Chapter 2: Literature Review

WPT was first developed by Nikola Tesla, who undertook numerous tests on it at Colorado Springs, USA, in the 1890s. To transfer energy between the receiver and transmitter WPT uses an air medium that will be electrified by charged particles as its receiver. An electric field, a magnetic field, or electromagnetic fields can all be used to transfer energy, depending on the applications, power ratings, and transmission range. The WPT techniques are split into near - field region and far field depending on the distance, as depicted in Figure 1-2. Near field approaches are used to transmit energy over small distances, whereas far field strategies are used to transmit energy over greater distances.

The idea of wireless vehicle charging has attracted more attention than stationary wired charging technique [6][8][14]. Parking lots with wireless charging stations might guarantee that your vehicle gets charged up to its time to leave the place [13]. Wireless charging facilities can be found on the conventional road network might even be positioned at crossroads or over longer stretches of highway, increasing the range of electric vehicles [16]-[18]. Other applications may benefit from improvements in wireless energy transfer, such as the continual use of electric vehicles in a warehouse attributable to the installation of wireless charging tracks in the floor [15]-[16]. The achievement of wireless energy transfer systems with simultaneous high efficiency and high-power transfer over a range of airborne distances has, however, proven challenging.

Electric vehicles (EVs) may have new chances to improve sustainable mobility, thanks to wireless power transfer (WPT), which delivers electricity via an electromagnetic field over a region in between. In this review, WPT technology for electric vehicle (EV) use is assessed from a technical and environmentally friendly standpoint.

The goals of this review are to:

- present the most recent technical advancements as well as bottlenecks in WPT advancement and applications within the field of transportation;
- define the demonstrations of WPT for EV systems; and
- assess sustainability and pinpoint problems and improvement opportunities.

With an emphasis on system performance, technological advancements in coil pad design, compensating topologies, power converters, and control strategies are discussed.

Nicola Tesla tested ways to transmit electricity wirelessly over a century ago [1, 2]. In order to accelerate the adoption of electric items in our daily lives, wireless power transfer (WPT) has been the subject of considerable study in recent decades. Cell phones that can charge wirelessly, EVs, robotics, implanted medical gadgets, and home electronics appliances are typical examples. Electricity is often transmitted via an electromagnetic field (EMF). WPT's widespread use and expanding demand are due to its inherent simplicity and ability for continuous and without charging shortfall, which are two important difficulties with wired chargers. WPT is classified into three types based on their operating principles: radiation from electromagnetic sources (resonant or inductive) WPT, which is appropriate for long-distance transmission of power, for instance, between satellites and the earth; electric induction/ coupling WPT, formerly referred to as capacitive coupling WPT; and magnetically coupled WPT (inductive or resonant), which additionally is suitable for near-field transfer but causes significantly less damage. When it comes to operating modes, WPT may be divided into two categories:

- Static or stationary WPT, which involves charging a vehicle while it is stationary, and
- Dynamic WPT, which involves charging a vehicle while it is traveling along a WPT-compatible road.

To address the limitations of wired chargers and remove certain barriers to automobile electrification and sustainable transportation, WPT for EVs has the potential [9]. In addition to being more convenient than cable chargers, WPT may significantly reduce the size of an on-board EV battery. A stationary WPT for electrical public transport vehicles may increases the overall range of electric vehicle charging. The installed rechargeable battery capacity may be reduced by at least two-thirds due to many possible "opportunity charges" during rider boarding and boarding at bus stops during bus operation [10, 11]. Because of these enrooted charges, it is possible to travel with a much smaller on-board battery despite still satisfying the requirements of the vehicle route. Given that batteries may account for over one-quarter of the entire weight of a fully electric transit bus to sustain daylong operation, this drastically decreases vehicle weight [12]. Downsizing the battery will significantly reduce the vehicle's weight and fuel economy [10]. Theoretically EVs would be able to have an unconstrained range and a small on-board battery capacity under dynamic WPT [13]. WPT for EVs, on the other hand, raises new sustainability sacrifices and issues that have sparked debate in business and the academic community. The cost of building significant WPT infrastructure must be balanced against the perks of reduced battery consumption and greater fuel efficiency.

This article summarises the most recent technological breakthroughs in WPT technology for electric vehicle (EV) applications, as well as the state of sustainability analyses of WPT EV systems. It discusses current research highlights, gaps, coil design, coil design for static and dynamic charging, various compensation topologies, briefing about converters and control technics, performance and challenges, and different applications of WPT technologies for EVs from a technological perspective.

