Chapter

Overview and Advancements in Electric Vehicle WPT Systems Architecture

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Abstract

Wireless Power Transfer (WPT) system is a rapidly evolving technology with vast potentials in consumer electronics, electric vehicles, biomedicals and smart grid applications such as Vehicle to Grid (V2G). Hence, this article is devoted to present an overview of recent progress in WPT with specific interest in magnetic resonance WPT and its system architectures such as compensation topologies, inputs and outputs, as well as coil structure. The strengths, drawbacks and applications of the basic compensations (SS, SP, PS, PP) and hybrid compensations (LCC and LCL) were presented and compared. Although primary parallel compensations perform well at low mutual inductance, they are rarely used due to large impedance and dependence of coefficient coupling on the load. Hence, the need for extra-compensations forming hybrid topologies, such as LCC, LCL, which usually choice topologies for dynamic WPT application or V2G application.

Keywords: compensation topologies, electric vehicle, vehicle to home, magnetic resonance, inductance

1. Introduction

In recent years, research trends on Electric Vehicles (EVs) have gained accentuating attention with focus on advancing the technologies for wireless power transfer (WPT) and applications such as Vehicle to Grid (V2G). Since growth in WPT in electric vehicles creates new possibilities in the V2G, it is hard to talk about the future of Vehicle to Grid (V2G) without including an efficient wireless power transfer system. In designing an effective V2G that integrates electric vehicles into the power grids, a bi-directional WPT system is required such as allows energy flow between the vehicle and the electrical grid [1, 2]. One of the major goals of EV WPT research is the development of alternative systems for powering battery reliant devices to limit the bottlenecks and issues related with the use of wired charging for batteries. Some of the outstanding benefits of WPT system includes improving portability and user-friendliness of devices; by eliminating wires; devices can now be developed with more flexibility and limited environmental design constraints as in the case of medical implantation and underwater *witricity*.

The philosophy of V2G thrives on the premise that EVs are parked for most of the day and the energy stored in their batteries can be utilized during this time provided that their initial state of charge (SoC) is restored before vehicle utilization by the user [2–4]. Although the traditional V2G is designed for wired charging, the system can be easily extended to WPT provided that all the unidirectional stages are replaced with bidirectional stages such that power can flow in both directions [1]. In a situation where the EV charging station is a domestic or residence, the V2G is known as Vehicle to Home (V2H) [5, 6], and in this case, the customer can either use the energy stored in the battery to power its own domestic loads or inject it into the grid if the loads are low-power [7–9]. A design procedure for a bi-directional WPT Vehicle to Home (BWV2H) application was presented, ensuring necessary constraints such as the rules for low voltage utilities and the standard SAE J2954 for EV WPT were satisfied [3]. It is expected that the widespread adoption of BWV2H technology will aid demand response, the smart grid transition, and the seamless integration of renewable energy sources. The V2H technique also helps to minimize the overall power cost by stabilizing or reducing the fluctuating power demand of home loads, in addition to compensation of users for the distribution system's service [3]. Some of the prospects of the study is the optimization of the system to allow load balancing, filling and peak shaving [10, 11]. A mathematical model for the estimation of the charge and discharge efficiency in an EV bidirectional ICPT wireless charger was presented [12]; the WPT system was characterized and validated experimentally using a 3.7 kW prototype. It was suggested that V2G systems need improvement in operational mechanism, compliance and control.

In the past few decades, there has been interesting progress in the wireless power transfer field, which has in turn triggered development and innovation in fields of consumer electronics, electric vehicles, biomedical etc. The transfer of 60 watts of power over a distance of 2 meters with an efficiency of 40% in 2007 by MIT researcher [13] opened up a new landscape of development in wireless power transfer. Other feats include the powering of 14 watts compact fluorescent lamp wirelessly in 2011 using a circular domino with repeater arrangement by researchers from Hong Kong Polytechnic University [14] and the transfer of 5 kilowatts of power over a gap of 20 cm at an efficiency of 90%, by researchers from Utah State University in 2012 [15]. Also in 2012, electric buses were deployed and charging pads were installed at bus stops for charging electric buses by an Uttah-based company, Wireless Advanced Vehicle Electrification (WAVE) [16]. The development and introduction of Online Electric Vehicle (OLEV) into public transit network in 2013, by the Korea Advanced Institute of Science and Technology (KAIST). The OLEV is an electric vehicle that can be charged both in-motion and in-stationary, and the charging system allows for a one-third reduction in the battery compared with that of a regular electric vehicle [17].

The analysis of the performance indices of wireless power systems [18–21], is an integral part of WPT research usually done using equivalent circuit, coupled mode theory or two port networks as modelling technique with a goal of improving the system performance [22]. In order to achieve a stable and functional WPT system for robots, an analysis of the WPT coupling mechanism, coupling coils and compensation topology was presented and extended into investigation of other means of enhancing coupling performance such as Multi-layer coil structure [23]. The use of circuit theory and mutual inductance in modelling various components of the system and solving for performance indices is also a common approach [18–21]. Using equivalent circuits and Neumann's formula [24], the relationship between maximum efficiency and air gap length in magnetic resonant coupling was analyzed and the conditions required to

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achieve maximum efficiency for a given air gap were proposed. The air gap length was confirmed to be related to the radius and number of turns of the coils. Maximum efficiencies are achieved at various air gap lengths through mutual inductance, characteristic impedance, internal resistance and resonance frequency by setting the optimized characteristic impedances in each case. To boost efficiency of WPT, Theodoropoulos et al. devised a control algorithm for load balancing in wireless EV charging [25]. A solution to the problem of pad misalignment was proposed by Zhao *et al.*, using a combination of the different resonant networks [26].

This work presents an overview and advancements in wireless power transfer, with specific interest in application of magnetic resonant coupling to the charging of electric vehicle. In the foregoing sections, the overview of the WPT system classification is presented; the system architectures were presented with focus on compensation topologies and the coil design aspects and charging standards.

2. WPT system classifications

WPT systems are generally classified using system attributes such as coupling strength, coupling type, transmission direction and transmission distance.; and when considering transmission distance, it can be near-field (non-radiative) or far-field (radiative) based on proximity (radiative). The requirements of the desired application largely determine which type of WPT is recommended (**Figure 1**).

