 0H) occurs right before the receiver pad enters the first transmitter pad (first point of the red curve) and soon after exiting the last transmitter (last point of the green curve). Therefore, DIPT controllers must cope with no-coupling scenarios and ensure that the limits for a safe operation are not exceeded.

2.2.4 Pad geometry

A power pad, in its basic form, is formed by a single coil, a ferromagnetic core and shield. Early designs used pot cores and U- and E-shaped cores but proved unfeasible for applications with large air gap and lateral displacements. The Auckland research group optimized the circular pad (CP) geometry back in 2009, by fracturing the ferromagnetic disk into several ferrite bars [31]. The construction simplicity makes it one of the most used MCs in current IPT systems. A limiting factor of CP is the total decoupling between the Trm and Rec pads when the lateral displacements exceeds the size of the CP by 40% or more and largers CPs are required to provide larger tolerances. To overcome this limitation, the same research group proposed several geometry alternatives with multiple coils including the solenoid pad (SP) in 2010 [32] and the double-D pad (DDP) and the bipolar pad (BPP) in 2011 [33, 34]. The aforementioned geometries are depicted in **Figure 6**. The SP corresponds to two solenoids connected electrically in series with a ferromagnetic core in the middle. This design exhibits high tolerance to both vertical and lateral displacements. Unfortunately, it produces unwanted magnetic fields in the back of the geometry and a shield is required to contain the stray magnetic fields. The DDP arose as a viable replacements to SP, by placing two D-shaped coils on top of a fragmented ferromagnetic core, as illustrated in **Figure 6**. The ferromagnetic core forwards the magnetic flux with little stray magnetic fields in the back of the pad. The DDP offers greater performance when compared with the CP in both vertical and lateral displacements with a smaller MC size. This geometry, however, has a poorer coupling pattern to displacements along the length of the DDP. To overcome this limitation the research group proposed

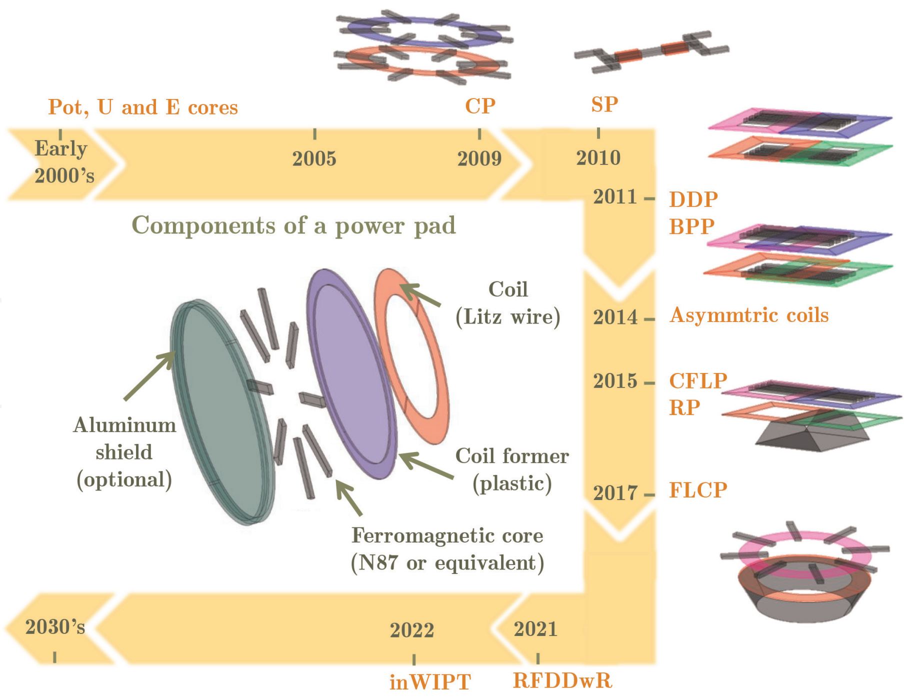


Figure 6.
Chronological evolution of MC geometries.