Technology	Description	Advantages	Challenges	Ref
Resonant Inductive	Uses magnetic fields to transfer energy wirelessly between coils tuned to the same frequency.	Efficient over short to medium distances, convenient charging.	Efficiency decreases with distance, requires precise alignment.	[12,13,20,78]
Capacitive Coupling	Utilizes electric fields to transfer energy between capacitive plates separated by air or dielectric material.	No physical contact, less affected by misalignment.	Efficiency drops with increased distance, lower power transfer.	[14,17,18]
Microwave Power	Employs microwave frequencies to transmit energy, often using beamforming to target specific receivers.	High efficiency over long distances, less affected by obstacles.	Safety concerns due to radiation exposure, expensive hardware.	[19,22,26]
Laser Power Transfer	Transfers energy using laser beams directed at photovoltaic cells on the receiver, converting light into electricity.	High efficiency, potentially longer range than other methods.	Susceptible to weather conditions, safety concerns with lasers.	[11,16]
Magnetic Resonance	Utilizes resonant coils to transfer energy, allowing for greater distance and misalignment tolerance compared to inductive methods.	Greater flexibility in positioning, suitable for dynamic charging.	Lower efficiency compared to other methods, complex system design.	[19]

Table 2-1Review of WPT technologies

2.1 Coil design:

One of the most important components of a wireless charging system is the coil, which also controls the quantity of power transmitted and the system's efficiency. The coil transforms energy between its electric and magnetic forms, enabling WPT. A coil system is often categorized in the literature as either two or four-coil system. In a quadruple-coil system [11]–[12] the load coil may be positioned and connected to the receiving coil to alter the equivalent of the load exhibited by the receiving coil in line with the load condition. The gearbox coil can be installed and connected to the transmitting coil to modify the input to the system impedance. A two-coil system excels in short-range applications, whereas a four-coil system excels in mid-range applications [18]. According to whether the gearbox distance is greater than the coil diameter or equal to it, limited-range and middle-range applications are differentiated [18]. In electric vehicle applications, the gearbox distance, referred to as the air gap, typically ranges from 100 mm to 200 mm [19]. The coil's size is always bigger than the distance between the gearboxes. The two-coil method is therefore preferred, and it will be covered in more detail in this thesis.

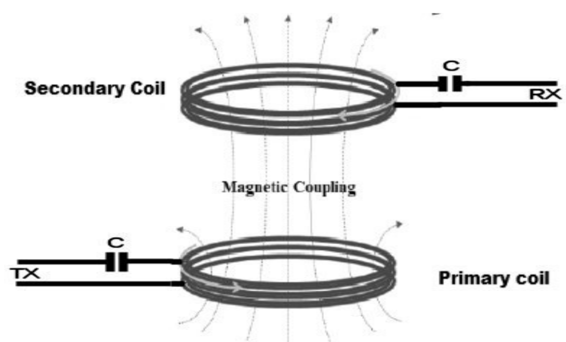

Figure 2-1 Two coil structure

A magnetic core is used in coil to direct magnetic lines of force and offer magnetic shield provides defend, guard, protect, and safe guard to ferrite bars or plates. Magnetic shields made of aluminium are frequently included in coil systems.

2.1.1 Coil structure for charging system:

Figure 2-2 illustrate the fundamental coil structures used in stationary charging systems. [20], circular coil architectures were researched and improved. The technology was capable of wirelessly transferring 2–5 kW at a reasonably high efficiency using the suggested coil shape [20, 21]. However, the circular coil can only create a certain amount of magnetic flux. Budhia et al. [22] created the solenoid coil construction to address this issue and enhance the magnetic flux route. According to [23], a 3-kW wireless charging mechanism was constructed utilizing a solenoid coil configuration and a DC efficiency of 95.5% was attained with a 35 mm of air gap. Moreover, a solenoid coil arrangement with a big air gap works well for wireless power transfer. In order to show a system for wireless charging that could supply 1.403 kW of power at a 3 m air gap, Park et al. [24] improved the solenoid coil geometry. The solenoid construction performs rather well; however, there is a significant flaw. It produces double-sided flux, of which only half is used for power transfer. Additionally, the leakage flux can combine with the car and metal body connected to ground, which would significantly reduce the magnetic coupling. Because of this, EV charging applications do not frequently employ this coil configuration. Bipolar coil architecture termed a DD coil architecture was created for the purpose to provide a one-side flux route and a bigger charging space compared to the circular coil topology. [26] Contains a coil design that is more sophisticated.

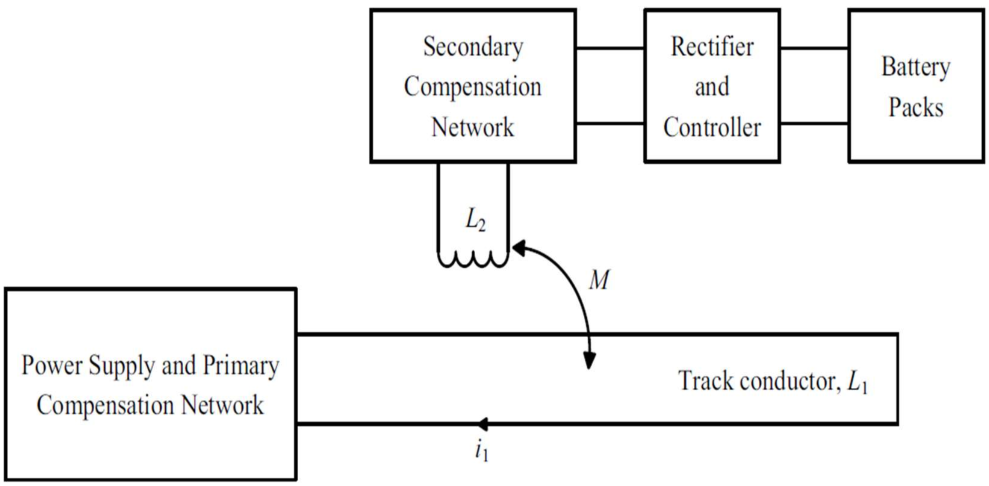

Figure 2-2 Dynamic charging systems with one coil design for primary coil L_1 = track conductor; L_2 = receiver coils; M = mutual inductance between L_1 and L_2; i_1 = excitation for primary coil [27,30].