2.1 Coupling strength

When considering coupling strength, WPT can be loosely coupled WPT (LC-WPT) or strongly coupled WPT (SC-WPT). Loosely coupled WPTs primarily consists of inductors and resistors, and they are used in applications where the coupling coefficient is low. On the other hand, strongly coupled WPT achieves improved efficiency through resonance and it finds wider range of usage in consumer applications. However, both LC-WPT and SC-WPT operate at the near-field region of the transmitting antenna. In EV WPT, SC-WPT is considered preferable due to optimal possibility of power transfer when the transmitter and receiver are synchronized to

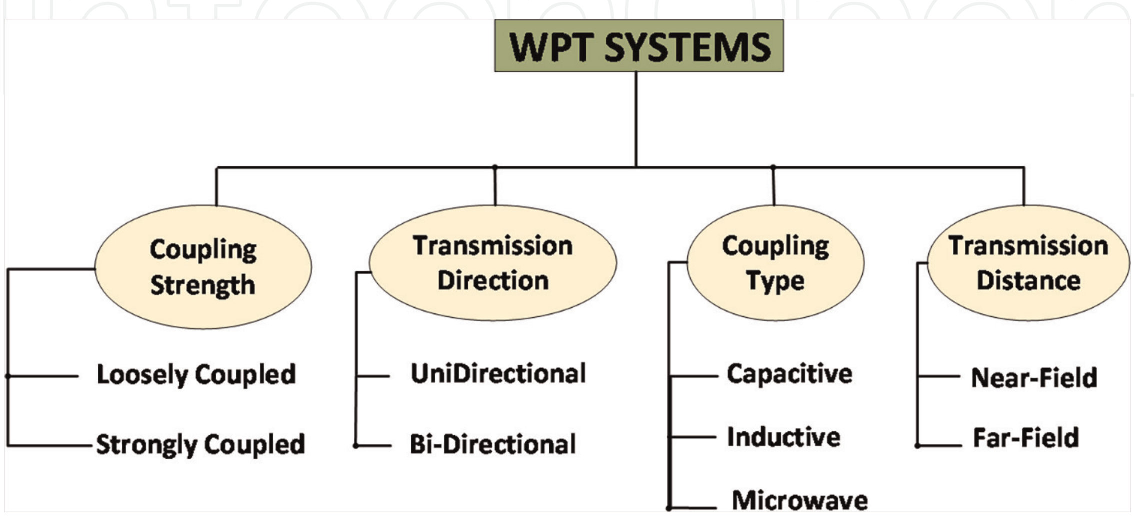

Figure 1.
Classification of wireless power transfer systems.

operate at resonance, hence eliminating reactive power which otherwise would increase system losses. The inductive wireless power transfer, which happens to be the most popular is based on Ampere's Law and Faraday's law.

When current flows through an inductor with N turns, a magnetic flux ϕ is produced. The voltage produced in the coil is proportional to the number of turns N and the time rate of change of the magnetic flux ϕ, according to Faraday's law [27] (**Figure 2**).

$$v = N\frac{d\phi}{dt} = N\frac{d\phi}{di}\frac{di}{dt} = L\frac{di}{dt} \quad (1)$$

Where L is the self-inductance of the coil, given as $L = N^{d\phi}/_{di}$. When another coil L2 with N2 turns is brought in close proximity to the current carrying coil L1, such that there is magnetic flux linking, the voltage in coil L1 and L2 are respectively given as;

$$v_1 = N_1\frac{d\phi_1}{di_1}\frac{di_1}{dt} = L_1\frac{di_1}{dt} \quad (2)$$

$$v_2 = N_2\frac{d\phi_{12}}{di_1}\frac{di_1}{dt} = M_{21}\frac{di_1}{dt} \quad (3)$$

Where $\phi_1 = \phi_{11} + \phi_{12}$ such that ϕ_{11} is the flux linkage on coil L1 and ϕ_{12} is the magnetic flux linkage of coil L1 on L2. The mutual inductance is the tendency of one inductor to induce voltage in a nearby inductor, given as;

$$M_{21} = M_{12} = M = N_2\frac{d\phi_{12}}{di} \quad (4)$$

$$M_{21} = k\sqrt{L_1L_2} \quad (5)$$

Where the coupling coefficient, $0 \leq k \leq 1$, is a measurement of how magnetically connected two coils are.

2.2 Coupling type

When considering coupling, WPT can be capacitive coupling (C-WPT), inductive coupling or inductive power transfer (IPT), magnetic resonance coupling (MRC), and

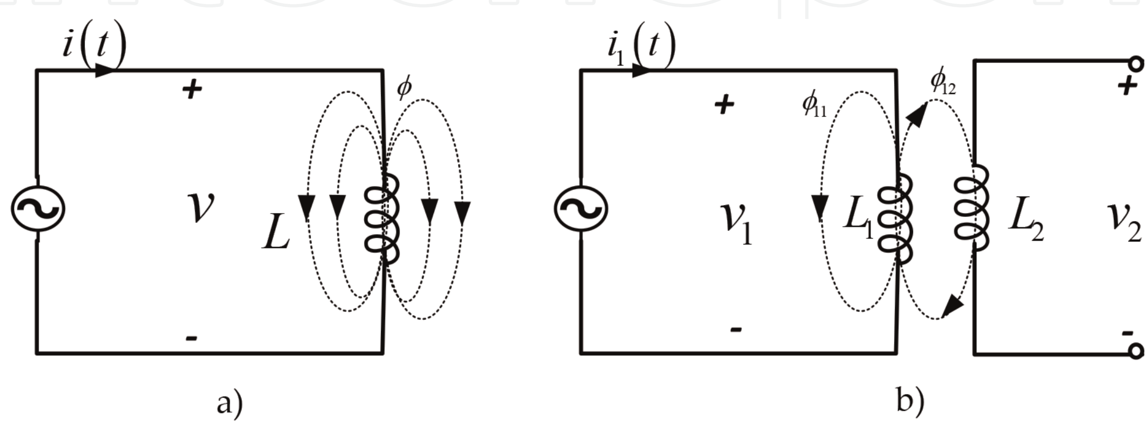

Figure 2.
(a) Self Inductance, (b) Mutual Inductance.

microwave coupling. Inductive coupling involves transfer of energy from the magnetic fields of an inductor on the transmitting end to another inductor on the receiving end. Although it has the ability of achieving a high efficiency (>90%) [28] and it requires minimal area for magnetic influence, a main drawback is the limitation in the distance of transfer between the transmitter and receiver. The efficiency reduces drastically as separation distance increases [29], and the operating frequency typically ranges from 10 kHz to MHz [30].

