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TOPICAL REVIEW

# An Extensive Overview of Inductive Charging Technologies for Stationary and In-Motion Electric Vehicles

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**ABSTRACT** The wireless power transfer (WPT) system holds potential as a viable solution for charging electric vehicles (EVs) owing to its benefits including safety, automated operation, efficiency, and simplicity. Among the WPT technologies, inductive power transfer (IPT) stands out as particularly well-suited for charging EV batteries. This is primarily due to its capability to transmit high power across considerable air gap distances, accommodating the ground clearance requirements of most EVs, operating automatically without driver involvement, ensuring safety and convenience even in challenging conditions such as snow, rain, and dust, and offering maintenance-free operation by eliminating the need for plug-in connections. This manuscript provides a comprehensive exploration and analysis of the progress made in IPT technology. The manuscript introduces the operational principle of the IPT system and highlights the benefits of its components. Additionally, it discusses the transmitter and receiver architectures, outlines the characteristics of various charging pads, in case of both stationary and in-motion charging scenarios. Furthermore, it delves into different compensation circuit topologies and various WPT designs based on compensating structures associated with the IPT system. It also categorizes the converter topologies utilized in the system and presents the operating technique for each one. In addition, the ongoing research and development (R&D) endeavors pertaining to each technology are discussed, addressing challenges, existing gaps, and offering recommendations for further advancements in both stationary and in-motion charging applications.

**INDEX TERMS** Review, IPT technology, R&D activities, compensation networks, control, challenges, opportunities.

## I. INTRODUCTION

In recent decades, transportation sector comes as one of the main sources of harmful emissions and greenhouse gases (GHG). It mainly depends on fossil fuels, such as petroleum, which are non-permanent sources of energy and likely to be depleted over time. There is an urgent need to electrify our transportation sector by promoting electric vehicles (EVs). Electric vehicles will not only assist to reduce reliance on fossil fuels, but will also lower the amount of energy consumed in transportation since electric drive systems are more efficient than internal combustion engines. These two items will help to reduce GHG emissions from transportation sector. Mass deployment of EV realizes challenges, such as driving range anxiety, long charging time, and infrastructure readiness.

There are three strategies for EV battery charging [1]; Wireless (stationary and in-motion), plug-in, and replacing batteries charging. In case of charging by replacing batteries, empty EV battery is exchanged with a charged one, which

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usually takes less than five minute leading to recharging process similar to gas station [2]. This model provides flexibility in charging time, where the charging process can be scheduled during off-peak periods. Despite the advantages offered by this method, the system cost, battery lifetime, swapping difficulties due to battery heavy weight, battery damage due to human misuse, and applicability of this system are still questioned and researched [2]. The second way for EV charging is using conductive (plug-in) technology, whether during long-term parking using AC Level 1 (L1) and 2 (L2) or opportunistic charging at DC fast charging stations. This approach offers appropriate option in terms of cost, efficiency, and reliability, and it is more convenient for passenger cars, especially those who have access to L1 or L2 charger at home or at workplace. Plug-in charging is relatively slow compared to gas station model, which may take from 20 minutes to 30 hours [3]. Also, it is a manual process and it becomes challenge to deal with heavy-duty cables at fast and extreme fast charging stations. Additionally, charging cables and plugs introduce safety concerns at public stations during harsh environment, such as heavy snow and rain.

The other way of charging an EV is to use the WPT strategy, that enables the battery of EV to be recharged wirelessly without the need for a wired connection. This technology offers a flexible solution that can charge EV when parked for an extended period of time (stationary charging), temporary halts (opportunistic or quasi-dynamic charging), and driving at high speed (dynamic or in-motion charging) [4]. Also, it can be installed at private garages for overnight charging, public parking, street parking, bus stops, or in the roads. WPT technology is automatic by nature, which makes it an ideal solution for charging self-driving cars. Additionally, the removal of cables makes it safer and more reliable in harsh environment and extreme weather conditions [5]. However, like other technologies, WPT systems faces challenges related to loss of efficiency due to misalignment, high unit and installation cost, and complexity in design, manufacturing, and integration.

The first spark of WPT technology may be dated back to the late of 18th century, when Hertz was trying to spread waves in form of electromagnetic field in air using a spark gap [6], [7]. Nicola Tesla examined the ability of radio waves to transport electric power through air in 1890. Between 1894 and 1918, he constructed an enormous coil attached with a ball made of copper and put it on the top of a turret. This system can be utilized for WPT by electrostatic induction [8]. In 1960, a WPT system was proposed by William Brown and tested to transport sunlight energy in space for use in powering spacecraft [8]. Between 2007 and 2013, a team of Massachusetts Institute of Technology (MIT) scientists recreated experiments and researches of Tesla that relied on the magnetic link of two resonators. They achieved a transported power of 60 W through an air gap of 2 meters with 40 % transmission efficiency utilizing coil with a diameter of 0.6 m [9]. From that time, experts around the whole world have been investigating WPT technology for a variety of applications, including mobile phones, EVs, domestic devices, healthcare equipment, and so on. The research described in [10] introduces a straightforward power management algorithm designed to oversee the integration of multiple energy sources for charging a vehicle, even while it is in motion. The system comprises a wireless charging system, a photovoltaic generator, a fuel cell, and a battery system. Additionally, a set of power converters is associated with each energy resource to facilitate the necessary adaptation between input and output electrical signals. The study's results indicate that all designed models function effectively, and the power management control loop has been successfully tested under simulation conditions. Statistics indicate that the utilization of this multi-recharge tool enhances vehicle power performance and extends vehicle autonomy.

As depicted in Figure 1, WPT technology is broken down to four primary classifications [3]: near-field technique [11], far-field technique, acoustic technique [12], and mechanical interaction technique by utilizing permanent magnets [13]. Magnetic gear wireless power transfer (MGWPT) technology uses mechanical interaction in energy transfer. At first, it was presented to replace conventional linked gear, it was later developed for a variety of applications, including healthcare equipment [14], EV driving [15], and EV static charging [16]. A transmitter turns electric power into squeezed sound waves that move through the air, and a receiver outfitted with a transducer transforms the motion generated by the sound waves into electric power [12].

Using electromagnetic fields (EMFs) is the other method of transporting the electric power wirelessly and these fields are far-field and near-field. Power is conveyed in far-field technology via electromagnetic radiations in the frequency domain of GHz [16], which include radio signals [17], microwave [18], and laser [19]. High levels of power can be transported over long ranges with this technique [6], but it necessitates giant antennas as well as intricate concentration and monitoring approach. This technique has seen widespread application in military and aerospace sectors [20]. Near-field technology utilizes inductive electromagnetic waves to convey electric power wirelessly, while fields remaining within a limited zone surrounding the transmitting coil. The fields in this region are classified into two types, electric fields that uses capacitors (capacitive power transfer [CPT]) [21], or magnetic fields generated by inductors (inductive power transfer [IPT]) [3]. IPT and CPT are regarded as the most appropriate techniques for charging EVs. CPT system has the ability to reduce electromagnetic interference by confining the electric flux between the two plates [22]. It requires two capacitor systems: one for transmission and the other for reception, to complete the electrical circuit and facilitate energy transfer between both sides. Additionally, to ensure effective energy transfer, proper isolation of the two electrodes from the ground and the car chassis is essential [23]. This system encounters various challenges, including the requirement for planar capacitors positioned in a straight line with minimal air gap between them. It also cannot accommodate significant misalignments [24], and necessitates a high oscillating voltage source to produce a strong electric field for energy transmission. Additionally, the capacitors must be of considerable size to effectively fulfill their function [25]. CPT faces a significant challenge stemming from the exceptionally low permittivity of air, resulting in very small coupling capacitance. Any misalignment between the coupling plates or a sizable air gap in CPT leads to a notable reduction in coupling capacitance. Consequently, this technique is unsuitable for charging electric EVs that necessitate power transfer over extensive distances and may encounter misalignment between the transmitter and receiver sides [26].

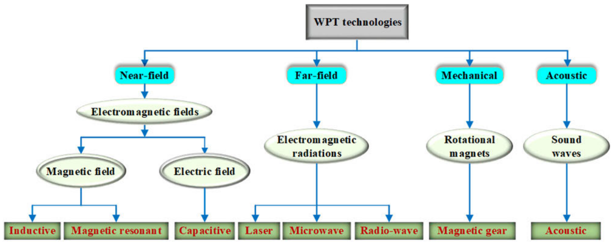

**FIGURE 1.** Categorization of WPT technologies.

IPT is a perfectly suitable system for charging EVs due to its merits including: (1) it is capable of transmitting high power (few kilowatts to Megawatt) across a relatively large air gap distance ranging from 100 mm to 400 mm, which meets the ground clearance requirements for most EVs [27]; (2) all components are electrically isolated, which makes the charging process safer for human [5]; (3) it is a self-operating (automatic) system and does not require user intervention; (4) it is reliable during extreme environmental circumstances, such as heavy rains, wind, and snow; (5) it eliminates the concern of EV users about interoperability between plugs and chargers [28]; and it has no moving or rotating parts, so it is less noise and requires less maintenance.