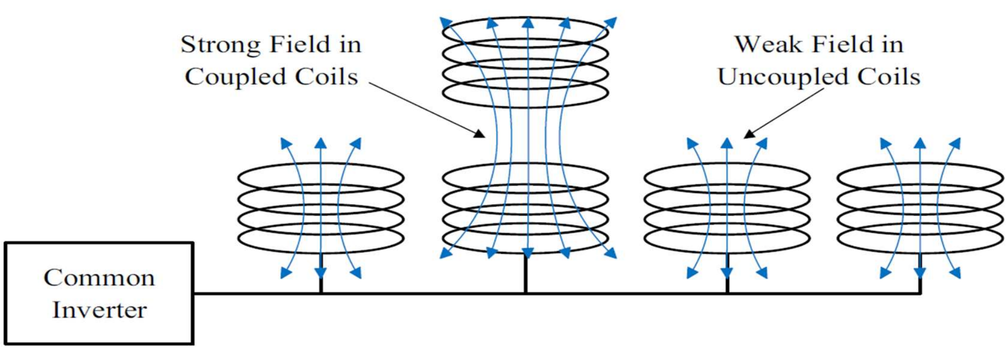

Figure 2-3 Dynamic charging systems with segmented-coil design for primary coil [27,30].

The suggested coil construction is shown in Figure 2-4, where the intermediate L_{int} is included in the primary coil's structure L_1. A passive resonant circuit made up of L_{int} and an associated resonant capacitor is energized by the coupling action between L_{int} and L_1. The secondary coil structures L_2 and Lint also have a coupling effect, which enhances the coupling of the entire coil system. Despite being more difficult to tune, this design promises to be more efficient than a circular coil system.

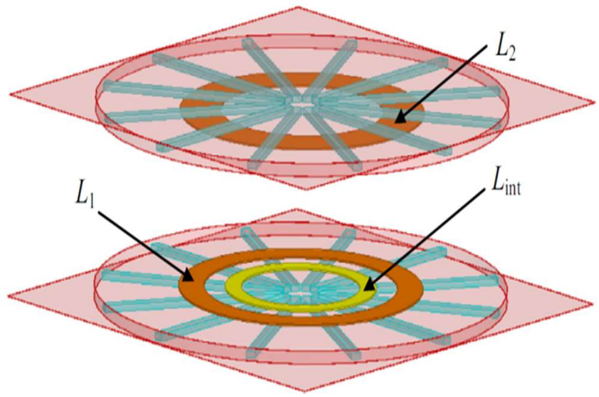

Figure 2-4 Coil with fixture. L_{int}= intermediate structure; L_1= primary coil structure; L_2= secondary coil structure [23].

A good inductive power transfer system requires the primary and secondary coils to be properly aligned. The charging pads may be misaligned in their angular, vertical, and horizontal shapes. Coil misalignment issues arise in a variety of contexts and for a range of purposes. Consequently, during the operation, mutual inductance, efficiency, and output power would vary. The EV's incorrect parking and the primary and secondary coils' mismatching will result in the greatest misalignment issues. The misalignment of coils leads to an increase in mutual inductance defragmentation, mismatches in impedance values, and magnetic flux leakage. Nonetheless, increasing the coupling coefficient and quality factor will result in the highest possible power transfer efficiency.

First and foremost, the transmitter and receiver coils need to be properly aligned. For the primary and secondary windings to be in this state, the driver or mechanical alignment mechanism must be precisely positioned. This is the IPT system's primary flaw. Various approaches have been put forth in the literature to deal with misalignment issues and preserve the effectiveness of different coupling components. Recent work has introduced a novel technique known as the Parity-Time Symmetric (PTS) circuit-based WPT system, which maintains a constant output power and transfer efficiency independent of the coupling coefficient [96]. At the PTS region, the PTS approach operates on the basis of the quantum physics notion. It is made up of connected parallel logic circuits. PTS systems can often be used for low-power (less than 1 kW) applications.

PTS systems can often be used for low-power (less than 1 kW) applications. We have to overcome greater current and voltage stress, coil ohmic losses, and switching losses when using the PTS system in high-power applications. As a result, this technique is only suitable for EV static charging and not for dynamic charging [97,98].