a 3rd coil, referred as quadrature coil (Q), and placed it in the Rec pad to improve the coupling. The Q coil is decoupled from the other two coils and captures the flux from the Trm pad in the event of lateral displacements. The BPP is formed by two slightly overlapped coils, decoupled from one another, and placed over a ferromagnetic core. The overlap coil design ensures the decrease of the induced power in one coil due to lateral displacement is compensated by the increase of the induced power in the other coil. This geometry has similar tolerance as the DDP + Q geometry using 30% less copper.

The Korea Advanced Institute of Technology (KAIST) introduces in 2014 the asymmetric coils geometry for SIPT systems. The geometry uses Trm and Rec pads with different size ratios to achieve large lateral displacement tolerances. The same group is also a reference on DIPT applications using elongated transmitter pads. The ultraslim S-type geometry, introduced in 2015, uses S-shape ferromagnetic cores along the roadway to channel the magnetic fields of an elongated wire. The solution allows a large lateral displacement of 300 mm with a compact Trm pad with the dimensions of 100x30x300 mm. In the same year, the research group from the Swiss Federal Institute of Technology (ETH) Zurich optimizes the rectangular pad (RP) geometry with a stripped ferromagnetic core. The optimized RP showed equivalent performance when compared with the DDP in terms vertical and lateral displacements for output powers up to 50 kW [35].

One major concern in DIPT systems is the cost of manufacturing the transmitter pads. The ferromagnetic core weights more than 50% in the total construction costs of the aforementioned geometries. The Auckland research group develops in 2015 a concrete ferrite-less pad (CFLP) geometry that uses a “pipe” coil instead of a ferromagnetic core to channel the flux in the backside of double-D coils [36]. The design offers reasonable coupling profiles and lateral displacement tolerances with vertical variations between 150 and 200 mm. Moreover, high currents can be tolerated in ferrite-less geometries, since there is no ferromagnetic material that can be saturated.

In 2017, the research group from University of Coimbra proposed a variant of the CP without the ferromagnetic core. The geometry, referred to as ferrite-less circular pad (FLCP), uses a cone-shaped coil to channel the magnetic flux in the backside of the Trm coil [37]. The coupling profile shows a reduction around 15% when compared with the CP in both vertical and lateral displacements. Another ferrite-less variant of circular geometries was presented in [38]. The new geometry, referred as circular non-ferrite pad (CNFP), uses a cancelation coil below the main circular coil to reduce the leakage flux around the geometry. The coils are wounded with one single wire in a series-opposing configuration that generates opposing magnetic fields. The turns ratio and height between the main and cancelation coils dictates effectiveness of the canceling field at a given lateral displacement. The coupling factors are lower than a CP but with reasonable values for dynamic operation.

Figure 6 summarizes the evolution of MCs since early 2000s. Most of the proposed discrete geometries appeared between 2010 and 2015. Since then, researchers have shift focus toward optimizing leakage magnetic stray fields using cancelation coils while avoiding entirely ferromagnetic cores [27, 39]. The advancements in IPT systems made in the last years paved the way to commercially available SIPT solutions. Their applicability ranges from simple parking lot IPT chargers for standard EVs to high-power (≈200 kW) solutions in transportation sector like city busses. Now, there are still many challenges to transit from SIPT into commercial DIPT systems.

3. Active and future research

3.1 Dynamic IPT systems

The movement of the vehicle creates additional challenges relatively to SIPT. Among them, the preferable Trm topology (elongated or segmented), vehicle positioning detection, road infrastructure, and communication system. **Figure 7** summarizes current and future developments regarding DIPT.