Therefore, this manuscript focuses on IPT technology that is applicable for EVs charging. Considering aspects related to power transfer capability, transfer distance, efficiency, and practicality, IPT show promising results for EV applications. The manuscript explored IPT technology including principle of operation, system architecture, compensation circuits, R&D activities, challenges, and technology gaps and recommendations.

## II. INDUCTIVE POWER TRANSFER SYSTEMS

IPT is an innovative method that wirelessly delivers electricity through the air using magnetic fields produced by inductive coupling coils. This technology is used in several applications such as biomedical devices [29], consumer electronic [30], and EVs [31]. Ampere and Faraday's laws explain the basic operation principle of IPT system as depicted in Figure 2. A magnetic field is generated when the current ($I$) passes through the transmitter coil according to Ampere's law, as in Equation (1). This equation means the flowing current in an enclosed path is equivalent to the line integral of the strength of the magnetic field ($H$).

$$I = \oint \vec{H} . \vec{dl} \tag{1}$$

As defined by Faraday's law when the magnetic field cuts the receiver coil with number of turns ($N_2$), an induced voltage ($V$) is generated, which can be expressed mathematically as in Equation (2), where $\phi$ is the magnetic flux [32].

$$V = -N_2 \frac{d\phi}{dt} \tag{2}$$

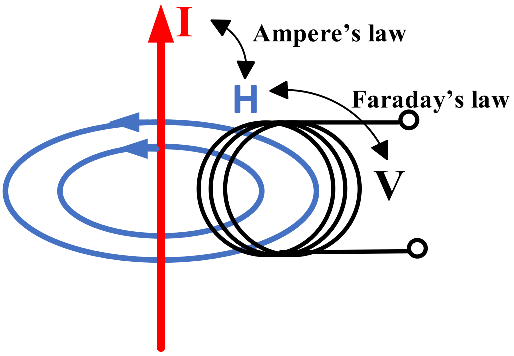

**FIGURE 2.** Illustration of the IPT system principle of operation.

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An IPT system includes two electrically isolated sides: the ground side includes a ground (transmitter) pad, rectifier and PFC, and high-frequency (HF) inverter; and the vehicle side incorporates the vehicle (receiver) pad, and rectifier, depicted in Figure 3 [3]. Both sides include a compensation (resonant) topology that keeps the system operating at resonance condition to transport the nominal power at the highest efficiency. This topology can be a single capacitor (C) or an LC-network [4]. The transmitter coil is fed by HF supply, which generates HF electromagnetic fields (EMFs). These EMFs induce voltage and currents to the secondary circuit to be rectified and charge the battery. According to the SAE J2954 standard, the frequency of operation of IPT system ranges between 79 kHz and 90 kHz, which makes it easier diminish the size of both transmitting and receiving pads. A wireless channel for communication exists between both receiver and transmitter controllers to provide services such as payment, ease of correct alignment, and alerting the battery status [33].

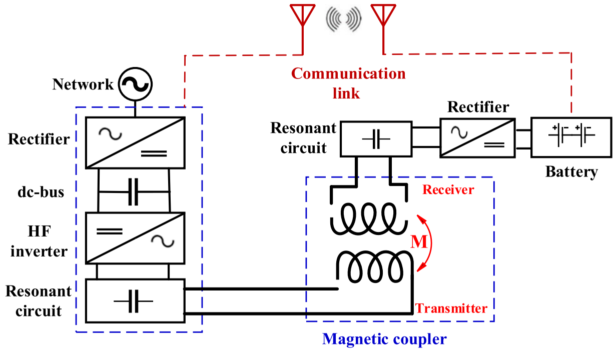

**FIGURE 3.** Components of an IPT system.

### A. MAGNETIC COUPLER SYSTEM ARCHITECTURE

The charging assembly is an essential element of IPT charging technique. It oversees transporting the electric power from the supply to electric car battery. Three fundamental parts with special specifications are involved in forming a charging pad: conductive coils [34], magnetic cores as field concentrators [35], and electromagnetic field shielding [36].

#### 1) STATIONARY IPT

Pad architecture in stationary IPT system includes the conductive coil, magnetic materials and metallic shield identifies the architecture of an inductive power pad. This architecture is momentous in identifying the performance of an IPT system, in terms of EMFs safety, transmission efficiency, coupling factor, and tolerance for misalignment cases [5]. U-cores [37], [38], E-cores [37], and pot cores [39] were initially the architecture used in conventional transformers, and were considered for IPT system. These architectures introduce undesirable performance with stationary charging of EVs due to their large size, crisp configuration, heavy weight, high cost, and very small tolerance to lateral misalignments [40]. Planar coils has been suggested in [5], [41], and [42] to overcome these obstacles.

The three components (coil, core, and shield) must be carefully designed to meet power and efficiency requirements; reduce the weight, size and thickness of the power transmission pad; and decrease sensitivity to lateral and rotational misalignments. According to the nature and the shape of electromagnetic field produced, the architecture of charging pad is classified into three categories: non-polarized charging pads that produce magnetic fields with perpendicular ingredients such as circular and rectangular charging pads [28]; polarized charging pads, like DD, DDQ charging pads [43], that generate horizontal magnetic field ingredients; and multiple coils pad such as bipolar and tripolar charging pads, which produce both perpendicular and horizontal field ingredients [44].

In contrast to the DDQ charging pad architecture [45], and bipolar charging pad architecture [46] which are suitable to act as a car-side transmitter, the vast majority of pad architecture works better on the transmitter side such as Double-D (DD) [47], multi-coil homogeneous [48], circular, and rectangular pad architectures [5]. In addition, most of these architectures achieve the interoperability concept, where any EV can be charged from any inductive charger without limitations from the EV or inductive charger producers [28].

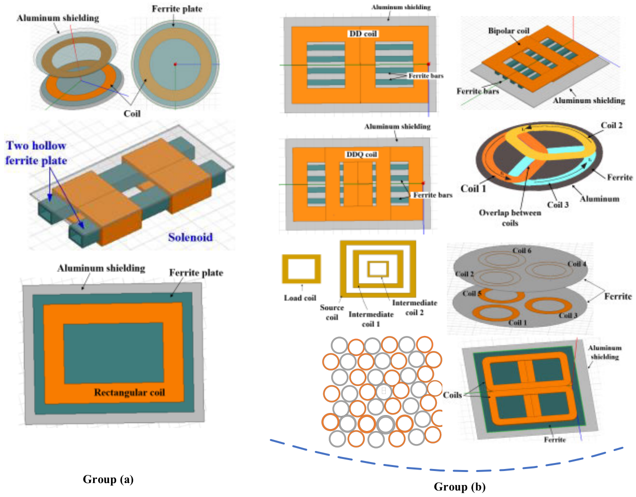

**FIGURE 4.** Different architectures for stationary inductive charging pads for both transmitters and receivers, (a) single-coil architectures, and (b) multiple-coil architectures.

Figure 4 and Table 1 describe and compare various charging pad architectures presented in the existing literature. This comparison is conducted across several attributes including shape, misalignment sensitivity, polarization, air gap distance, interoperability, and others.