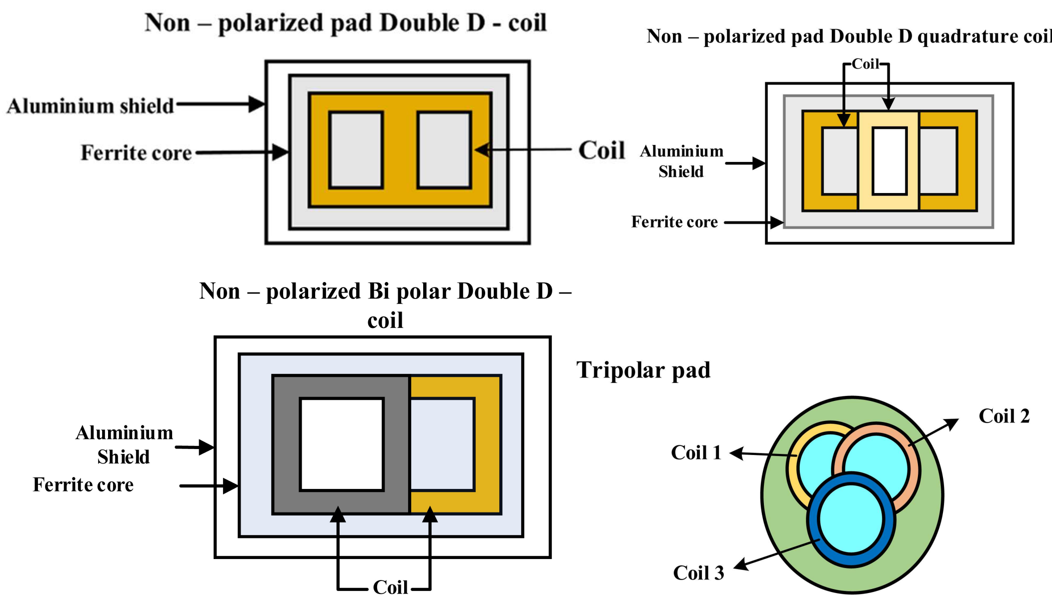

Figure 2-5 Different types of coil structures [104-106]

Second, using various charging pad shapes and coil designs such as ring, cone, coaxial, and arc shapes to reduce misalignment issues is recommended [99]. More recently, EV experts have suggested a few anti-misalignment strategies. Phase angle optimization, the balanced particle swarm optimization methodology [100], and electromagnetic induction position sensors can all be used to accomplish the anti-misalignment techniques. Phase angle optimization allows for misalignments between -200 and +200 mm. After comparing the phase angles of the various pad positions with the predetermined phase angle value, the appropriate value can be changed [101]. The screw or servo motor arrangement is fastened to the transmitter pad, and the electromagnetic induction position sensors are fixed in the reception pad. The motors can align the transmitter and receiver pads based on the output from the position sensors [102].

Lastly, because of the large airgap between the primary and secondary coils, appropriate electrical manipulation techniques are employed, such as compensating topologies. The next sections provide a brief explanation of each of these three solutions. It is easier to implement the temperature extraction from the coil and the quantity of magnetic field removed for a given coil design when the Finite Element Analysis (FEA) approach is used [103].

By utilizing various core shapes and the right coil design, additional research will maximize efficiency and minimize the size of the charging pad. The three fundamental designs of magnetic cores for charging pads are E-cores [104], U-cores [104,105], and pot cores [105, 106]. The ferrite core material should be covered by the primary and secondary coils. Another critical safety factor for wireless charging is this ferrite core material. By utilizing ferrite core materials and resonator designs that are appropriate, magnetic flux leakages can be minimized [104]. The primary considerations for choosing ferrite core materials for core design are the size and shape of the coils, the permeability of the medium, the operating frequency, and the cost.

Nonetheless, the coupling between the primary and secondary coils will be impacted by these ferrite cores. The basic geometries of the ferrite core material are double D, Bi-polar and Tri-polar [103, 104, 105]. Coils come in a variety of shapes, each with benefits for certain uses. On the other hand, they could make the charger heavier and result in lateral misalignments. These core shapes are inappropriate for use in electric vehicle applications. These shortcomings of simple core forms have been addressed by the implementation of different cores or resonator shapes.

Two types of planar coils are used in the structure: Non-Polarized Pads (NPPs) and Polarized Pads (PPs). PPs include Bi-Polar (BP), DDQ, and DDQP. Magnetic flux can be produced in both parallel and perpendicular directions. NPPs, like circular and rectangular pads, are single-layer pads.

2.2 Compensation topologies:

A loosely connected transformer with leakage inductances, known as a two-coil system [4], necessitates the use of compensating topologies. The compensation topology is provided with primary (or transmitter) side, which is for providing zero phase angle (ZPA). This ZPA eliminates the requirement for the electrical supply to offer reactivity, allowing the apparent output power to equal the real power. This decreases the power supply's VA rating. The compensatory topology adjusts the circuit on the secondary (or receiver) side to have a comparable resonant frequency to that of the circuit on the transmitter side to maximise power transmission [32]. These topologies also aid in soft power transistor switching and lower switching losses. Constant current or constant voltage charging is another advantage of compensation topologies, meaning that while the input voltage's root mean square value is fixed, the output DC current or DC voltage will also be fixed.