Resonant Inductive Coupling is an approach used for reducing system impedances of inductive coupling WPT systems by compensating the primary and secondary coils with capacitors, leading to higher power transfer efficiency through magnetic resonance [13]. It is also found that the coil parasitic inductance can be used for compensation, provided the operating frequency is significantly high enough for the coil's self-resonant frequency [31, 32]. The differences between IPT and MRC is the presence of compensation capacitors in MRC for tuning the secondary and the primary coils to a resonant frequency, whereas, IPT WPT has no resonant circuit involved. Also, MRC is preferred for low- or medium-powered WPT applications while IPT WPT is preferred for high-voltage WPT applications [1].

Capacitive coupling is unique in its coupling approach as it engages capacitance effect in transmitting power from the source to the receiver such that the transmitter's set of electrode couples with the set of electrodes at the receiving end [33]. This makes it considerably suitable for low power lightweight application that is in few kW. However, safety concerns increase as the power rises and large electric fields are transmitted.

2.3 Transmission distance

The near field WPT includes loosely coupled, strongly coupled, inductive coupled, capacitive coupled and any other coupling whose transmission distance is in the near-field region. Microwave coupled WPTs operate in the far-field zone. Due to the possibility of transmission distance to meet design requirements, magnetic resonance coupling is gaining momentum in applications such as Electric Vehicle (EV) charging. In near-fields, the power transfer distance is shorter than the operating wavelengths, and examples include the inductive and capacitive coupling. While the efficiency of power transfer is much higher than the far-field techniques and has higher misalignment tolerance, the transfer distance is small and efficiency deteriorates with increasing distance.

Far-field WPT are characterized transfer distance significantly larger than the electromagnetic wavelength and can power devices at tens of thousands of kilometers. Examples include wireless power transfer from solar satellites to ground rectennas. However, a major drawback is the low efficiency and directivity constraints; the misalignment tolerance is too low hence requiring high alignment for successful transference of power. In order to improve the transmission characteristics of wire antennas for wireless power transfer, such as directivity, analysis of dipole transmitter elements for WPT was carried out [34]. Using the half-wave dipole, the current distribution and radiated fields were computed via Method of Moment technique (MoM). The design and analysis of 5, 6, 7, 10, 20 and 30 elements of broadside and endfire arrays at 0.3, 0.4 and 0.5 inter-element spacing. Despite the fact that far-field evanescent resonant-coupling techniques can transmit energy over longer distances than near-field induction methods [35, 36], much research attention is focused on near-field power transmission [17, 37], which has applications in consumer electronics, biomedical devices, electric vehicles, and other areas [20, 38, 39]. This is owing to the fact that when utilizing the radiative approach, the efficiency of wireless power transfer drops dramatically.

2.4 Transmission direction

When considering the direction of energy transmission, WPT can be unidirectional or bidirectional the unidirectional is the commonly used WPT for electric vehicles. However, when the system requires power transfer in both direction as in the case of V2G, a bidirectional system is deployed. The figure below shows the equivalent circuit topology of a bi-directional WPT for V2G, containing three basic elements; the DC voltage source, the inverter, and a compensation network [40] (**Figure 3**).

Both the primary and secondary sides of a bi-directional WPT system can act as transmitters or receivers. Consequently, both DC sources must be able to release and absorb energy. In practice, a rectifier connected to voltage input is frequently used as the primary voltage source, and a battery stack is frequently used as the secondary voltage source [40].

There are also four power electronic switches, which serves as inverter on the primary side, and as rectifier on the secondary side. Compensation is also introduced so as to improve the efficiency caused by low coupling leading to high reactive power.

3. System architectures

When designing the circuit architecture of the WPT system, there are certain design objectives required, the system losses increase with increasing reactive power. To achieve this, the circuit is compensated using capacitors, so as to achieve one or more of the following requirements [17, 41, 42]:

1. **Power Transfer:** It is mostly desired to maximize the power transfer and this is achievable by cancelling leakage inductances on both primary and secondary sides [17, 43–45].

2. **VA rating:** It is usually desired to minimize the VA rating of the power supply by providing regulated reactive power needed for establishing and sustaining the magnetic field [17, 46]. Reactive currents increase semiconductor and

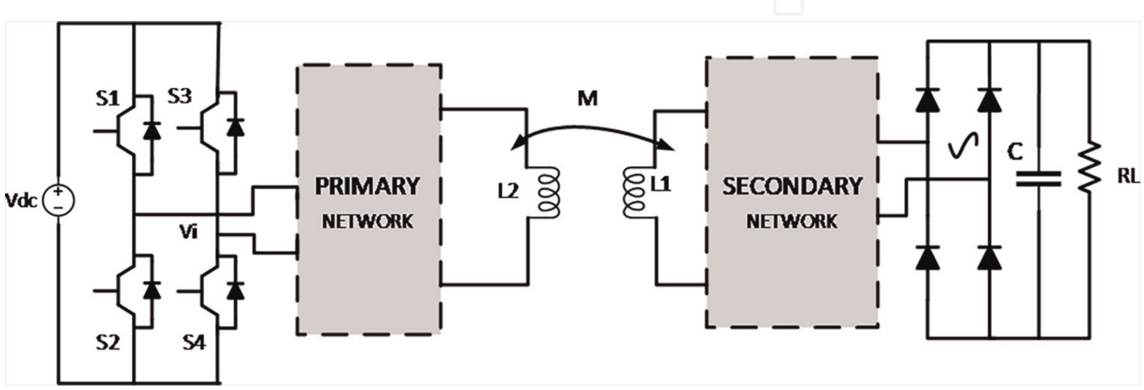

Figure 3.
Circuit Topology of bidirectional WPT system.

conduction losses, mostly in diodes. The primary leakage inductance is cancelled by primary resonance to increase the power factor to near unity.