#### 2) IN-MOTION IPT

In-motion charging technique is capable of being utilized to charge EVs during their movement on the highways without resorting to a complete stop or waiting even for small periods. The in-motion charging technology has several merits including, increasing the driving range while reducing the size of the storage battery. It also increases the chances of developing and designing autonomous cars which makes it easier for the user to take advantage of the time spent in the driving process. In-motion charging technology is occurred by inhumation the power transmitter track beneath the surface of the ground and hanging the power receiver coil at the vehicle chassis. The power transmitter and receiver coils are fed from a high frequency (HF) AC source. The generated EMFs from the transmitter are cut with the receiving coil while the EV moves above charging track in order to transport

**TABLE 1.** Characteristics of some stationary charging pad for electric vehicles.

| Pad Architecture | Misalignment tolerant | Magnetic flux type | Charging area | Air gap distance | Polarization state | Interoperability process | Leakage flux amount | Studies |
|---|---|---|---|---|---|---|---|---|
| **CP** | Poor | Single-sided | Small | Short | Non-Polarized | Weak | Large amount | [5],[40] |
| **RP** | Medium | Single-sided | Small | Short | Non-Polarized | Very weak | Medium | [49],[50] |
| **SP** | Medium | Double-sided | Medium | Medium | Polarized | Medium | Medium | [51],[52] |
| **DDP** | Medium | Single-sided | Medium | Medium | Polarized | High | Small amount | [53] |
| **BP** | Medium | Double-sided | Large | Long | Polarized | High | Small amount | [5],[40] |
| **DDQP** | High | Double-sided | Large | Long | Polarized | High | Small amount | [5],[45] |
| **Quadrupole pad** | High | Double-sided | Large | Long | Polarized | High | Small amount | [54],[55] |
| **QDQP** | High | Double-sided | Large | Long | Polarized | High | Small amount | [56],[57] |
| **MT-OR** | High | Single-sided | Large | Long | Non-Polarized | High | Medium | [40],[58] |
| **DT-DR** | High | Single-sided | Large | Medium | Non-Polarized | High | Small amount | [59],[60] |

* *MT-OR: multi transmitter-one receiver*
* *DT-DR: dual transmitter-dual receiver*

the required power with highest transmission efficiency. Additionally, there are several limitations that hamper the prevalence of in-motion charging, such as the expensive price of initial implementation, needing to provide independent charging lanes, that is not easy to be available in packed cities, and an ideal alignment between receiver and transmitter track must be realized to avert a loss during the transmission of power [51]. The transmitting track for in-motion technology may be one of two pad kinds; stretched (single long) track and segmented track [61], [62].

The in-motion charging pads at receiver side are the same kinds as that available for stationary charging. This helps to reduce the size of the vehicle ingredients, resulting in less EV weight and expense, as well as increases the possibility of interoperability between different architectures on the transmitter side, whether in stationary or in-motion charging. The vehicle side may hold one or several pads, according to the EV class. The EV can carry a single pad which is more appropriate for charging the small light-duty electric vehicles or multiple pads, that may be required for intermediate- and high-weight levels of EVs in order to comply with the power demands [63].

For stretched transmitter track the length of the coil is larger than its counterpart on the vehicle side. The track length is between 1m to 100 m in the ground, which leads to the possibility of charging more than one electric car on the same track, simultaneously [64]. The elongated transmitter consists of a lengthy track of litz wire supplied from a primary station. This station incorporates a compensation network, HF DC-AC converter (inverter), and AC-DC converter (rectifier), as illustrated in Figure 5(a). This design possesses several characteristics, including simplicity, ease of control, a consistent coupling coefficient when the vehicle aligns with the track, and it requires a straightforward resonant compensation network. The charging system with stretched track was constructed for general transport buses and shuttle utilities with a name known as online electric vehicle (OLEV) in South Korea [64].

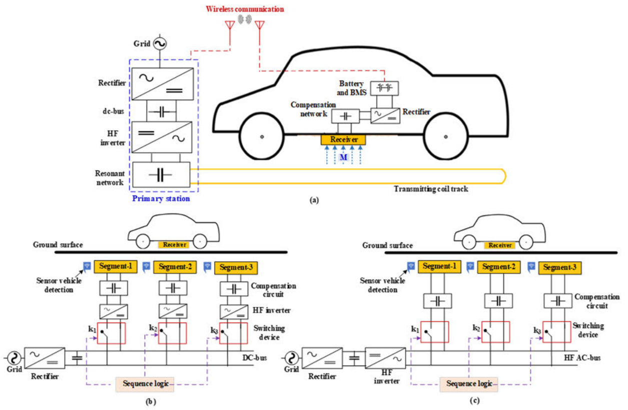

**FIGURE 5.** Different architectures of transmitter for in-motion inductive charging, (a) single extended coil path architecture, (b) sectionalized transmitter architecture utilizing individual HF inverter for each coil, and (c) sectionalized transmitter architecture utilizing collective HF inverter.

From another point of view, this architecture has some defects, which are summarized as follows, generating excess electromagnetic fields in cases of misalignment, the need for periodic maintenance work [65], low coupling factor, which leads to a decrease in power and efficiency [66]. There are several classes for the extended transmitter lane depending on the core configuration of magnetic pad; U- core form [67], E-core form [67], I- core form [68], S- core form [69], ultra slim S- core form [69], and cross sectionalized form (X-path) [70],

**TABLE 2.** Performance evaluation of several stretched transmitter track utilized in in-motion charging arrangements.

| Parameters | I-core | U-core | E-core | X-path | S-core | Ultra slim S-core |
|---|---|---|---|---|---|---|
| **Output power** | High | Small | Small | High | High | High |
| **Efficiency** | High | Low | High | High | Low | Low |
| **Lateral misalignment** | Large | Large | Small | Large | Large | Very large |
| **Air gap** | Long | Medium | Short | Long | Long | Long |
| **Leakage EMF** | Medium | Large amount | Small | Very small | Small | Very small |
| **Track width** | Small | Very large | Medium | Small | Small | Small |
| **Research** | [68],[70] | [67],[71] | [67],[71] | [68],[70] | [67],[69] | [69],[71] |

as depicted in Figure 6. Table 2 compares and highlights the performance of the core classifications.

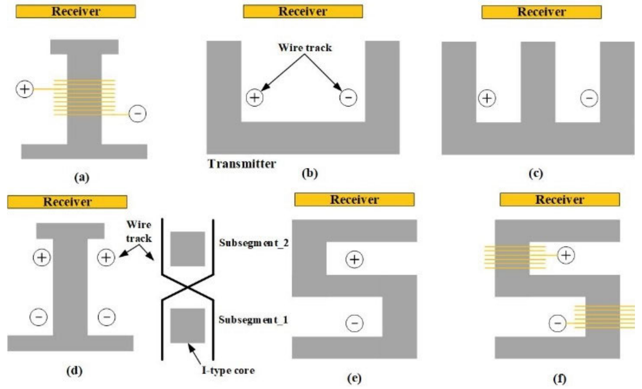

**FIGURE 6.** Types of cores for the extended track employed in an in-motion charging system (a) I- core, (b) U-core, (c) E- core, (d) X-path (e) S- core, and (f) ultra slim S- core.

The segmented charging track requires many compensation circuits and several converters and coils for transmission, so this system is of high cost and complex in construction. It is also vital to remove the self-coupling that occurs between the transmitter segments, therefore the horizontal distance between these segments and each other must be increased, which leads to the fluctuation of the transmitted power and its arrival in the middle of this distance to almost zero when the receiver is one straight with the middle of this distance. Power fluctuation can be decreased by shortening this distance and positioning the transmitter segments near to each other, which affects the resonant components due to the self-coupling of the coils [64].

The transmission segmented track can be fed in two arrangements, the first is to feed each segment separately with a high-frequency inverter as in Figure 5(b), [66], and the second is to use a common high-frequency inverter for all segments in the transmission track as in Figure 5(c) [73]. In the initial configuration, the charging system is activated or deactivated based on the vehicle's alignment, with a high-frequency inverter connected to each transmission segment. Each segment's inverter operates at low power and is linked to a compensation circuit to enhance system performance, efficiency, and reliability. While this setup offers simplicity and straightforward installation and configuration, it poses safety risks due to high-power and voltage DC line operation. Moreover, it requires a large number of inverters and sensing devices, driving up system costs.

In the second configuration, a shared high-frequency inverter powers the system through switches, with an independent compensation circuit for each charging segment. Switching devices control the activation or deactivation of each charging segment, reducing safety risks compared to other setups. However, this arrangement faces challenges such as increased system costs due to the longer transmitting track [74]. Despite the advantages that are available as a result of using a common inverter, the arrangement needs to use a large number of switches and sensors [71].

## III. RESONANT CIRCUITS

Compensation (Resonant) network components are utilized in inductive charging system due to several merits including, compensation for the large leakage inductance resulting from large air gap distance, which improve the system power and efficiency [100]. Furthermore, it minimizes the source apparent power by giving the demands of reactive power. Additionally, it permits electronic devices to work with soft switching [77]. Bifurcation is additionally averted by operating the compensating elements at unity power factor (UPF) to reach zero phase angle. The main reason for introducing compensation networks into WPT technique is a study by a team of MIT scientists [78]. This study was carried out in 2007, where it showed a significant improvement in the transmitting efficiency during the distance of an air gap after the introduction of the compensation elements to the charging circuit.