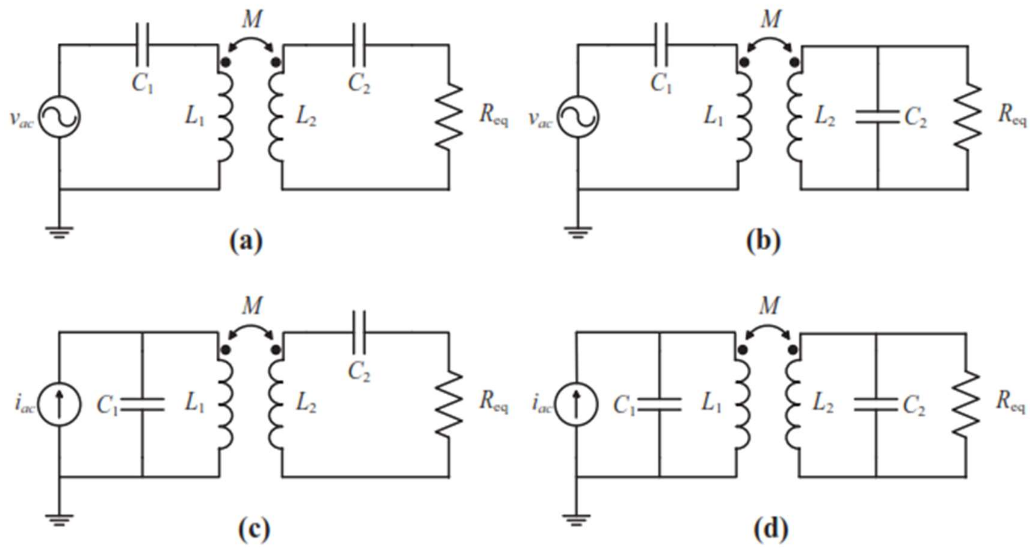

Figure 2-6 Compensation topologies: (a) SS, (b) SP, (c) PS, and (d) PP.

Figure 2-5 illustrates the four fundamental compensation topologies: SS, SP, PS, and PP. Here, "S" or "P" denotes the series or parallel connection of the compensating capacitors to the coils, respectively. Both the first and second letters stand for the transmitter and receiver sides, respectively. A key technique for analysing circuits is first harmonic analysis (FHA), where the input voltage of the inverter stage's fundamental component is v_{ac}.

Here C_1, C_2 are capacitors, L_1, L_2 are inductive coils, v_{ac} is alternating source voltage, i_{ac} is alternating current, M is mutual inductance between the primary and secondary coils and R_{eq} is equivalent resistance.

Despite the fact that the battery is a voltage source-based load whose voltage varies with the degree of charge, the voltage corresponding to the battery value must be provided as an essential requirement for establishing a wireless charging system at the required power level. The equivalent resistance for the input portion of a rectifier circuit is referred to as R_{eq}, and the battery is treated as a resistive load. In [33–36], the four fundamental compensation topologies were examined. For high-power transmission, SS and SP offer more economically viable options [36]. The four fundamental compensation topologies were researched, and the bifurcation phenomenon was proposed by Wang et al. [1]. They showed that, in contrast to SS and SP topologies, the main capacitance C_1in PS and PP topologies is dependent on the load status. Because the resonance is ensured, SS and SP compensation topologies are better suited for fluctuating load circumstances. Researchers from the University of Michigan, Dearborn (UM-Dearborn) put up the double-sided LCC compensation topology as a more modern compensation topology [2].

As seen in Figure 2-7, the compensating coil L_{f1}, L_{f2} resonates with the capacitor C_{f1}, so once v_{ac} is set and the voltage generated by the source $j\omega Mi_1$ (ω is the angular frequency radians/ second) is constant, the current i_1 is constant.

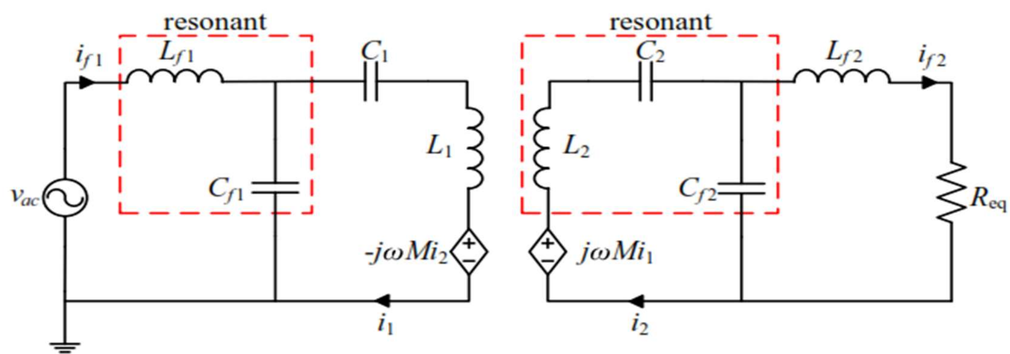

Figure 2-7 Two-sided LCC compensation.