3. **Phase Angle and Soft Switching**: Since the VA rating on the power supply is determined by the phase angle between the input voltage and the current, the minimum VA rating requires the phase angle to be zero while the switching of MOSFETs requires that phase angle be large than zero. Hence, phase angle is usually selected to be slightly greater than zero to achieve soft-switching, and low enough for acceptable VA rating [42].

4. **Constant Voltage (CV) or Constant Current (CC):** It is sometimes desired to provide Constant Voltage or Constant Current at the output. Usually, the end load for a wireless power transfer system is a battery and it requires constant current while charging at low states (0–85%), and constant voltage for charging state [17, 47]. In some applications, compensation networks are specially designed to keep the output voltage constant or output current constant so as to meet the battery charging requirements [17, 42]. Primary series compensation is necessary for voltage source, while parallel compensation is used for current source drive.

5. **Bifurcation Tolerance:** It desired to improve the Bifurcation tolerance of the system. This is done by designing the compensation network for single zero phase angle, while ensuring system stability for different loading conditions and frequency variation control [17, 41, 42].

6. **Misalignment Tolerance:** Each compensation topology has a varied sensitivity to altering location (misalignment). This necessitates a more complex control mechanism to ensure that the resonance frequency is maintained on both sides.

Table 1 shows a summary of the Requirements and the dependencies. In addition to the aforementioned points, frequency splitting usually occurs in strongly coupled systems, where the electromagnetic coupling between coils are high [22], leading to various adaptive controlling measures to maximize the power transfer; such as frequency tuning [48, 49]; impedance matching [50, 51], and coupling manipulations [52, 53]. One of the two goals of WPT is to attain maximum power transfer, and this occurs when the source impedance and the input impedance are matched. Recent

Requirement	Dependency
Maximum power transfer	Compensation topology
Minimal VA Rating	Primary resonance
Zero phase angle	Soft switching
CV or CC output	Load, compensation, topology
Bifurcation tolerance	Load quality factor, compensation topology and
Misalignment tolerance	Compensation topology
Bidirectional flow	Compensation topology, power control

Table 1.
WPT system requirements for compensation network designs.

WPT research has been focused on strategies for increasing PTE in wireless EV charging systems and improving pick-up power [54].

3.1 Compensation topologies

As mentioned in the last section, compensations are introduced to obtain desired characteristics, when the coupling coefficient reduces to less than 0.3. The WPT pads are loosely coupled and have large leakage inductance and hence prompts the need for a compensation network to suppress this. Compensation circuits are typically required for both TX and RX in order to increase the system's power transmission metrics such as power transfer efficiency (PTE) and power delivered to the load (PDL). PTE and PDL are two crucial characteristics in WPT technology that influence the range of power transmission and interference with other devices [55].

A compensation circuit has several advantages, including lowering the power supply's volt-ampere (VA) rating and more efficiently adjusting the value of current in the supply loop as well as the voltage in the receiving loop. The easiest way to achieve compensation is adding a capacitor to each side of the system, and this produces basic topology or hybrid topology. Factors that influence the selection of the L and C values of the resonant circuit includes the primary or secondary topology, the quality factor and the value of the magnetic coupling coefficient [56].

3.1.1 Basic compensation topology

There are four basic compensation circuits and numerous hybrid compensation circuits in MRC WPT. The four basic compensation systems are Series–Series (SS), Series–Parallel (SP), Parallel–Series (PS) and Parallel–Parallel (PP). The figure below shows the circuit schematic of the four basic compensation networks (**Figure 4**).

Where the impedance for primary series is given as $Z_p = j\omega L_p + R_p + \frac{1}{j\omega C_p}$, secondary series impedance is given as $Z_s = j\omega L_s + R_s + \frac{1}{j\omega C_s}$; and secondary primary impedance is $Z_p = j\omega L_s + R_s + \frac{R_L}{j\omega C_s R_L + 1}$. The table below presents the resonant

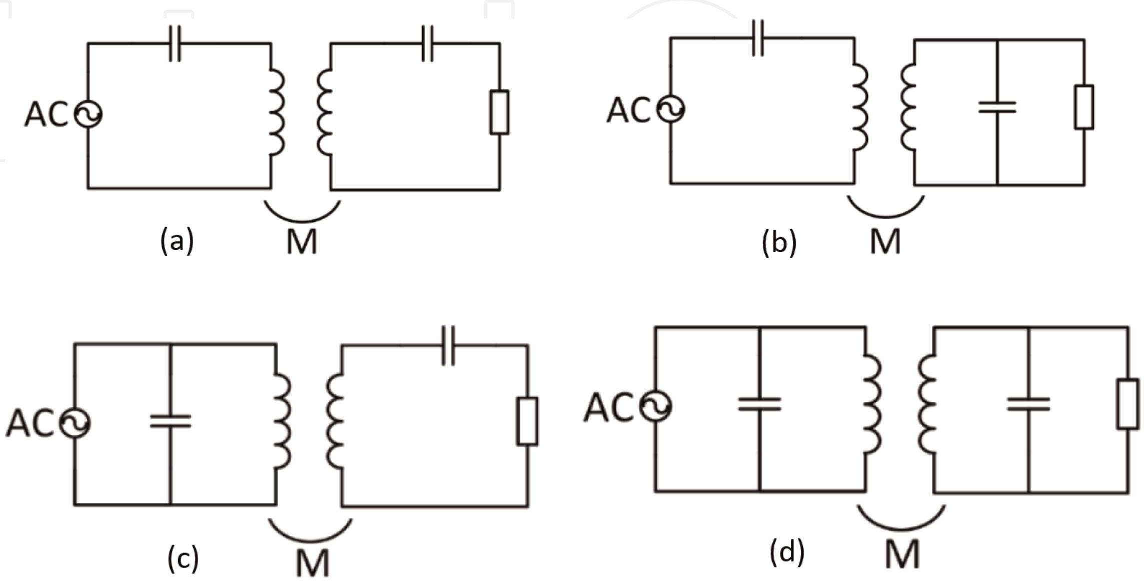

Figure 4.
Circuit Schematic of Basic WPT Topologies (a) SS, (b) SP, (c) PS, (d) PP.