Compensation (Resonant) techniques can be classified into basic (classical) compensation techniques as shown in Figure 7 from (a), to (d), and mixed (composite) compensation techniques as depicted in Figure 7 from (e) to (l). There are four basic compensation techniques obtained by connecting a parallel or series resonant capacitor to each side of the transmitter and receiver. These basic techniques are series primary capacitor-series secondary capacitor (S-S) [79], [80], series primary capacitor -parallel secondary capacitor (S-P) [81], parallel primary capacitor-series secondary capacitor (P-S) [82], and parallel primary capacitor -parallel secondary capacitor (P-P) [83]. When mixing these basic capacitors with inductors, hybrid compensation techniques are produced, which include more than one inductor and/or capacitor on one side such as LCL-P [84], LCL [85], LCL-LCL [86], LCCL- LCCL [28], LCC [87], S-CLC [88], CCL [89], and others.

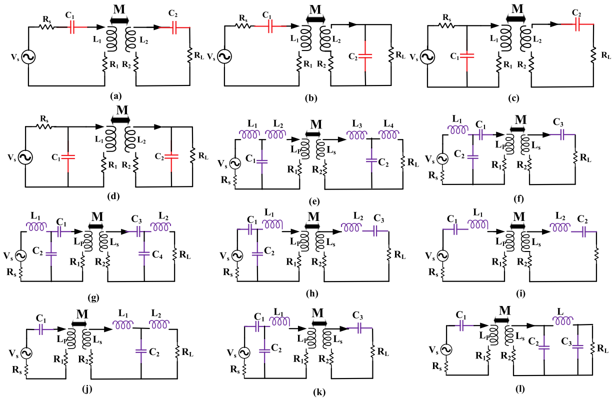

**FIGURE 7.** Different compensation topologies, with (a)-(d) representing fundamental topologies and (e)-(l) depicting mixed topologies.

Most of the studies dealt with basic compensation circuits such as [40], [51], [83], and [90], while others dealt with hybrid compensation techniques such as [49] and [91]. In [90], a -phase bipolar pad was utilized to transport a 50 kW output power through 150 mm air gap with a transmission efficiency of 95% using a series compensation circuit. In [92], With the goal of enhancing the charging system efficiency while utilizing asymmetric coils, an analysis of series-parallel and series-series compensation techniques was performed. This analysis is done on double models, one of them is achieved by using equal size transmitter and receiver, and the other when using unequal size coils. The efficiency of the two models was observed at various transmission distances. As a result of this, the series-parallel compensation technique introduces higher efficiency than series-series compensation when using transmitter that is larger than receiver (asymmetry coils). According to the quality factor, coupling factor, and compensation technique on both sides, the capacitance ($C$) and inductance ($L$) values can be selected [93]. Because of the enormous impedance of input, the difficulty of the computations, and the load's dependability, parallel compensation is rarely utilized on the transmission side [94].

The capacitance in S-S compensation technique relies on the inductance of transmitter ($L_1$) and the resonance frequency value, whereas the S-P compensation technique depends on both $L_1$ and resonance frequency, as well as the mutual inductance ($M$) between the transmitting and receiving coils [95]. In P-P and P-S compensation techniques, the capacitance of transmitting side not relies only on the coupling factor and inductance but also on the load impedance. In P-S and P-P compensation circuits, to transport a sufficient amount of power, a high operating voltage is required because of the large input impedance of these compensation techniques [96]. These techniques have some advantages including high power factor, wide load variability and high transfer efficiency at small mutual inductance [97]. Additionally, they utilize the same operating frequency and operate at minimal power levels with a reasonably long transmission distance [98].

When using mixed compensation circuits on both sides of the transmitter and receiver, such as inductor-capacitor-capacitor (LCC)/ inductor-capacitor-capacitor (LCC) and inductor-capacitor-inductor (LCL)/ inductor-capacitor-inductor, the efficiency of the IPT system is increased throughout the total range of coupling and loading. The extra leakage resistance in capacitances and inductances increases copper losses significantly in mixed compensation techniques than those in S-S compensation technique [99]. The both-sided LCL and LCC techniques are a perfect compensation for EVs battery charging, because of the behavior of the current source at vehicle side while a voltage source inverter was working at the ground side. In [91], The double-sided inductor-capacitor-capacitor compensation technique has been studied. It was concluded that when adjusting the LCC circuit, it is possible to reach the zero current switching, in addition to that when the supply voltage is constant, the output current rms value is constant. The reactive power at the receiver side can be compensated by using LCC compensation technique to fulfill unity power factor operation. Also, this compensation technique doesn't rely on loading circumstances and coupling factor [100]. LCC compensation technology is affected by several obstacles, including the size and the increase in the system ingredients which leads to a high cost [91]. Other than these limitations, this compensation technology is the most common used because of its merits such as the independence of the load characteristics, high efficiency and allowing a large variation in the cases of misalignment, in addition to reducing the inverter current stress [91].

The basic and mixed compensation techniques are compared in Table 3, considering several metrics like operating frequency ($f$), load power ($p_o$), coupling coefficient ($k$), transmission efficiency ($\eta$), air gap distance and coupler configuration {Circular (CP), Rectangle (RP), Double-D (DDP), and Bipolar (BP)}.

## IV. CONVERTER TOPOLOGIES

Power electronics represent an essential ingredient in wireless EVs battery charging. For better charging efficiency, it is vital to concentrate on enhancing the effectiveness of the power converters. The converters are relied upon the sort of compensating strategy implemented as well as the wireless system's applications. In the beginning, an IGBT-based push pull converter had been employed to finish off the transformation procedures; however, with the advancement of MOSFET infrastructure while employed at medium voltages that vary between 60 V and 1200 V and raising the value of frequency at which the switching occurs, the key reliance to finish the step of conversion has been changed to the full bridge MOSFET to work as power converter [111], [112]. Power converters are divided into two main categories:

**TABLE 3.** Various WPT designs depending on compensating structure.

| Compensation | $k$ | $f$ | $p_o$ | $\eta$ | Air gap | Configuration | Ref. |
|---|---|---|---|---|---|---|---|
| **S-S and LCC-LCC** | 0.135 | 85 kHz | 1 kW | 95% for SS<br>93% for LCC | 200 mm | CP-CP, Cored | [101] |
|  | 0.188-0.311 | 79 kHz | 7.7 kW | 96% for LCC | 200 mm | DDP-DDP, Cored | [102] |
| **S-S and LCL-LCL** | 0.1 | 85 kHz | 3.3 kW | 93.1% for SS<br>89.5% for LCL | 100 mm | RP-RP, Coreless | [86] |
| **LCC-LCC** | 0.18-0.32 | 79 kHz | 7.7 kW | 96% | 200 mm | RP-RP, Cored | [103] |
|  | 0.14-0.3 | 95 kHz | 5.6 kW | 95.36% | 150 mm | DDP-DDP, Cored | [104] |
|  | 0.153 | 85 kHz | 3.3 kW | 92.6% | 150 mm | CP-CP, Coreless | [83] |
|  | 0.1877 | 85 kHz | 3 kW | 95.5% | 150 mm | DDP-DDP, Cored | [91] |
|  | 0.13 | 85 kHz | 1.4 kW | 89.78% | 150 mm | RP-RP, Cored | [64] |
| **LCL-S and LCC-S** | 0.18-0.32 | 140 kHz | 1 kW | 93% | 100 mm | CP-CP, Cored | [106] |
| **LCL** | 0.37-0.54 | 85 kHz | 5 kW | - | 240 mm | DDP-DDP, Cored<br>BP-BP, Cored | [107] |
| **S-P** | - | 23 kHz | 2 kW | 92% | 100 mm | CP-CP, Cored | [108] |
| **S-S** | - | 85 kHz | - | 97.6% | 200 mm | RP-RP, Cored | [109] |
|  | 0.4 | 85 kHz | 20 kW | 80% | 100 mm | RP-RP, Coreless | [110] |

those used on the ground side and those used on the electric vehicle side, as shown in Figure 8. The former typically involve one or two conversion stages, while the latter can be achieved using rectifiers.

### A. CONVERSION PROSSES OF GROUND SIDE

The importance of the conversion prosses at ground side is the ability to raise the network's AC power frequency from low value (60 Hz) to high value for matching the power levels to be achieved according to the application to be used. There are two ways to complete this conversion process, the first way is to employ an AC-to-AC converter in order to directly convert minimal-frequency AC power to high-frequency AC power {single (one) stage AC-to-AC conversion}. This conversion way can be achieved by using matrix converters. The second conversion method takes place in two steps (AC-to-DC then DC-to-AC) and is called dual (two) stage conversion.