Here, v_{ac} is alternating voltage, L, L_{f1}, L_{f2} are inductance of coils; C_1, C_2, C_{f1}, C_{f2} are capacitors, i_1, i_2, i_{f1}, i_{f2} are currents, R is equivalent resistance; $j\omega Mi_1$ is induced voltage and $j\omega Mi_2$ is the voltage induced by the secondary coil [40].

The resonant frequency has no influence on the load situation or coupling coefficient on the receiver side since L_2 and C_2 are combined to resonate with C_{f2}. The symmetry of double-sided compensation topology causes L_{f2} to resonate with C_{f2}, whereas L_1 and C_1 together resonate with C_{f1}. The following equations 2-1 through 2-3 yield the formulas for load current i_{f2}, output load power P, as well as coefficient of coupling k, respectively:

$$i_{f2} = \frac{k\sqrt{L_1 L_2}v_{ac}}{j\omega L_{f1}L_{f2}} = \frac{2\sqrt{2}}{\pi}.\frac{k\sqrt{L_1 L_2}V_{in}}{\omega L_{f1}L_{f2}}\angle -90^0 \qquad 2\text{-}1$$

$$P = \frac{8k\sqrt{L_1 L_2}V_{in}V_{out}}{\pi^2 \omega L_{f1}L_{f2}} \qquad 2\text{-}2$$

$$k = \frac{M}{\sqrt{L_1 L_2}} \qquad 2\text{-}3$$

Where M is the mutual inductance between primary (L_1) and secondary (L_2) coils and V_{in} is the source voltage of inverting stage, V_{out} is output voltage. Equations 2-1 and 2-3 demonstrate that the output current remains steady wherever V_{in} is constant. In a two-coil system, output power is in relation with direct proportion to coupling coefficient k. First [38, 39] included the compensated coils within the two-coil system. At a 150 mm air gap, their system produced 6.0 kW of electricity with a DC-DC efficiency of over 95%. After their integration, though, redundant coupling effects started to emerge. In order to streamline the design and analysis, Kan et al.[38] presented a novel integration approach that maintained compactness as well as high transmission efficiency while eliminating or greatly reducing the annoying coupling effects brought on by amalgamation.

2.3 Converters and control techniques:

Electronics converters on the source side convert utility AC electricity at 50 Hz into elevated frequency AC power at the necessary level. Following are two approaches to convert:

- The less popular technique is to employ AC/AC converters to convert direct power from 50 Hz conventional AC power to higher-frequency AC power.
- The most common technology is indirect two-step power conversion, in which 50 Hz utility AC electricity is rectified into DC power before being turned into high-frequency AC electricity via a full-bridge inverter.

A full-bridge rectifier converts high-frequency AC power to DC power for the sole purpose of charging battery cells on the receiver side. The resonant frequency is determined by the compensation networks and realized by the inverter. The switching frequency, usually the resonant frequency, of the inverter in EV wireless charging systems ranges from 20 kHz to 100 kHz. The resonant frequency can now reach 1 MHz thanks to the invention of new silicon carbide MOSFETs [41]. The wireless charging system becomes less bulky at higher frequencies; however, other issues caused by high-frequency AC, such as EMF emissions, necessitate further investigation.

Power electronics converters are a crucial subject that is intimately tied to the way a wireless charging system is controlled. In fixed charging systems [21,42,45] as well as dynamic charging systems [46, 47], several control strategies have been established.

Several converter configurations and topologies have been proposed to efficiently transfer power wirelessly. Here are some existing and proposed configurations along with their control techniques and challenges:

Association	Power (KW)	Efficiency	System frequency (Hz)	Misalignment (mm)	Primary coil size (cm^2)	Secondary coil size (cm^2)	Year	Reference
Uni. of Auckland	2		20k	200	3848	3848	2011	[20]
	2-7		20k	100-250	3100	3100	2013	[25]
	1	91.3%c	85k	100	1385	1385	2015	[26]
UM-Dearborn	3.3	95%b	1 M	150	1024	1024	2015	[41]
	6	95.3%b	95k	150	3600	3600	2019	[38]
	7.7	96%b	79k	200	4800	4800	2014	[5]
KAIST	5-15		20k	150	9900	1400	2014	[50]
Utah State University	5	90%a	20k	175-265	5191	5191	2012	[21]
Saitama University	3	90%b	50k	200	960	960	2012	[23]
ETH Zurich	5	96.5%b	100k	52	346	346	2021	[51]

a AC to DC efficiency .

b DC input to DC output efficiency.

c Coil efficiency.

Table 2-2 System parameters of certain stationary charging systems.