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Topologies	C_p [56]	Z_{in} [57]	η [57]
SS	$\frac{1}{\omega_r^2 \cdot L_p}$	$Z_p + \frac{\omega^2 M^2}{Z_s}$	$\frac{\omega^2 M^2 R_L}{\lvert Z_s \rvert^2 R_p + \omega^2 M^2 (R_L + R_s)}$
PS	$\frac{L_p}{\left(\frac{\omega_r^2 \cdot M^2}{R}\right) + \omega_r^2 \cdot L_p^2}$	$\frac{Z_p - \frac{1}{j\omega C_p} + \frac{\omega^2 M^2}{Z_s}}{j\omega C_p \left(Z_p + \frac{\omega^2 M^2}{Z_s}\right)}$	
SP	$\frac{1}{\left(L_p - \frac{M^2}{L_s}\right)\omega_r^2}$	$Z_p + \frac{\omega^2 M^2}{Z_s}$	$\frac{\omega^2 M^2 \frac{R_L}{1+\omega^2 C_s^2 R_L^2}}{\lvert Z_s \rvert^2 R_p + \omega^2 M^2 \left(\frac{R_L}{1+\omega^2 C_s^2 R_L^2} + R_s\right)}$
PP	$\frac{L_p - \frac{M^2}{L_s}}{\left(\frac{M^2 \cdot R}{L_s^2}\right) + \omega_r^2 - \left(L_p - \frac{M^2}{L_s}\right)^2}$	$\frac{Z_p - \frac{1}{j\omega C_p} + \frac{\omega^2 M^2}{Z_s}}{j\omega C_p \left(Z_p + \frac{\omega^2 M^2}{Z_s}\right)}$	

Table 2.
WPT System requirements for compensation network designs.

capacitors, input impedance and efficiency of the basic compensation networks (**Table 2**) [56, 57].

Series–Series (SS) Compensation: In SS, unity power factor occurs at resonant frequency, making the compensation desired where high efficiency and high-power factor (PF ≈ 1) are required. The importance of these two metrics is hinged on how they fluctuate with coupling and load variation [42]. One of the advantages of the SS compensation includes the independence of the value of the primary capacitance on coupling coefficient and load [45, 47]. It finds application in dynamic WPT where the coupling coefficient changes as the device moves; an example is the segmented dynamic WPT charging in EV. Series compensation, in which the compensation capacitors are connected in series along the primary track, is ideally suited for systems with lengthy primary tracks. This permits the track voltages to be kept within acceptable levels. Because concentrated windings are often high-current systems, parallel compensation is better suited for them [56]. A major drawback however is the light-load condition that occurs when the receiver is not present, thereby creating a zero-impedance at the primary resonance frequency. Hence, the voltage transferred to the load under this condition is very high. The only thing that limits the current in this situation are the parasitic impedances of the coil and capacitor.

1. Series–Parallel (SP) Compensation: In SP, regardless of the load, there are some impedances that are transferred to the primary and at resonance, there would still be a short circuit if the load is absent which facilitates the need for a current limiting control. Also, variations in the mutual inductance leads to changes in the power factor and system dynamics, hence making power factor more challenging [42, 45]. Also, as the mutual inductance changes, the resonant frequency and consequently, the value of the capacitance are changes. The SS and SP compensation are most commonly utilized in actual applications and implementation because they have the highest efficiency, with efficiencies exceeding 93 percent and approaching 97 percent at various transmission power levels [56, 58, 59].

2. Parallel–Series (PS) Compensation: The reflected impedance to the primary is the same for the series–series and parallel–series configurations. At relatively low mutual inductances and relatively large range of changes in load and mutual inductance, the efficiency and power factor are high [60, 61]. Also, since the system requires current source input, to avoid instantaneous changes in voltage, the P-S is compensated by adding an inductor to create an LCL resonant task. A

study shows that variation in coupling influences the compensation capacitance required in secondary parallel circuits [62]. It is also possible to combine the characteristics of SS and PS to achieve SPS constant output power without adjusting the power supply [11, 63]. Although PS allows for soft switching in semiconductors [64], compensations on the primary side are rarely employed due to high impedance, calculation complexity, and coupling coefficient dependence on load, among other factors [65]. In PS and PP, the increased input impedance necessitates a high driving voltage to transfer sufficient power [66].

3. Parallel–Parallel (PP) Combination: Since series compensations requires higher voltage and current than parallel compensation, a combination of both is used to obtain the required capacitance needed to achieve the desired voltage and current ratings. Also, a combination of series–parallel–series topology is proposed to suppress the effect of misalignment [63]. In general, analysis of the four basic compensation circuit topologies shows that the maximum power transfer capability is attained by reducing the reactive power flow through varying the operating frequency; however, control complexity caused by frequency bifurcation occurs and triggers system instability [67].

3.1.2 Hybrid compensation topologies

In order to achieve further improvement such as constant current/voltage, higher efficiency, designs of hybrids of capacitors and inductors topology have been explored for the MR WPT circuit, such as LCL, LCC, LCCL etc. The LCL and LCC are considered briefly below:

1. LCL Compensation: This is formed by adding an inductor to parallel resonance network [44] and it has the ability of overcoming the problems associated with series and parallel compensations. Using an LCL compensation [1], a phase-angle control method was introduced to effectively regulate the direction and magnitude of power flow in a WPT device, and a mathematic model of a bidirectional power flow was presented. As a strength, the source current of LCL can be easily controlled for variations in coupling coefficient and load conditions using a full bridge converter with minimized VA rating. The secondary side can be a parallel compensation, series compensation or hybrid. Common secondary combination of LCL primary compensation includes, LSL-S, LCL-P, LCL-LCL. In order to achieve constant current and constant voltage in the transmitting coil, a dynamic LCL-S/LCL topology was proposed [68]. Parallel compensation is popular because it offers flexibility to variations in load [69]. However, the reflected impedance on the primary has both real and imaginary components of the load, which contributes to reactive power. To ensure continuity of conduction through the rectifier, a large dc inductor is required, which increases the cost and loss in the system. Comparing LCL-S with LC/S, they are identical in structure but have different tuning methods. However, the LC provides a better load independent voltage output and strong capability of high voltage suppression than LCL-S [70]. Also, the LC compensation network with LCL in the primary side performs like a current source at the resonant frequency irrespective of the coupling and load condition because the current in the primary side coil is controlled by the high frequency square wave voltage from the power converter. This makes LCL adopted for many designs [15, 71, 72],

LCLC compensation is employed in cancelling the nonlinear effect of the rectifier diodes, to achieve an exactly unit power factor at predetermined load condition. Both LCL and LCLC achieve remarkable improvement in efficiency as compared with traditional LC parallel structure.