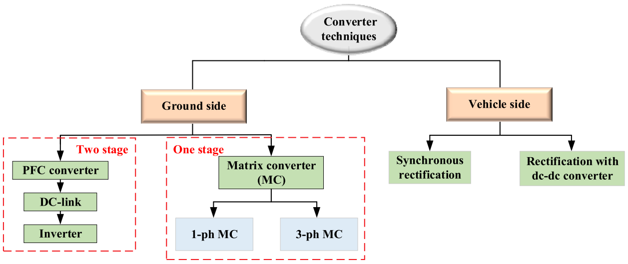

**FIGURE 8.** Classification of converter techniques for IPT systems.

When talking about two stage power conversion, it can be said that minimal-frequency AC power goes through two conversion processes: the first is to convert it into DC power, then the inverter comes in the second conversion stage to convert this DC power into high-frequency AC power [62]. Inverters have multiple merits that make them well-suited for employment in EVs wireless charging. These features are that; they can be implemented and controlled simply and easily, through which the on/off prosses of the power assemblies that make up the charging coupler can be controlled, in addition, being harmonious with various coil configurations, whether a single coil or multiple coils.

Most common inverter configurations in an inductive charging system can be identified as shown in Figure 9. These configurations include class EF [113], current source push-pull [114], [115], and voltage source 1-ph, 3-ph, or multi-phase [68], [116], [117], [118].

In [119], the authors propose the use of an H-bridge converter on the ground side. On the vehicle side, two H-bridge converters are employed, with one supplying active power to the battery and the other regulating the charging current. This proposed system requires an external backup DC source in the vehicle to provide approximately 50% of the power to the battery, while the magnetic charger (coils) furnishes the remaining 50% required to complete the battery charge. Consequently, the overall cost of the electric vehicle will rise due to increased size and weight. To make the ground side devices more isolated and safer, the authors in [120] suggested a HF transformer that minimizes the voltage to the required levels. Through this system, conductive losses are minimized by taking into account high voltage and low current, and this helping to improve the efficiency of the ground side inverter.

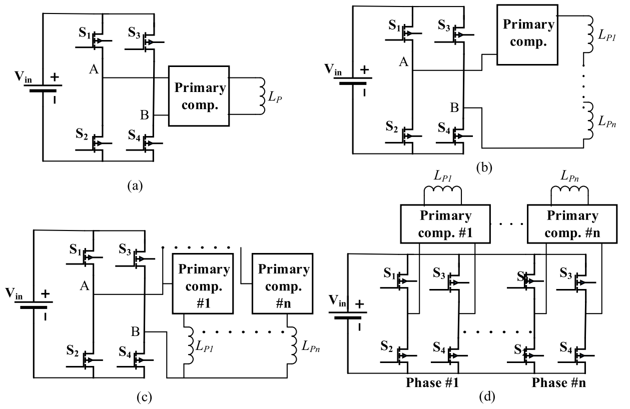

**FIGURE 9.** **Inverter structures of DIPT (a) only one coil is energized by a 1-phase inverter, (b) Several series coils are energized by a 1-ph inverter, (c) Several parallel coils are energized by a 1-ph inverter, (d) inverter with several phases.**

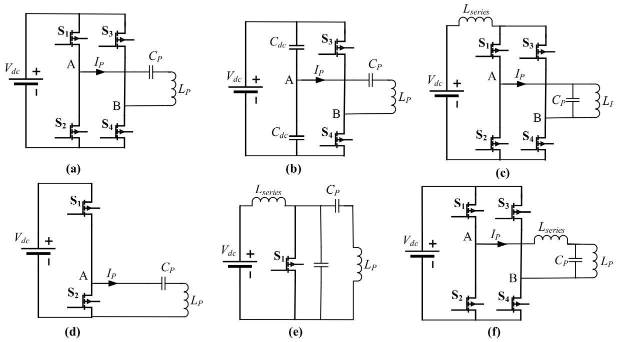

**FIGURE 10.** **Various types of transmitter converters, (a) voltage fed full bridge, (b) voltage fed half bridge, (c) current fed full bridge, (d) voltage fed class D amplifier, (e) current fed class E RF amplifier, (f) voltage fed LCL converter.**

Most of the high-frequency converters utilized in wireless systems are illustrated in Figure 10. Regardless of fluctuations in the coupling coefficient between the ground and the vehicle, or changes in the load, it is feasible to maintain constant and specific values for the load voltage and current by employing various compensation circuits. These compensation circuits, comprising a rectifier composed of diodes connected to a soft output filter along with a DC-to-DC converter, can be referred to as power conditioners.

While one-stage converters have a straightforward architecture, they are unable to fully execute the variable frequency process. On the other hand, two-stage converters can achieve voltage and frequency regulation, but they require extensive passive components, including a large filter and a sizable capacitor for the DC link. Consequently, system reliability diminishes and overall costs increase [121]. An alternative converter architecture for wireless power transfer systems, distinct from both one- and two-stage converters, is known as matrix converters (MC) [122]. Originally, these converters found applications in solar energy systems, aircraft, and machinery utilizing induction principles, among other uses [123]. Using this matrix converter (MC) architecture allows for the elimination of bulky passive storage components and DC link elements, thereby enabling efficient one-stage power conversion [124]. The matrix converter (MC) functions by linking the load to the three-phase voltage supply through its internal components, consisting of a series of bidirectional semiconductor switching devices.

In [125], the introduced conversion technology was represented by a one stage converter connected with two sorts of compensation circuits, one S-S and the other S-P. Comparing the two sorts of compensation, it was found that the S-S topology results in the generation of a massive leakage inductance at the car side, but it is preferable to use it in WPT applications that required high power. In [126], at high load cases and to increase the overall efficiency of the three-coil charging coupler, a conversion topology was proposed consisting of series or parallel compensation elements connected to both the H-bridge converter and the H-bridge rectifier at the ground side and the vehicle side, respectively.

An alternative approach to the conversion process involves the use of a one-phase (1)-ph) matrix converter (MC). In this configuration, four bidirectional switching devices are utilized to achieve an output with adjustable amplitude and frequency at a predetermined switching angle, as shown in Figure 11(a) [127]. From a theoretical perspective, achieving an analysis of the open circuit (OC) and short circuit (SC) conditions without any hindrances or issues requires the use of a conventional 1-ph matrix converter (MC) capable of synchronous and instantaneous switching. However, in practice, attaining an ideal switching state is not feasible, leading to the utilization of switching strategies in the MC. One-phase Z-source matrix converters (MCs) offer the capability for amplitude control and adjustable frequency, which contrasts with traditional one-phase MCs that only provide reduced amplitude as the frequency of operation increases [128]. Figure 11 (b) depicts the arrangement of 1-ph Z-source MC. Because of its enhanced dependability and capacity to directly transform the power in a single step [129], the benefits of the Z-source MC drew the attention of numerous applications [130], [131], [132]. It is made up of an impedance grid consisting of double capacitors and double inductors, 5 two-directional switches, an inductor-capacitor (LC) filter, plus a load. The boost function is accomplished by exploiting the impedance grid's storage elements.

Figure 11(c) illustrates the complete architecture of a 6-switch buck-boost matrix converter (MC). In contrast to the one-phase Z-source MC, which features double capacitors and double inductors and offers variable amplitude control and frequency of operation, the 6-switch buck-boost MC stores energy in a single inductor. The 6-switch buck-boost MC consists of an inductor, 6 bidirectional switches, and double capacitors functioning as a filter [133]. In [134], a HF transformer insulated MC architecture was suggested, in order to establish electrical insulation, therefore the huge line transformer can be abandoned as well as give a variable frequency and rectified voltages at output. It is made up of a HF transformer with 4-switches at ground side and 2-switches at vehicle side. Additionally, an inductor-capacitor (LC) filter and DC isolating capacitor are employed at vehicle side as demonstrated in Figure 11(d).

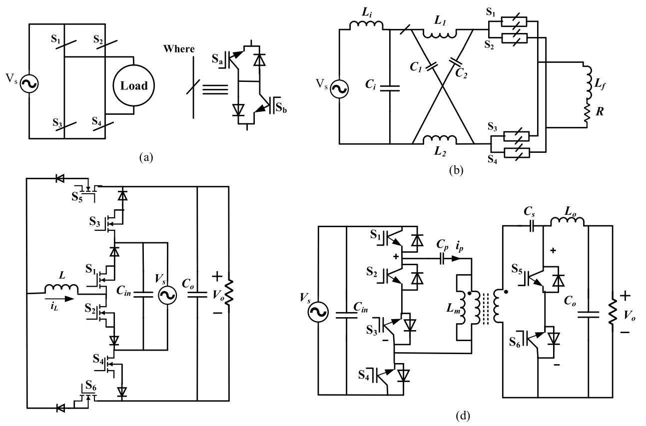

**FIGURE 11.** Types of 1-ph MC, (a) traditional 1-ph MC, (b) 1-ph Z-source MC, (c) 6-switches buck-boost MC, and (d) HF transformer-isolated MC.