Early DIPT applications employed long-track coils, typically between 10 and 100 m long, allowing the simultaneous charging of multiple vehicles. Different magnetic core shapes were analyzed by KAIST researchers for long-track DIPT systems such as E, U, W, I, S, X-type (or cross-segmented) and, ultra-slim S-type. The last

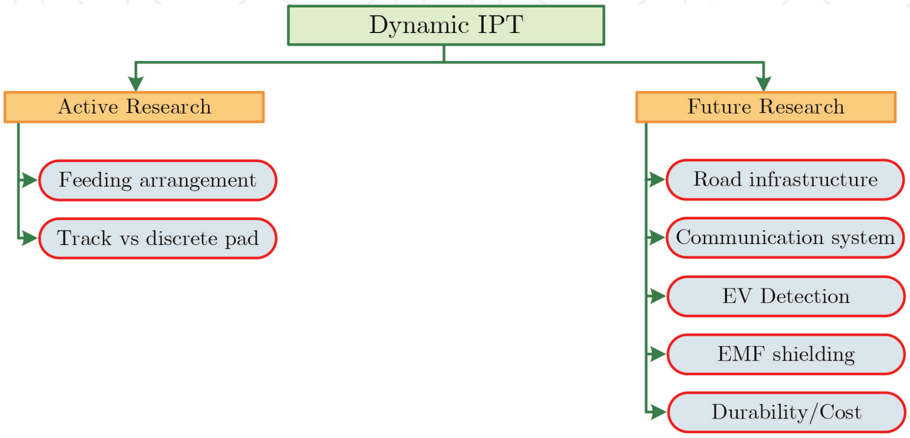


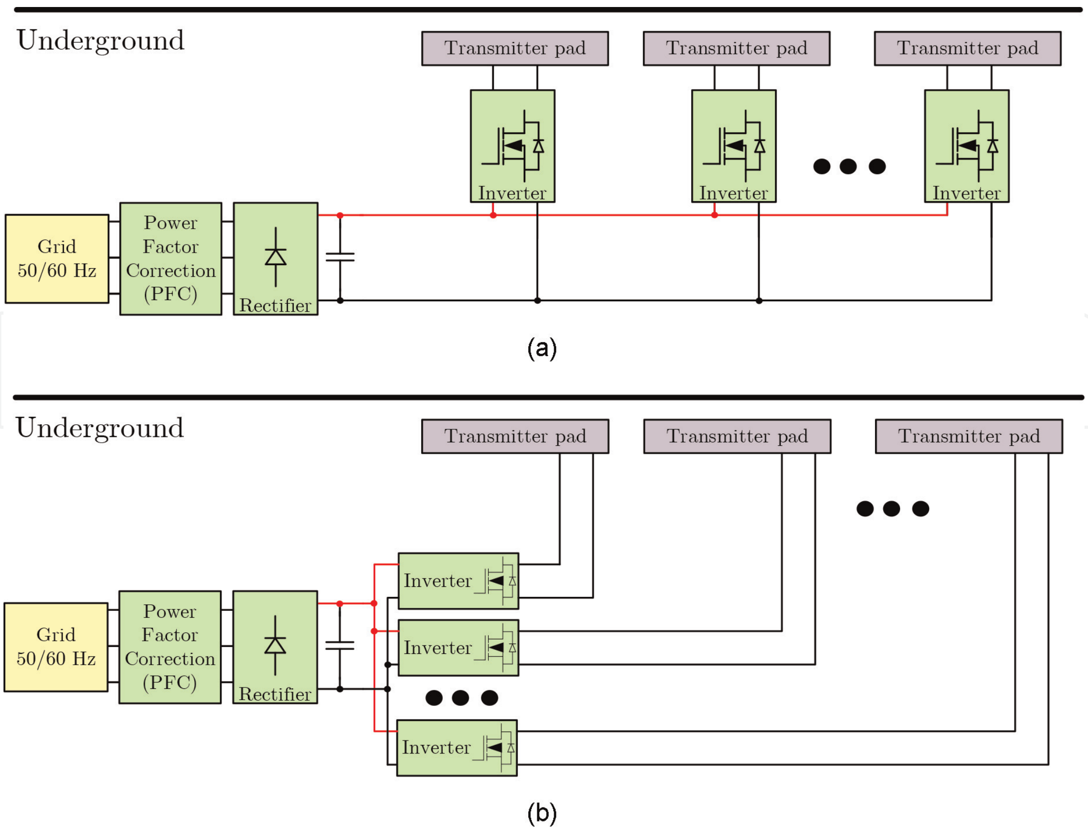
Figure 7.
Dynamic IPT current and future research.