2. LCC Compensation: The LCC is formed by adding an inductor in series and a capacitor in series to a parallel resonant circuit. Several researches have been conducted on the double sided LCC [73–77]. As a strength, it can be used to compensate the power factor at the secondary side to achieve unity power factor. It is also independent of coupling coefficient and load conditions while ensuring Zero Volt Switching (ZVS) for MOSFETs [78]. In general, researchers favor double sided LCC because of the high misalignment tolerance, load independence, reduction of current stress in the inverter, higher efficiency [73]. A comparative analysis between S-S and LCC-LCC in EV WPT shows that LCC-LCC outperforms S-S topology in efficiency stability with respect to variations in self-inductance due to lateral displacement of receiving and transmitting coils [76]. But when compared to the LCCL compensation topology, LCCL has a higher efficiency and a higher power transfer level, as well as a larger coupling coefficient. Compared with LC-S, LC-S experiences a 2.5% improvement in efficiency [79].

3.2 Variation in number of transmitters, receivers and stages

Based on the number of transmitters or receiving elements, the WPT system can be classified as single-input single-output (SISO), multiple-input single-output (MISO), single-input multiple-output (MISO) or multiple-input multiple-output (MIMO).

3.2.1 SISO, SIMO, MISO and MIMO

SISO and MISO: SISO WPT is a basic and simple WPT System prototype in which the distance and orientation of the coils have a significant impact on the reflected load. In MISO WPT, cross coupling occurs between the transmitters which increases the effects of the load on the transfer function and system efficiency. Two scenarios of system node coupling are Increased Density and Constant Density. In increased density scenario, the number of receivers increases within a constrained region as well as the cross couplings between receivers, while the mutual coupling between receivers and transmitters remains constant. This results in reduction in point to point efficiency as number of nodes increases. In constant density scenario, the region and the number of receivers are increased, mutual coupling is reduced while cross coupling between transmitters remains constant. The power efficiency and output power vary as number of receivers are changes.

SIMO and MIMO: In SIMO WPT, the systems performance is influenced not only by the mutual coupling between transmitter and receivers, but also by the cross couplings between receivers as well. MIMO WPT is popular for wireless sensors and other electromagnetic radiation WPT applications [80–82]. Drawbacks in designing efficient MIMO include determining exact resonant frequency. An algorithm was proposed [83] for isolating the desired receiver and maximizing the power while limiting power to unintended receivers. Notable advantages of SIMO over MISO include greater power transmission efficiency (PTE) and lower magnetic field strength requirements, making it safer for human health [79, 84]. As a result, the MISO WPT system is a strong contender for biomedical implants, general electronics, and dynamic electric car charging.

3.2.2 Variation in transmission stages

The WPT system can also be designed using more than two coils, such as the 3-, 4-coil etc. The two-coil WPT is the basic SISO prototype, consisting of two electromagnetic subsystems with the same natural resonant frequency. Using the resonance frequency as a key parameter, mathematical expressions of optimal coupling coefficients of 2-coil WPT were examined and the system efficiency was analyzed with respect to the air gap values for various [85]. It was shown that the maximum PTE always occurs at the resonance frequency and reduces with decline in coupling coefficient. The efficiency values were calculated using three kinds of softwares in order to determine the difference between the software outputs. The results show that the equivalent circuit analysis by means of numerical computing is best suitable for determining the voltage and current waveforms. It was suggested that minimum distance between coils should be used to keep the energy transfer at an optimum, and this can be solved by optimizing the relation between the quality factor and frequency. A 4-coil system, which consists of the transmitter (source coil and a sending coil) and receiver can be conventional or unconventional (asymmetric). In conventional 4-coil [86–88], the input impedance of the system can be adjusted by mounting and coupling the source coil with the sending coil. Similarly, the equivalent load resistance can be adjusted to match the load condition by mounting and coupling the load coil with the receiving coil. The asymmetric 4-coil system, proposed by Moon [89], is made up of primary side (source coil and two transmitter coils) and secondary side (receiver or load coil). When compared to conventional 4-coils, the asymmetric 4-coils have a higher PTE and a longer range between the source and load coils; this is owing to improved augmentation of the apparent coupling coefficient.

3.3 Static and dynamic charging

Static Charging finds application in designs where the electrical loads are required to be stationary during the wireless powering. Examples include consumer electronics [90], biomedical devices [91, 92] and electric vehicles [16, 72, 93]. In a static WPT, the source transmitting coil is excited with a high frequency electric field and transmits magnetic field (B) to the receiving coil through the air gap. The electromagnetic field, landing on the receiving coil induces an electric current in the coil capable of transmitting several watts of power across the air gap. One of the common applications of static WPT today is the electric vehicle WPT charging stations where charging cables, extensions and sockets are replaced with coils and also aid the easy realization of complete design and implementation of autonomous vehicle operations. Some of the design goals for static EV WPT include [79]; maximizing the power transfer efficiency (PTE) for a given cost and specification; increasing the magnetic coupling to increase induced voltage; compactness in size; and managing fluctuations in resonant frequency and coupling coefficient caused by pick-up position misalignment and air-gap variation. In stationary EV WPT, the utility power is converted from low frequency (LF) to high frequency (HF) by high frequency inverter. This generated HF electromagnetic field energizes and transfers power to the receiving resonator. Generally, wireless power converters can be direct or indirect power converters. Although the transmitter track is easier to control, some of its major drawbacks include safety need to suppress harmful electromagnetic emissions; also, the need to distribute compensation capacitor to minimize the large inductance is costly, low coupling coefficient and others.