### B. CONVERSION PROSSES OF VEHICLE SIDE

In most applications, such as wireless medical equipment's, it is preferable for the power conditioner to composed of the rectifier only, which makes the size of the receiving coil small to suit the small size of these devices. The full bridge diode rectifier transforms the HF AC power generated at vehicle side into DC power in order to charge the electric car battery. DC power is obtained at the load (battery) by employing a diode rectifier or synchronous rectification method. A DC-to-DC converter can be connected after the rectifier in the first method for the possibility of controlling the receiving side, while the second method does not provide any possibility of control but rather works to increase efficiency [107], [114], [135], [136], [137].

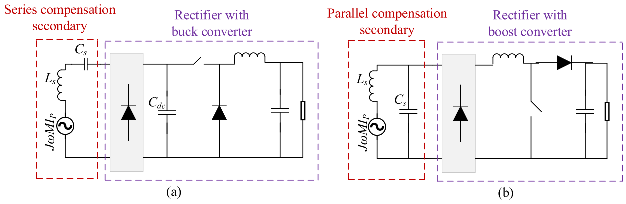

**FIGURE 12.** Receiver side converters, (a) series adjusted receiver buck converter, and (b) parallel adjusted receiver boost converter.

Rectifiers are categorized into two types: current-fed rectifiers and voltage-fed rectifiers. Additional buck, boost, or buck-boost converters can be employed with current-fed rectifiers, which occurs when compensation circuits are S-S or LCC on the car side. Conversely, with voltage-fed rectifiers, boost or buck-boost converters are used, particularly when employing parallel compensation on the car side. The most common types of converters utilized in wireless charging systems are depicted in Figure 12. When the vehicle incorporates multiple coils architecture or a DDQ architecture on its side, it becomes feasible to achieve multiple rectification stages but at the same time the dimensions of the vehicle are increased. Therefore, this coils architecture is not commonly employed [107], [114], [137].

In [138], the authors achieved a solution to charge the car battery with the appropriate DC voltage by inserting a DC-to-DC converter after the diode rectifier, which works to convert the HF voltage on the car side to the appropriate voltage level for the battery. To improve system efficiency, [139] suggested a universal strategy feasible to all wireless charging systems, which included a system-level study of a serial buck-boost DC-to-DC converter and optimum impedance matching. The serial buck-boost DC-to-DC converter accomplishes two objectives, which may be stated as follows: the first is to provide dynamic load isolation, and the other is to match the optimum impedance of the amplifier, coil, and rectifier. To prove this strategy, laboratory tests were conducted for a wireless system that transmits 40 W of power at a frequency of 13.56 MHz with a grid-to-battery (G2B) efficiency of up to 70 %. This efficiency is achieved for various loads, whether they are resistors, batteries, or supercapacitors.

## V. STATE OF THE ART

There are three methodologies of inductive charging for electric cars: stationary inductive charging, which is achieved when the car is stopped for a long time in parking lots [33], quasi-dynamic inductive charging, such as what happens at traffic lights while driving at low speeds [51], and in-motion inductive charging when the vehicle is moving on fast roads, in which a stretched coil or multiple segmented coils are buried under the ground [51].

### A. STATIONARY INDUCTIVE CHARGING

The stationary charging system of electric vehicles must be carefully and precisely designed to suit the operating requirements in terms of different power levels and air gaps through which the power is transmitted. Therefore, the development, research and demonstration activities of the wireless inductive charging system take place. The power levels that are suitable for EVs can be classified into two main categories according to the global criterion and guidelines [140]. The first is to transmit power ranging from 1 kW to 22 kW and is suitable for light-duty electric vehicles (LDEVs). The other category is suitable for medium- and heavy-duty electric vehicles (MDEVs/HDEVs) and transmits power higher than 22 kW. Furthermore, the influence of EV dimensions on power demands, every car category has distinct levels of ground clearance. Therefore, the air gap from the ground pad to the vehicle pad of the inductive system is affected. This air gap distance is between100 mm and 400 mm for LDEVs and is larger for MDEVs and HDEVs. The receiver pad must be consistent in size to the size of the EV and not negatively affect the total weight of the vehicle or the power consumption. The stationary wireless charging system must efficiently transfer the desired power through the appropriate air gaps, using designs with a weight and size consistent with the vehicle. All this to meet the operating restrictions and requirements (size, weight, air gap and power levels). Inductive charging systems for EVs also have an extensive domain of operating frequencies as well as with various maximum power and transmission distance. Though, several inductive systems work at domains of frequency from 10-to-100 kHz, limited researches have been conducted on air-core coils at higher frequencies [141].

Based on the findings from literature, Table 4 presents a comprehensive summary of various prototypes and models of stationary inductive charging systems for electric vehicles. This summary includes details such as power level ($P_o$), operating frequency ($f$), distance between the ground pad and the car pad (air gap), architecture of the magnetic coupler, and transmission efficiency ($\eta$). Efficiency values are categorized as pad-to-pad (P2P), reflecting the efficiency of inductive pads; utility-to-load (U2L), indicating the efficiency of the entire system; and DC-to-DC, encompassing all components from the DC-bus of the ground side to the vehicle's battery. The table illustrates the wide range of stationary inductive prototypes, with power levels spanning from 1 kW to 100 kW, developed worldwide at research centers, universities, national labs, and elsewhere. Additionally, beyond research endeavors, several vehicle manufacturers have also initiated the development of stationary inductive charging systems. Table 5 provides an overview of the commercially available products, detailing their power levels, transmission efficiency, operating frequency, and other specifications.

### B. IN-MOTION INDUCTIVE CHARGING

In 1976, the first inductive charging design was created to suit the in-motion charging technology. This model could transmit a power of 8 kW, but it did not work at full efficiency [161]. Another prototype, the Santa Barbara electric bus, was developed in 1979 [162]. In 1992, an in-motion charging system was attempted in the lab and on the real field by PATH project (Partners for Advanced Transit and Highways). Inductive charging system model are manufactured and suspended in a bus. The roads have been built and equipped with power transmission systems, and then it has been possible to study and analyze the negative effects that may be generated in the environment surrounding the charging system. The PATH project design was capable of transporting a 60 kW of power with an efficiency of 60% through an air gap distance of 76 mm. But this prototype of the project was not commercially popular due to its disadvantages including the large weight and size of the magnetic coupler, the setting up of the whole system is very expensive, the increment of current because of the use of a low operating frequency of up to 400 Hz, and high acoustic noise, in addition to that it transmits the power through an air gap distance not convenient for the various levels of air gaps for electric cars. Even though the presence of all these obstacles in this project, it was a good first spark that opens the field for scientists and engineers to create and enhance in-motion charging strategy [163].

In [164], it was suggested to use a transmission coil extending inside the ground with a length commensurate with the vehicle's speed and power consumption per km. On the other side of the charging system, a rectangular coil was suspended in the car, and the system was operated with LCC-S compensation technology, considering the calculation of the transmitted power value and the efficiency of the system, and the maximum value of the power is employed to deduce the minimal value of the transmission current. It was found that this system transmits efficiency slightly higher than 85%. In [165], the segmented transmitter track is suggested with several pads, each pad contains DD coils. A finite element model was created to study the mutual induction between the transmitter and receiver pads. A study and analysis were also done to obtain the best dimensions for the design and to determine the appropriate horizontal distance between the pads that achieve the optimal properties of the system.

In [166], a two-spiral repeater was utilized in order to ameliorate the efficiency, enlarge the air gap, and raise the tolerance of the lateral misalignments. Transmission efficiency can be enhanced to 60 % at an air gap distance of 350 mm, as well as 81% at an air gap distance of 100 mm, by optimizing system elements such as the horizontal distance between sectionalized transmitter coils, the number of the segments, and the loading circumstances. In [72], a two-coupled charging system was utilized for the sectionalized transmitter. The system works at a 20 kHz frequency, and transport power of 5-kW at an efficiency of 92.5%.

It is clear that the possibility of spreading the in-motion charging system within cities and on highways is considered an urgent need these days to provide self-driving cars and to help spread environmentally friendly electric cars. Therefore, scientists and researchers are working with great continuous effort to develop and improve in-motion charging systems. Table 6 presents the R&D achievements in in-motion charging systems in terms of power level ($P_o$), frequency of operation ($f$), efficiency ($\eta$), air gap distance, transmitter ($T_x$) architecture, receiver ($R_x$) architecture, and misalignment range ($M.R$).