two, ultra-slim S-type and X-type, present the best characteristics, low leakage EMF, and high efficiency with the ability for large air gap and lateral displacements.

Despite the core configuration, long-track coils still create unwanted leakage EMF, since the track is driven by a current during the vehicle's absence. Alternatively, the long-track coil can be divided into multiple subtracks, where each subtrack can be activated and deactivated by supplying them through a switch box fed by a HF inverter. Different types of switch boxes can be used including centralized switching, distributed switching, or auto-compensation switches.

Smaller segmented pads where the overall dimension of the transmitter is similar to the receiver, typically around 1 m, are an active focus of research. The design and optimization ferrite-less geometries in terms of power transfer capabilities and leakage flux control is ongoing. The use of reflection coils, also known as cancelation coils, are being employed in ferrite geometries like the DDP to form a ferrite-less double-D pad with reflective coil (FLDDwR) with controllable leakage flux [38]. Other geometries place an IC closer to the receiver pad to constrain the leakage flux lines in charging conditions with higher air gap values [27].

Besides the MC geometry, the pads disposition along the roadway and their feeding arrangement is also object of investigation. The simplest configuration uses a single high-frequency (HF) power supply to feed multiple Trms, either in series or parallel. Alternatively, lower HF power supplies can be employed to power each Trm individually. The configuration of **Figure 8a** extends the DC bus from the roadside cabinet to each individual converter and respective power pad. This configuration is simple to implement but arises safety concerns as it uses high-voltage and high-power rating DC lines. The configuration from



(a)

(b)

Figure 8.
Overview of different segmented pad configurations.