Dynamic wireless power transfer (DWPT) allows for mobility of load during the transfer of power with vast applications in electric vehicles as well as bio-medicals, where ingested sensors can continue operating and charging while customer is breathing or moving around [94]. In EV, charging of the vehicle while in motion promises to help improve the requirements for driving range and battery charging of EVs. Dynamic WPT can be classified based on the transmitter array design; either a single transmitter track and or segmented transmitter coil array. The single transmitter usually consists of a long transmitter track connected to the power source, while the receiver is smaller in comparison. Segmented coil array usually consists of multiple coils of transmitting resonators connected to a high frequency power source. While the dynamic suppresses field exposure and the need for distribution of compensation capacitors, it also presents peculiar challenges some of which include; need for right optimization of transmitter coil design parameters, such as setting the appropriate distance without compromising the mutual inductance and design cost. The dynamic EV wireless charging already finds application in electric buses and trams at low speeds in urban areas [94]. Despite the prospects of the DWPT, issues such as the problem of accurately forecasting and responding to private EV's dynamic charging demands is still a major drawback since the routes and speed are largely unpredictable. Unlike plug-in and static WPT that charges for hours at low power ratings, DWPT is expected to take few seconds or few minutes. Another challenge is the need to keep track of receiver position and regulating power supply appropriately as the load navigates the array. Some enquiries relevant to the advancement of this research direction include finding impact of inter-coil mutual inductance on the overall power transfer efficiency, influence of inter-element distance on coil efficiency and how this can be optimized. Examples of the track based dynamic WPT includes [95, 96]; the online electric vehicle (OLEV), designed by Korean Advanced Institute of Science and Technology (KAIST). The OLEV has 5 to 60 m long rails powering pickup modules of 80 cm in length. Another notable example is the track-based dynamic wireless power transfer system of UC Berkeley.

4. Coil designs

The coil architecture is one of the critical areas of consideration in the design of an optimal WPT system because of its influence on the minimum efficiency requirements, misalignment tolerance, cost, volume, weight and other performance benchmarks as assessed and presented using analytical and numerical methods [37, 97–99]. For instance, the shape of the coil affects transmission efficiency and studies show that different shapes (spiral, square, circular, solenoidal) all have different efficiencies [100–102]. A comparison between the solenoidal coil and spiral coil was presented using experimental analysis [103]. The impact of each parameter of a circular coil structure was investigated in order to determine the limit of design parameters in improving the coil performance, and determination of misalignment performance which leads to exploration of alternative structures for coils, such as the double D coils (DD-coils) and double D quadrature coil (DDQ coils) [104, 105, 106–108]; and XPAD [109]. The use of circular coil of Litz wire was proposed for transferring 1 kW power through an air gap distance of 300 mm at 100 kHz, and achieved an efficiency greater than 80% [110]. In addition to the coil shape, the structural composition of the coil also affects the system performance. For instance, it is proposed that an efficiency of 40% can be achieved at 0.5 cm transfer distance [111] using a coil of high Q planar-Litz. To increase the inductance, Mizuno *et al.* proposed a magnet plated copper wire with a magnetic thin layer coated around the circumference to boost inductance; and the resistance due to proximity effect is lowered because eddy current loss is minimized [112]. Unlike in EV WPT system, space limitation is a major design constraint in some applications such as medical implants, thereby furthering the need to optimize the coil design [113]. Some of the coil parameters that affect the system performance include; ratio of coil diameter to air-gap (R:L); coil geometry, Q-factor etc. [114]. A study shows that the transmission efficiency exceeds 80% when air-gap (L) is lesser than half of coil diameter (R), i.e. $L/R < 0.5$, and the transmission efficiency reaches 90% when $L/R < 0.25$ [114].

4.1 Coupling pads

The coupler is considered the most important part of the WPT system [17], and it consists of the transmitter and receiver coils separated by a magnetic gap. When designing coupling coils, the desired attributes include: high coefficient of coupling (k); high quality factor (Q); and high misalignment tolerance [62, 115].

High Q: Designing the inductors to have high self-inductance and low series resistance at high frequency helps improve the Q. However, considering the standard by SAE J2594/1, the maximum operating frequency is limited to approximately 85+/− 3.7 kHz. Hence, increasing the quality factor means reducing the resistance of the coil.

$$Q = \sqrt{Q_1 Q_2} \tag{6}$$

Where $Q_{1,2} = \omega L_{1,2} / R_{1,2}$ and $L \, \alpha \frac{\mu N^2 A}{l}$.

The Coil inductance is directly proportional to the square of the number of turns, while the ESR is directly proportional to the no of turns. Although, increasing number of turns also increases ESR but it increases inductance more. Hence the coil Q can be increased by increasing the number of turns [116, 117]. Hence to find an optimum self-inductance for the coil, a balance must be found between the wire diameter and the number of turns. Alternatively, ferrite bars are proposedly used on the coil to increase self-inductance by guiding the flux so that leakage flux can be reduced and high coefficient of coupling can be realized [17]. The coil ESR consists of DC and AC resistances. The DC resistance can be reduced by increasing the area of the conductor, while the use of Litz wire is adopted to reduce the AC resistance [118]. The product of kQ, which affects the efficiency of the coupled inductors in the system, is determined by the geometry, the core material as well as the magnetic gap [116, 117, 119].

High Coefficient of Coupling (k): In order to improve the coefficient of coupling and maintain high quality factor, several coil structures such as Circular Pads, Flux Pads, DD Coils, Multi-Coil Polarizer have been proposed [30, 117, 120].

1. Circular Pads – Several reports on the design and optimization of circular pads have been reported in the literature [116, 117]. Using Pareto for optimization, guidelines for optimizing the design of circular coils with respect to area-related power density and efficiency are discussed [116, 117]. It was proposed that the diameters of the coils should be 600-800 mm to keep the coupling coefficient in the range of 0.15–0.2, when the magnetic gap is 150–200 mm [118]. A good

assessment of WPT for automotive applications was also provided, as well as techniques for sizing circular pad and performance metrics in EV [30].