- Inductive Coupling:
  - Control Technique: Typically, resonant converters such as Class-E or Class-D are used to achieve efficient power transfer. Phase-locked loop (PLL) based control is common for frequency tracking and synchronization.
  - Challenges: Limited range due to the strong dependency on the distance between coils. Efficiency drops significantly with larger distances.
- Resonant Inductive Coupling:
  - Control Technique: Various control techniques like frequency and phase control, impedance matching, and adaptive tuning are employed to maintain resonance and maximize efficiency.
  - Challenges: Complex control algorithms are required for maintaining resonance across variable load conditions and distances. Efficiency can still degrade over longer distances.
- Magnetic Resonant Coupling:
  - Control Technique: Similar to resonant inductive coupling, but with additional challenges of managing multi-resonant frequencies and optimizing coupling coefficients.
  - Challenges: Complex control algorithms are needed to manage multi-resonant frequencies and mitigate interference from nearby resonant systems.
- Microwave Power Transfer (MPT):
  - Control Technique: Phase and frequency control techniques are used to ensure efficient power transfer.
  - Challenges: Safety concerns due to high-frequency radiation, beam alignment issues, and high cost and complexity of implementing phased array antennas.
- Electric Field Coupling:
  - Control Technique: Capacitive coupling techniques, such as impedance matching and frequency control, are employed.
  - Challenges: Efficiency is typically lower compared to magnetic coupling, and the system is sensitive to environmental factors like humidity and nearby conductive objects.

Topology	Control Techniques	Challenges	Novelties
Inductive Coupling	Class-E Class-D	Limited range [34,13] Efficiency drops significantly with larger distances [25,76,47].	Efficient power transfer
Resonant Inductive Coupling	Frequency and phase control	Complex control algorithms [32,43]	
	Impedance matching	Maintaining resonance across variable load conditions and distances Efficiency can still degrade over longer distances [45,65,66].	Maximize efficiency
	Adaptive tuning	Maintaining resonance across variable load conditions and distances Efficiency can still degrade over longer distances [45,65,66].	Maximize efficiency
Magnetic Resonant Coupling	Similar to resonant inductive coupling [32,43]	Complex control algorithms[32,43] are needed to manage multi-resonant frequencies.	2014
Microwave Power Transfer (MPT)	Phase and frequency control techniques	Safety concerns due to high-frequency radiation, beam alignment issues, and high cost and complexity.	2012
Electric Field Coupling:	Capacitive coupling techniques	Efficiency is typically lower compared to magnetic coupling.	System is sensitive to environmental factors

Table 2-3 Converter and Control techniques

- Existing converter configurations used in WPT, such as:
  - Single-stage vs. multi-stage converters[29,103].
  - AC-DC, DC-DC, and DC-AC converter topologies[34,56].
  - Resonant vs. non-resonant converters[22].
  - Full-bridge, half-bridge, and other converter topologies[12,89].
- Overview of control techniques employed in WPT converters, including:
  - Pulse Width Modulation (PWM) control [12-14].

- Phase-shift control [18,36,67].
- Frequency control[22,23,101].
- Phase-locked loop (PLL) control[42,44].
- Maximum Power Point Tracking (MPPT) control[34,35.87].

- Identification of existing challenges and limitations in WPT converter design and control, such as:
  - Efficiency optimization under varying load conditions[65,54].
  - Mitigation of electromagnetic interference (EMI) and electromagnetic compatibility (EMC) issues[27.39].
  - Achieving high power density and compact converter designs[22,29].
  - Thermal management and reliability concerns[14,28,102].

Compatibility with different WPT standards and specifications[25,44].

2.4 Performance and challenges:

The schematic parameters of a few different stationary charging methods are summarized in Table 2-2 System parameters of certain stationary charging systems. Although the efficiency is good at the desired output power level, it should be noted that the literature has conflicting efficiency measurements. For instance, some studies report coil efficiency; use an AC grid for battery pack measurements; and some report battery pack efficiency using DC input. Knowing the AC grid to determine battery pack efficiency is preferable from the perspectives of system analysis and sustainability assessment because it provides a thorough characterization performance of charger and is straight correlated to the assessment of largely energy depletion and the calculation of electricity costs for the economic estimation. The suggested common practice for efficiency measurement is to consistently provide AC grid efficiency for battery pack efficiency.

Most of the time, main and secondary coil sizes are bigger than conductive charger sizes. The power density of a wireless charging system created by ETH Zurich researchers is greater than that of any other technology described in Table 2-2. System, nevertheless, could be more susceptible to misalignment than the other systems on the list. Compact and lightweight construction can compromise system performance [49], and it is a constant practical problem for researchers to strike a balance between the dimensions of the static charging system also its misalignment tolerance.

2.5 Applications and certain examples:

2.5.1 Public transportation buses:

Because of the permanent-route characteristics of urban transportation bus networks, a significant amount of modern wireless charging application and development have been concentrated on electric transportation buses. As shown in Table 2-4, an increasing number of experiments with wireless charging electric buses have been recorded. Wireless charging has the potential to address a significant impediment to the deployment of city electric transportation buses with range limitations.

The Chattanooga Area Regional Transportation Authority (CARTA) project found that a quick "opportunity charge" of one minute at 60 kW can increase the range by about one mile (1.61 km); therefore, multiple charges throughout the day might be able to overcome the range restriction and allow for the completion of the required regular route of 100 miles (161 km), which would otherwise necessitate battery switching during the day [60].