### C. STANDARDIZATION ACTIVITIES

As a nascent technology, wireless charging systems require standards that offer precise specifications and directives for technology advancement, testing, installation, and functioning. EV supply equipment firms and automotive manufacturers intending to introduce this technology to the market will depend on these standards to streamline development, cut expenses, hasten adoption, and adhere to interoperability goals, safety standards, and efficiency requirements. Furthermore, standardization will aid in enabling interoperable system operation with various vehicles.

**TABLE 4.** Present power levels for stationary inductive charging prototypes.

| $P_o$ (kW) | $f$ | Air gap (mm) | $\eta$ | Coupler | Ref. |
|---|---|---|---|---|---|
| 1 | 85 kHz | 100 | 95.57 %-U2L | CP-CP, Cored | [142] |
| 1 | 60-kHz | 200 | 83 %-U2L | DDP-DDP, Cored | [143] |
| 1.6 | 150 Hz | 150 | 81 %-U2L | CP-CP, Coreless | [144] |
| 2 | 20 kHz | 100 to 250 | >80 %-U2L | DDP-DDP, Cored | [62] |
| 2 | 20 kHz | 200 | 85 %-U2L | CP-CP, Cored | [5],[65] |
| 3 | 50 kHz | 200 | 90 % U2L | SP-SP, Cored | [145] |
| 3 | 20 kHz | 160 | >80 %-U2L | CP-CP, Coreless | [146] |
| 3.3 | 1 MHz | 150 | 95 %-U2L | Square-Square, Coreless | [141] |
| 4 | 85 kHz | 150 | 93 %-U2L | RP-CP, Cored | [147] |
| 5 | 20 kHz | 150 | 80 %-U2L | DDP-DDP, Cored | [148] |
| 5 | 20 kHz | 200 | 90 %-U2L | CP-CP, Cored | [111] |
| 5 | 20 kHz | 150 | >85 %-U2L | CP-CP, Cored | [5],[65] |
| 5 | 1 MHz | 52 | 96.5 %-DC-to-DC | CP-CP, Cored | [125] |
| 5 | 20 kHz | 175 to 265 | 90 %-U2L | CP-CP, Coreless | [111] |
| 5 | 20 kHz | 152 to 167 | 90 %-U2L | CP-CP, Coreless | [149] |
| 6 | 95 kHz | 150 | 95.3 %-U2L | Square-Square, Cored | [100] |
| 6 | 100 kHz | 300 | 81 %-U2L | CP-CP, Cored | [150] |
| 7.7 | 79 kHz | 200 | 96 %-DC-to-DC | BPP-BP, Core | [100] |
| 7.7 | 20 kHz | 200 | 93 %-P2P | RP-RP, Cored | [16] |
| 11 | 85 kHz | 150 | 91.4 %-DC-to-DC | DDP-DDP, Cored | [151] |
| 22 | 100 kHz | 135 | 97 %-P2P | RP-CP, Cored | [152] |
| 25 | 85 kHz | 210 | 91 %-U2L | CP-CP, Cored | [153] |
| 50 | 85 kHz | 10 to 200 | 95.8 %-DC-to-DC | RP-RP, Cored | [154] |
| 100 | 22 kHz | 127 | 98 %-P2P | DDP-DDP, Cored | [155] |

**TABLE 5.** Commercial EV products for stationary inductive charging system.

| $P_o$ (kW) | $f$ (kHz) | Air gap (mm) | $\eta$ | Supply voltage | Ref. |
|---|---|---|---|---|---|
| 3.6 | 85 kHz | 100-250 | >90 %-U2L | AC: 240 V | [89] |
| 3.6 -7.2 | 20 kHz | 102 | 90 %-U2L | AC: 208-240 V | [65] |
| 2 -10 | 85 kHz | ≤ 304.8 | ≥85 %-U2L | AC: 208-240 V | [40] |
| 3.6 | 85 kHz | 160-220 | >90 %-U2L | AC: 240 V | [65] |
| 50 | 23.4 kHz | 165-190 | 89 %-92 %- DC-to-DC | AC: 277 V | [157] |
| 60 -180 | 20 kHz | 40 | >90 %- U2L | AC: 460 V | [65] |
| 10 | 20 kHz | 200 | >92 %- U2L | AC: 240 V | [158] |
| 200 | 20 kHz | 203.2 | 94 %- U2L | NA | [159] |
| 25 | 20 kHz | 241.3 | 90 %- U2L | AC: 240 V | [160] |

Numerous national and international organizations are in the process of developing standards, guidelines, specifications, and recommended practices for wireless chargers catering to various vehicles and operational environments. These entities include the Society of Automotive Engineering (SAE) [140], the International Electrotechnical Commission (IEC) [173], the Japan Automobile Research Institute (JARI) [174], the International Organization for Standardization (ISO), Underwriters Laboratories (UL), the National Technical Committee of Auto Standardization (NTCAS), International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [175], etc. Some of these standards delineate system configurations for different power levels and air gaps, such as SAE J2954 and IEC 61980-1, while others offer guidance on data communication and interfaces, as exemplified by IEC/TS 61980-2. ICNIRP has established safety thresholds for leakage electromagnetic fields across varying operating frequencies. These standards address various aspects of the technology. However, there are still challenges encountered during the standardization process, as outlined below:

- Standards take into account different coil shapes, like CP, RP, and DDP, which may not efficiently work together. This raises concerns about interoperability and complicates system design to ensure interoperability, consequently increasing system costs.

- The standard lacks comprehensive details and information concerning compensation topologies, power converters, control mechanisms, and system operation.

- The standards have been formulated specifically for light-duty EVs with slow charging capabilities. However, there is currently a lack of standards addressing fast wireless charging for EVs across various weight categories, including light, medium, and heavy-duty vehicles.

## VI. CHALLENGES, GAPS, AND RECOMMENDATIONS

Inductive charging, although offering automatic and convenient charging, encounters several challenges (gaps) such as efficiency, compatibility, positioning, complexity, standardization, safety, interoperability, and cost. It's imperative to address these challenges and provide recommendations for both stationary and in-motion inductive charging for EVs. This is crucial to enhance the charging experience, boost efficiency, and expedite the adoption of EVs in the transportation sector. This section introduces several challenges encountered by the system along with corresponding recommendations for addressing each challenge.

### *A. STATIONARY INDUCTIVE CHARGING*

#### 1) POWER TRANSFER EFFICIENCY

Inductive charging systems for electric vehicles often encounter energy losses during the charging process, primarily due to factors such as distance between the charging pad and the vehicle, alignment, and electromagnetic interference. Optimize the design of the coils used in the charging pad and the receiving device to maximize the coupling efficiency between them. This includes selecting appropriate coil geometries, materials, and configurations to minimize resistance and maximize magnetic field strength. Improving power transfer efficiency is crucial to reduce energy loss and enable quicker and more efficient charging.

#### 2) HIGH POWER CHARGING

Effectively transmitting high power wirelessly presents a notable obstacle in inductive charging for EVs. Addressing constraints in technology efficiency and heat dispersion is vital to facilitate safe and efficient high-power charging, thereby minimizing charging duration and optimizing the usability of EVs.

#### 3) STANDARDIZATION

The absence of standardized charging protocols poses compatibility challenges in the inductive charging industry for electric vehicles. Diverse charging standards and protocols adopted by different automakers and charging infrastructure providers hinder seamless interoperability. Develop and implement standardized technical specifications for IPT systems, including parameters such as power levels, operating frequencies, communication protocols, and physical interfaces. This ensures compatibility between different IPT systems and components, allowing for seamless integration and interoperability.

#### 4) INFRASTRUCTURE DEPLOYMENT

Establishing an extensive and accessible infrastructure for stationary inductive charging is a formidable task. The installation of charging pads at diverse locations necessitates substantial investments and coordination among stakeholders. Expanding the charging infrastructure over extensive geographical regions is essential to promote widespread adoption and facilitate convenient usage of electric vehicles.

### *B. IN-MOTION INDUCTIVE CHARGING*

#### 1) ALIGNMENT AND POSITIONING

In-motion inductive charging systems for electric vehicles require precise alignment and positioning between the charging infrastructure embedded in the road and the receiver installed on the vehicle. Implementing automated alignment systems can help ensure precise positioning of the charging pad and the receiving device without requiring manual intervention. This could involve the use of sensors, cameras, or other technologies to detect and adjust alignment as needed.

#### 2) POWER TRANSFER EFFICIENCY

In-motion inductive charging systems face additional efficiency challenges compared to stationary systems. As the vehicle moves over the charging infrastructure, the alignment and distance between the charging pads can vary, affecting power transfer efficiency. Overcoming these hurdles and guaranteeing reliable and efficient power transfer during dynamic charging is crucial. Implement dynamic power control algorithms that adjust the power delivery in real-time based on factors such as the distance between the charging pad and the receiving device, the state of charge of the battery, and environmental conditions. This ensures optimal power transfer efficiency under varying operating conditions.