2. Flux Pipe – The use of rectangular bars of ferrite with a coil wounded along the length is also proposed, and report shows that it exhibits good lateral misalignment tolerance and further guides the flux to terminate at the ends of the coils [104, 120]. Although it has the merit of increasing horizontal misalignment tolerance and providing fundamental flux path that is half the receiver pad's length, the main drawback which causes loss of Q and low efficiency is that it is solenoidal. This results from the aluminum shielding on the solenoidal coil, which causes loss of quality factor when it is close to one side of the coil and has flux interception [120].

3. DD Coils: To combined the advantage of flux pipe and circular pads, the use of polarized single-sided flux coupler was proposed; where the middle portion of the DD coil, similar to the flux pipe, are connected magnetically in series [120]. And it offers a single sided flux path; higher coefficient of coupling resulting from flux path height proportional to half of the pad length; lower losses in aluminum shielding; low leakage flux from back of the coil and improvement of no-load Q [121].

4. Multi-Coil Polarized Coupler: this includes the use of couplers with different coils either on secondary or primary side [120, 121], usually derived from DD coil and circular coils. The advantages include; tolerance to misalignment and minor variations in magnetic gap spacing. Examples include the DDQ Coil, Bipolar Pad, Tripolar Pad etc.

4.2 Coil performance evaluation

Based on ANSYS simulation, the performance of different coil structures were evaluated and the relative benefits of the geometry was compared [17, 116, 117]. With respect to coefficient of coupling and misalignment tolerance, Bipolar Pads demonstrates the highest performance but with a drawback of decrease in coefficient of coupling with addition of aluminum shield. With respect to shielding, circular coil performs better because its coefficient of coupling is not affected much based on the one sidedness of the flux pattern. Hence, bipolar pad and circular pads are the most popular amongst the coupler [116, 117].

The aforementioned improvement procedures provide sub-optimum outcomes in some situations because they search for a single objective while keeping the other parameters constant. Whereas, the objectives are dependent on multiple parameters, and optimizing one parameter may inadvertently affect another parameter. This facilitated the use of evolution algorithm, such as Genetic algorithms to evaluate the coil performance with different parameter combinations [122, 123], and formulation of procedures to handle multi-objective optimization of benchmarks such as coil to coil efficiency [124–126], figures of merit, coupling and Quality Factor as well as cost, weight and volume [125–128].

5. International charging standards

In order to achieve compatibility across different devices, there are standards of regulation such as the Qi Standard, Alliance for Wireless Power (A4WP), SAE, and International Electrotechnical (IEC) standards.

1. The Qi Standard: The Wireless Power Consortium developed the Qi standard, which is suitable for electrical power transfer over distances of up to 40 mm. It finds application mostly in inductive WPT and comprises of two fundamental elements; the Base Stations and the Mobile devices. The base stations, which is the power transmitter provides inductive power for wireless transmission while the Mobile devices are the end loads that consume the wireless power. Qi wireless chargers are classified as low power or medium power depending on their power delivery range. Low-power chargers are those that can give up to 5 watts at a frequency of 110–205 kHz, and most consumer electronics such as cell phones, music players, and Bluetooth earpieces, fall within this category. Chargers in the medium power category can offer up to 120 watts at a frequency of 80–300 kHz. A variety of mobile phones, such as the iPhone 8, iPhone 8 plus, and iPhone X, adopted the Qi certification. Moreover, thousands of Qi wireless charging stations can be found in public places such as hotels, restaurants, coffee shops, pubs, and public transportation. The Qi standard also includes two positioning types, guided and unguided positioning of the mobile device relative to the base station, to ensure enough coupling for effective transmission. Alliance for Wireless Power (A4WP): The A4WP was established to develop and maintain standards for a type of wireless power that allows for more spatial freedom than previously available standards. The A4WP's magnetic field is spread out across a large area, making device location less important and allowing a single power TX to charge multiple devices at once (SIMO). A4WP, on the other hand, supports Z-axis charging, allowing the device to be detached from the charger [79]. Similarly, to Qi standard, A4WP has two main elements; the Power TX unit that is responsible for power transmission and the Power receiving unit.

2. SAE Standard: SAE International, a multinational organization dedicated to serving as the engineering profession's ultimate knowledge source, ratified the TIR J2954 standard for plug-in hybrid EV wireless charging. All light-duty vehicle systems use the 85 kHz (81.39–90 kHz) frequency band established by SAE TIR J2954. WPT levels are also divided into four PH/EV classes: 3.7 kW (WPT 1), 7.7 kW (WPT 2), 11 kW (WPT 3), 22 kW (WPT 4); and higher power levels may be added in future editions [129]. Many wireless vendors and companies, such as Qualcomm, WiTricity, Evatran, and others, are operating wireless charging using J2954 [79].

3. IEC: Some of the standards published by the IEC includes, IEC 61980-1 in 2015, which addresses general requirements for EV WPT systems, including efficiency, electrical safety, electromagnetic compatibility, electromagnetic field (EMF) protection, as well as general background and definitions. The second part of the series, IEC 61980-2, contains communication needs between electric road cars and WPT systems, as well as some background information and definitions. IEC 61980-3, the third part of the series, will contain special specifications for EV magnetic field WPT systems [79].

6. Conclusion

WPT is a rapidly developing technology with enormous possibilities. This article provided an overview of WPT advancements, with a focus on magnetic resonance

WPT and its system architectures; compensation topologies, inputs and outputs, and coil structure. Basic compensations (SS, SP, PS, PP) and hybrid compensations (LCC and LCL) are given and contrasted in terms of their strengths, limitations, and applications. Primary parallel compensations operate well at low mutual inductance, but they are rarely employed due to high impedance and coefficient coupling reliance on the load. As a result, extra-compensations are required, resulting in hybrid topologies such as LCC and LCL, which are commonly used for dynamic WPT or V2G applications. Considerable attention will be paid in future to novel ways of achieving the improved design objectives.

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