The size, price, and battery life of traditional all-electric transportation vehicles are additional barriers to their growth. A long-distance all-electric bus's battery pack can make up about 26% of its overall weight and 39% of its overall cost [10, 12, 65]. The KAIST On-Line Electric Vehicle (OLEV) project in Korea, one of many bus efforts, uses cutting-edge technology that enables buses to charge while stationary or in motion, significantly reducing the size of the battery. Dynamic wire-free EV charging became commercially viable in 2009 thanks to the Shaped Magnetic Field in Resonance (SMFIR) technology that the OLEV research group created and implemented on buses and a tram [57].

2.5.2 Passenger cars:

The U.S. Department of Transportation acknowledged the development of WPT for EV applications and noted the requirement to comprehend the effects of dynamic wireless EV charging on American roadways [12]. While Utah State University constructed a cutting-edge testing facility for dynamic wireless charging in 2015 [67]. Dynamic WPT could allow EVs to extend their range indefinitely [12]. In regions where dynamic WPT infrastructure is readily available, EVs can operate continuously without stopping. Additionally, the battery's capacity might be decreased to less than 20% of that of a typical EV battery [68].

Scheme	**Year**	**Place**	**Efficiency**	**System Frequency (Hz)**	**Power (KW)**	**Battery rating (KWh)**	**Misalignment (mm)**	**Reference**
Bus projects in Italy	2003	Turin, Italy	90%b	15–20k	60		40	[55,56]
KAIST On-Line Electric Vehicle (OLEV)	2009	South Korea	72–83% a	20k	6–100		170–200	[7,57]
Bombardier PRIMOVE IPT for Electric Buses	2010	Germany, Belgium	>90% b	20k	40–200	36–90		[7,58]
Chattanooga Area Regional Transportation Authority (CARTA)	2011	United States (TN)	90% a	15–20k	60		40	[55,59,60]
Wireless Advanced Vehicle Electrification	2017	United States (UT, CA, TX, MD)	90% b	20k	25–50		150–250	[55,61]
(WAVE) ZTE Corporation projects	2019	China (Various cities)	90% a	45k	30, 60		200	[62–64]

a. AC grid to vehicle terminal efficiency.

b. Measurement terminals unknown

Table 2-4 Summary of selected wireless charging electric bus project

To investigate the viability of implementing a designated WPT lane on significant thoroughfares for in-motion charging, many feasibility studies were carried out. A feasibility study on dynamic wireless charging was carried out by ORNL in collaboration with three additional U.S. Department of Energy laboratories.

Data from arena tests of innovative vehicles at Idaho National Laboratory and the chassis dynamometer testing facility at Argonne National Laboratory were used to characterize the power need vs. the vehicle speed profile. To satisfy the minimum speed criteria for the operating condition of common commuter highways, a vehicle travelling at 40 miles per hourwas chosen, which equates to an electricity transfer of roughly 25 kW. This level of electricity is necessary to support vehicle motion and keep the SOC operational. For faster speeds, a greater power transfer level and comparatively advanced power via the vehicle impulsion systems are needed. Using data from the National Renewable Energy Laboratory, including the most heavily trafficked roads based on vehicle usage, the arterial routes with the highest return on investment for highway electrification were found.

2.6 Summary and Implications:

The first segment covered the procedural aspects of stationary and dynamic charging systems of three areas: coil architecture, compensation configurations, and power electronics conversion and control mechanisms. The system's performance has improved as a result of technical improvements. Dynamic wireless charging systems are on their way to powering moving vehicles, but stationary wireless charging systems exhibit system performance comparable to conductive charging systems. There are two major research gaps from a technological viewpoint:

- How to maximise the energy acquired by vehicles and charging without contact while improving the system efficiency for static charging systems; and
- How to balance the electrical charging technique's size with its misaligned tolerance.

From a sustainability standpoint, the advantages of battery reduction and vehicle light weighting must be balanced against the trade-off of extensive infrastructure deployment. WPT technology has the potential to offer advantages such as higher energy performance, fewer adverse environmental effects, cheaper life cycle costs, greater comfort, and operational safety benefits compared to wired EVs and conventional ICEVs. The following research gaps must be solved before WPT EVs may fully realise their potential:

- Managing the electrical grid to maintain a balance between the supply and demand of power for stationary cars;
- Maximising the deployment of large-scale charging infrastructure and battery capacity while taking into account battery life for both passenger car and public transportation applications and
- Strategies that coordinate WPT technology improvements and implementation of other burgeoning EV techniques, such as connected and automated vehicles (CAVs).

Given its technical maturity and economic viability, stationary WPT for both private and public charging is predicted to experience wider adoption before dynamic WPT might be introduced gradually if the market expands sufficiently to drastically lower the high initial infrastructural cost as opposed to static charge. The implementation of WPT technology will be accelerated by the use of features (such as charging alignment precision) to improve driving performance and energy efficiency in connected and autonomous vehicles (CAVs). WPT technology also enables more active contact with the electric grid through V2G and G2V bidirectional power transfer, turning EVs into mobile energy storage devices that help manage the grid by storing surplus generation from uncontrolled sources of renewable energy.