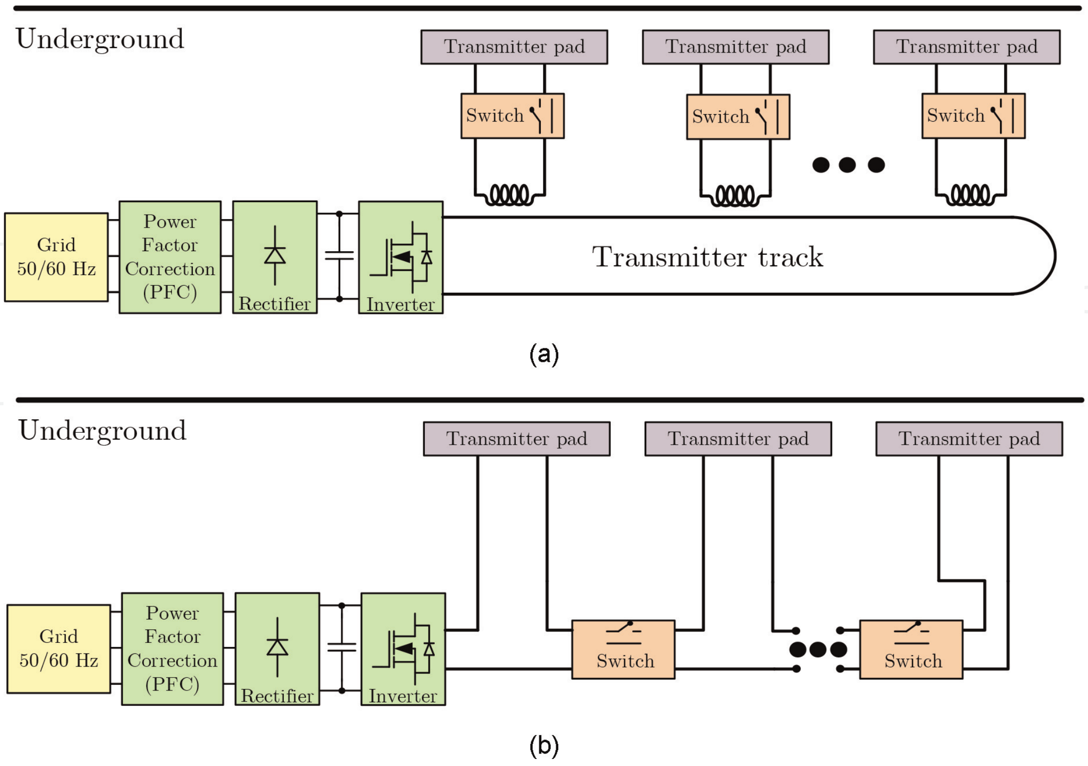


Figure 9.
Overview of different segmented pad configurations with switch breaks.

Figure 8b overcomes the limitations of **Figure 8a** and the maintenance of the power converters, since they are all concentrated in the roadside cabinet. Unfortunately, the installation costs increase exponentially with the number of segmented power pads.

Figure 9a depicts a segmented pad configuration that allows an independent operation of each segmented pad. This feature is accomplished by using a magnetic coupler connected to a bidirectional AC switch that turns "on" or "off" the power pad. A benefit of such configuration is individual maintenance of each segmented pad without affecting the normal operation of the remaining system. The configuration illustrated in **Figure 9b** uses two turn Trm track configuration in which the current direction in one of the turns can be changed using the switch boxes to turn "on" or "off" the magnetic fields in a specific segmented pad. Since all switch boxes are connected in series, all components have to be rated for the nominal current of the Trm pad. Other feeding arrangements include a second coupler or the Trms are connected in series in a push-pull array configuration. All existing configurations have merits and limitations, but additional research is required to assess the preferable configuration in a large-scale application.

Among the future research in DIPT, different research topics are being aim of research. These include the adaptation of road infrastructure to wireless technology and the use of magnetizable concrete to boost the effective coupling factor. Furthermore, a communication system, between the off-board and on-board sides, is required that synchronizes power converters and exchange batteries information. Additionally, precise EV detection systems are needed to activate and deactivate the transmitter pads, thus avoiding unnecessary no-load operation. These systems can use optical or magnetic sensors to detect the position of the vehicle or estimation algorithms that use off-board electrical quantities together with mapping methodologies and artificial intelligence solutions. Finally, the continuous optimization of shielding solutions with resource to cancelation coils or optimized MC geometries.

3.2 In-wheel

One milestone of IPT technology is its applicability into heavy duty vehicles like trucks or off-road vehicles. Unfortunately, these vehicles have typical ground clearances between 350 and 550 mm. This limitation requires high driving current on the off-board side to transfer significant amounts of power. However, the high leakage magnetic fields pose significant concern to the human body. New MC geometries with leakage flux control are under investigation, as stated the previous section. One way to maintain the air gap between the Trm and Rec pads of the MC to a minimum and independent of the vehicle type is to use the wheels as an intermediary stage between the off-board and on-board sides of the vehicle. An early mention of In-wheel IPT (inWIPT) system was made in 2017, and the authors envisioned the placement of several coils in the inner rubber surface of the tire [40]. Each coil is connected in series with a capacitor and a H-bridge rectifier to form a DC bus. The drawback in the proposed configuration is the use of slip rings to transfer the DC bus from the wheel to the on-board side. The low reliability and high maintenance of carbon brushes make it an undesired solution. Alternatively, the receiver pad can be placed in the inner side of the rim to reduce the air gap between the transmitter and receiver pads [41]. This approach, however, requires the use of carbon fiber-reinforced plastic rims, a costlier solution to traditional aluminum rims. The research group from University of Coimbra proposed in 2021 a double coupling in-WIPT system, illustrated in **Figure 10** [30]. The energy transfer from the off-board side to the on-board side occurs via two consecutive MCs without any physical contacts. The proposed solution avoids the use of slip rings to transfer the energy between the wheel and the on-board side. In addition, the aluminum rim shields the leakage flux lines above the receiver coils and avoids the use of additional shielding materials.