#### 3) SAFETY AND RELIABILITY

In-motion inductive charging systems must ensure the safety and reliability of both the charging infrastructure and the vehicle. Safeguarding the charging pads integrated into the road from environmental elements like moisture, debris, and extreme temperatures is essential. Furthermore, robust safety protocols need implementation to avert inadvertent electrical contact and uphold the system's reliability during operation. Ensure that the IPT system complies with electromagnetic compatibility standards to prevent interference with other electronic devices and systems, maintaining the integrity of communication networks and avoiding potential safety risks.

#### 4) STANDARDIZATION AND INTEROPERABILITY

Similar to stationary inductive charging, In-motion charging systems also encounter challenges related to standardization

**TABLE 6.** R&D for in-motion inductive charging system.

| **Para.** | | **$P_o$ (kW)** | **$f$ (kHz)** | **Air gap (mm)** | **$\eta$** | **$T_x$** | **$R_x$** | **M.R** | **Studies** |
|---|---|---|---|---|---|---|---|---|---|
| **KAIST** | 1st G | 3 | 20 | 10 | 88 % | E-type | E-type | ~3 mm | [67] |
| | 2nd G | 6 | 20 | 170 | 72 % | U-type | Flat -type | ~230 mm | [67] |
| | 3rd G | 15 | 60 | 120 | 80 % | W-type | DDP | – | [67] |
| | 4th G | 27 | – | 200 | 74% | I- type | DDP | 240 mm | [62] |
| | 5th G | 22 | – | 200 | 71% | S-type | DDP | 300 mm | [67] |
| | 6th G | 3.3 | 85 | 100-300 | 83% | W-type-ferrite plate | RP | 700 mm | [167] |
| **ORNL** | | 1.5 | 23 | 100 | 75 % | Cir-ferrite bars | CP-ferrite bars | – | [108] |
| | | 20 | 22 | 162 | 93 % | R-ferrite core | RP-ferrite bars | 150 mm | [168] |
| **UoA** | | 20-30 | 12.9 | 50 | 85 % | – | – | 50 mm | [40] |
| **USU** | | 25 | 20 | – | 86 % | Cir-ferrite bars | CP-ferrite bars | 150 mm | [135] |
| **CW** | | 120 | 15-20 | 40 | 90 % | E-type | F-type | – | [40] |
| **NRC** | | 1 | 90 | 100 | > 90 % | R | CP-ferrite core | – | [169] |
| **NCSU** | | 0.3 | 100 | 170 | 77%-90% | Cir | CP-ferrite plate | ~ 30 mm | [170] |
| **WAVE** | | 50 | 20 | 152-254 | 90 % | – | – | ~254mm | [40] |
| **JRTRI** | | 50 | 10 | 7.5 | – | Bip | DDP | – | [171] |
| **Bombardier** | | 200 | 20 | 60 | 90 % | – | – | Few mm | [40] |
| **FDIAU** | | 80 | 20 | 100 | 88%-90% | – | – | – | [65] |
| **PATH** | | 60 | – | 76 | 60 % | – | – | – | [172] |

and interoperability. Diverse manufacturers adopting varying standards and technologies for dynamic charging impede compatibility between charging infrastructure and electric vehicles. Collaboration within the industry to establish standardized protocols and specifications for IPT technology can facilitate interoperability, streamline development efforts, and accelerate market adoption.

### 5) COST AND COMPLEXITY

cost of infrastructure are challenges that need to be addressed. Implementing inductive stationary and In-motion charging technology requires the installation of charging pads and supporting infrastructure in various locations, such as homes, offices, public spaces, and roads. The cost of infrastructure setup and maintenance, as well as the need for widespread adoption to justify the investment, pose significant challenges for the wide-scale deployment of inductive charging. Initiatives aimed at reducing the overall cost of IPT systems should be pursued, including advancements in manufacturing techniques, component optimization, and economies of scale.

By tackling these shortcomings and putting into action the recommended strategies, IPT technology can advance and mature, opening avenues for its extensive adoption for static and dynamic charging of EVs.

## VII. CONCLUSION

This manuscript offers a comprehensive overview of inductive charging technologies applicable to both stationary and in-motion electric vehicle (EV) charging. IPT emerges as the most appropriate choice for EV battery charging owing to its numerous advantages. It discusses and presents the working principle and components of the IPT charging system. Furthermore, it explores the different pad configurations at both the transmitting and receiving sides that employed in stationary charging systems, while assessing their effectiveness in terms of factors such as tolerance to misalignment, dimensions of charging zones, interoperability, etc. It then introduces the configurations employed at transmitter side in dynamic charging systems, providing a comparative analysis among them and an overview of the feeding arrangements accessible. It discusses the various topologies of compensation networks, including traditional and hybrid, and then summarizes different WPT designs based on the compensating structure. The manuscript investigates different converters used in inductive charging system, assessing their appropriateness for both the transmitting and receiving sides. Additionally, the research and development (R&D) that took place in stationary and in-motion IPT was presented, and they were compared based on output power, efficiency of transmission, distance between components, frequency, and other factors. Ultimately, it highlights the challenges and gaps observed in both stationary and in-motion inductive charging systems, offering recommendations to tackle these challenges. These endeavors aim to serve as a manual for individuals intrigued by the wireless charging technology of electric vehicles (EVs), ultimately fostering the wider adoption of these eco-friendly vehicles. The various wireless charging technologies also marks the initial steps toward achieving self-charging and self-driving electric vehicles.

## ACRONYMS

| | |
|---|---|
| **WPT** | Wireless power transfer. |
| **EVs** | Electric vehicles. |
| **IPT** | Inductive power transfer. |
| **R&D** | Research and developmen. |
| **GHG** | Greenhouse gases. |
| **DC** | Direct current. |
| **AC** | Alternating current. |
| **L1** | AC Level 1. |
| **L2** | AC Level 2. |
| **EMFs** | Electromagnetic fields. |
| **CPT** | Capacitive power transfer. |
| **IPT** | Inductive power transfer. |
| $I$ | Current. |
| $H$ | Magnetic field intensity. |
| $N_2$ | Receiver coil turns. |
| $\phi$ | Magnetic flux. |
| **HF** | High frequency. |
| **QDQP** | Quad D quadrature pad. |
| **CP** | Circular pad. |
| **RP** | Rectangular pad. |
| **SP** | Solenoid pad. |
| **DDP** | Double-D pad. |
| **BP** | Bipolar pad. |
| **DDQP** | Double-D quadrature pad. |
| **MT-OR** | Multi transmitter-one receiver. |
| **DT-DR** | Dual transmitter-dual receiver. |
| **OLEV** | Online electric vehicle. |
| **UPF** | Unity power factor. |
| **L** | Inductor. |
| **C** | Capacitor. |
| $L_1$ | Transmitter inductance. |
| $L_2$ | Receiver inductance. |
| **PFC** | Power factor correction. |
| $M$ | Mutual inductance. |
| $k$ | Coupling coefficient. |
| $P_o$ | Load power. |
| $\eta$ | Transmission efficiency. |
| $V$ | Induced voltage. |
| **MC** | Matrix converters. |
| **G2B** | Grid-to-battery. |
| **MDEVs** | Medium-duty EV. |
| **HDEVs** | Heavy-duty EV. |
| **U2L** | Utility-to-load. |
| **P2P** | Pad-to-pad. |
| **DIPT** | Dynamic IPT. |
| $T_x$ | Transmitter. |
| $R_x$ | Receiver. |
| **M.R** | Misalignment range. |
| **MGWPT** | Magnetic gear wireless power transfer. |
| **MIT** | Massachusetts Institute of Technology. |
| **SAE** | Society of automotive engineering. |
| **PATH** | Partners for Advanced Transit and Highways. |
| **IEC** | International Electrotechnical Commission. |
| **ISO** | International Organization for Standardization. |
| **UL** | Underwriters Laboratories. |
| **NTCAS** | National Technical Committee of Auto Standardization. |
| **ICNIRP** | International Commission on Non-Ionizing Radiation Protection. |
| **JARI** | Japan Automobile Research Institute. |

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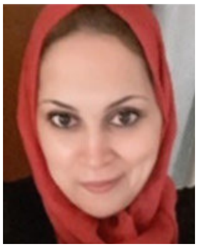

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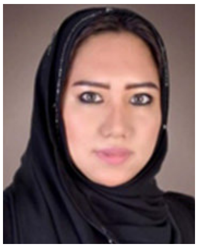

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