In-wheel IPT systems just follow the tendency of moving the powertrain and batteries charger from the vehicle into the wheels, leaving only the batteries itself within the vehicle [42]. The development of new airless tire designs with sustainable and nonmagnetic materials (glass fiber and resins), like the Uptis model from Michelin, strengthen the viability of inWIPT systems. These new airless tire designs also eliminate the risk of pressure increase in the tire caused by the Joule losses of the coils placed within the tire. This solution, however, presents new challenges, among them the sizing of both

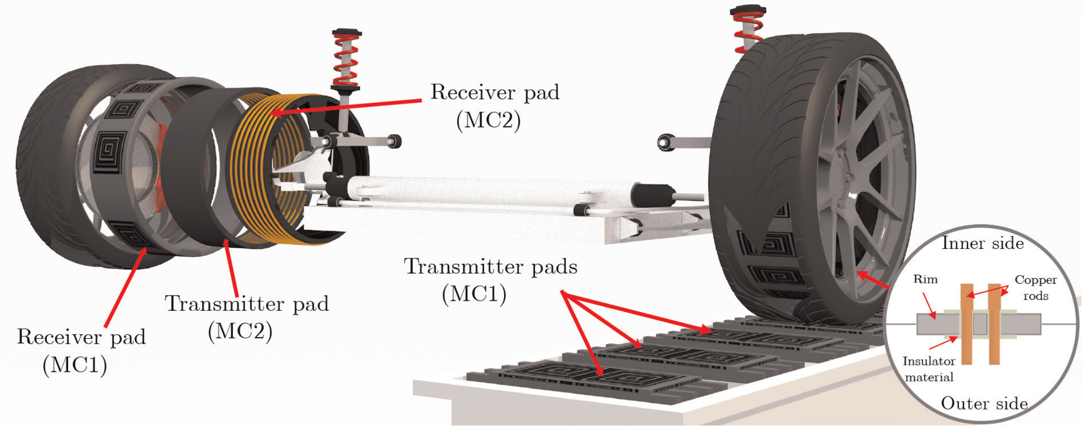


Figure 10.
Double coupling inWIPT.

MCs, since traditional IPT approaches do not take into account the curvature of the coils. Moreover, the rotational effect requires additional research regarding coils support, temperature dissipation, and power flow regulation in both static and dynamic modes.

4. Conclusions

EV technology has proven to be a propulsion technology of the future but urgently needs to address challenges such as lower-priced, reasonably sized EV for higher market penetration, higher life cycle efficiency, and increased power density. Nonetheless, this will not be enough if the issue related to reluctance to EV adoption due to the lack of charging stations, despite number increase, or especially limited range is not solved. Therefore, range extension, particularly in urban scenarios, is critical. IPT technology solves these limitations and offers additional recharging comfort when compared with traditional combustion vehicles.

Over the last decade, a great number of IPT solutions reached the market for static charging of small EVs and busses. These already available solutions offer high-power transfer capabilities with efficiency values comparable to plug-in chargers. Despite these advancements, there are still many challenges that need to be addressed, especially in dynamic IPT applications. Therefore, this chapter revises the past, active, and future research areas. During this transition, review of the resonant compensations and chronological evolution of MC geometry is presented. Then, future research areas namely DIPT and inWIPT systems are presented along with their main challenges not yet addressed.

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