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Chapter

Wireless Power Charging in Electrical Vehicles

Nassim Iqteit, Khalid Yahya and Sajjad Ahmad Khan

Abstract

Wireless Power Transfer (WPT) technology can transfer electrical energy from a transmitter to a receiver wirelessly. Due to its many advantages, WPT technology is a more adequate and suitable solution for many industrial applications compared to the power transfer by wires. Using WPT technology will reduce the annoyance of wires, improve the power transfer mechanisms. Recently, the WPT gain enormous attention to charging the on-board batteries of the Electric Vehicle (EV). Several well-known car manufacturing companies start efforts to adopt WPT technology and enhance its features. Therefore, WPT can be achieved through the affordable inductive coupling between two coils named a transmitter and a receiver coil. In EV charging applications, transmitter coils are located underneath the road, and receiver coils are installed in the EV. The inductive WPT of resonant type is generally applied to medium-high power transfer applications like EV charging because it achieves better energy efficiency. In this chapter, various WPT technologies are discussed and tested in EV wireless charging applications. Furthermore, extensive information is given to developing an advanced WPT technology that can transfer maximum power by achieving maximum efficiency.

Keywords: Wireless Power Transfer (WPT), Electric Vehicle (EV), Energy Efficiency

1. Introduction

A Wireless Power Transfer (WPT) is one of the promising technologies used to transfer electric energy from a transmitter to a receiver wirelessly. WPT is an attractive solution for many industrial applications due to its enormous benefits over wired connections. The advantages include the no hassle of carrying wires, easy charging, and smoot of power transmission even in unfavorable environmental circumstances.

The idea of wireless power transfer (WPT) was first introduced at the end of the 19th century by Nicola Tesla. He manufactured a wireless lighting bulb that was used to receive electrical charge wireless [1]. Tesla used two metal plates that were closely placed to each other. A high-frequency Alternative Current (AC) potentials were passed between these two plates, and the bulb powered ON. However, some of the issues appeared while using WPT technology. One of the main issues is that the minimum power density and low transfer efficiencies affect when the distances increase. As a result, the performance of WPT technology becomes very slow. Therefore, the WPT technology is improved and used "strong coupled" coils when the distance increases more than 2 m while charging wirelessly [2]. The two

important WPT technologies are Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT). CPT is only applicable to low power applications with very short air gaps between 10–4 and 10–3 m, whereas IPT can be used for large air gaps around several meters, and its output power is much higher than CPT.

Figure 1 Compares between CPT and IPT, **Figure 1a** shows the power transfer capability versus gap distance with efficiency values. Furthermore the figure indicates both IPT and CPT can achieve ≥90% efficiency at kilowatt power levels in their respective gap ranges. **Figure 1b** plots the transmitter/receiver area versus throughput power with efficiency. The coupler area is the cross-sectional area through which magnetic or electric fields transfer energy. **Figure 1c** plots the output power density (output power divided by the gap volume) versus frequency [3]. WPT technologies can be applied in television, phone chargers, and induction heating, medical devices, pacemakers, radiofrequency identification, sensors, robotics, and deeply used in wireless charging for EV [4–11].

In CPT and IPT power transfers, the respective energy stored in a unitary volume of space is

$$W_e = \frac{1}{2}\varepsilon_0 E^2$$

$$W_m = \frac{1}{2}\mu_0 H^2$$

where E and H are the intensity of the electric and magnetic fields and, ε_0 and μ_0 are the permittivity and the permeability of the free space.

Health and safety, and economic impact are the critical points that should be considered in any technology of WPT for charging EVs or in any other applications. WPT technology for charge replacement, EVs can become gorgeous option. WPT charging has the advantage that it can make the charging process automated, suitable and safe for users and large scale introduction of WPT charging infrastructure
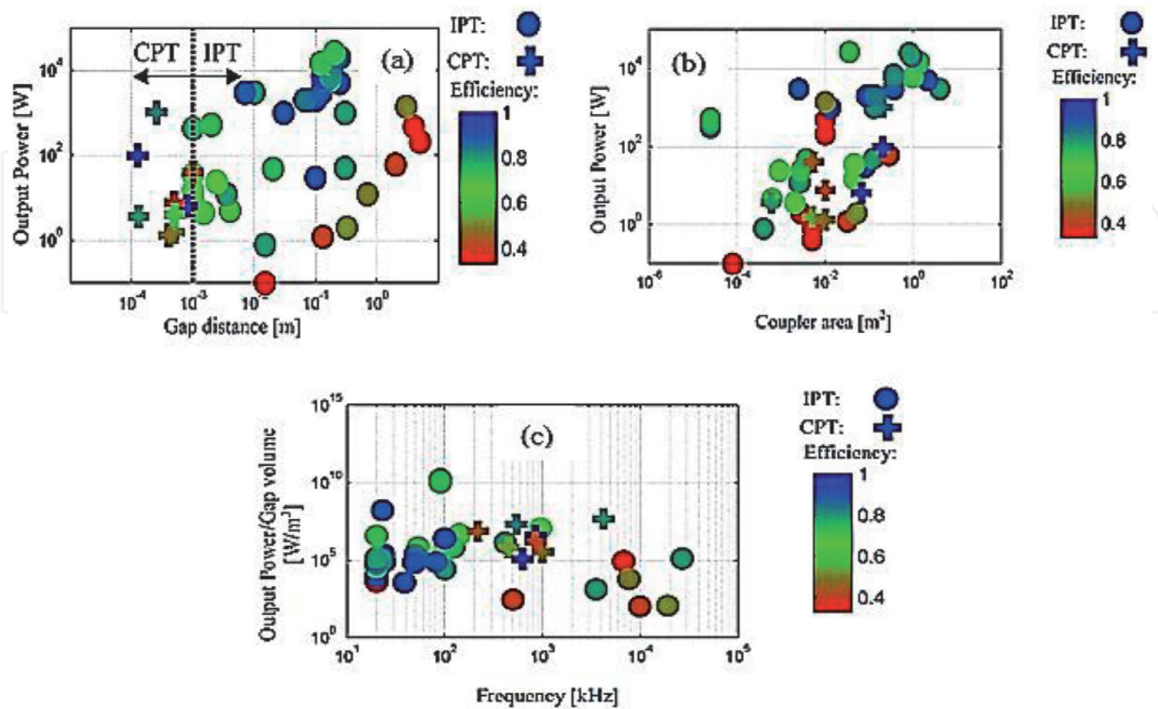

Figure 1.
Comparison between CPT and IPT technologies [3], (a) gap distance and output power with efficiency value , (b) coupler area and output power with efficiency value, (c) frequency and output power density with efficiency value.
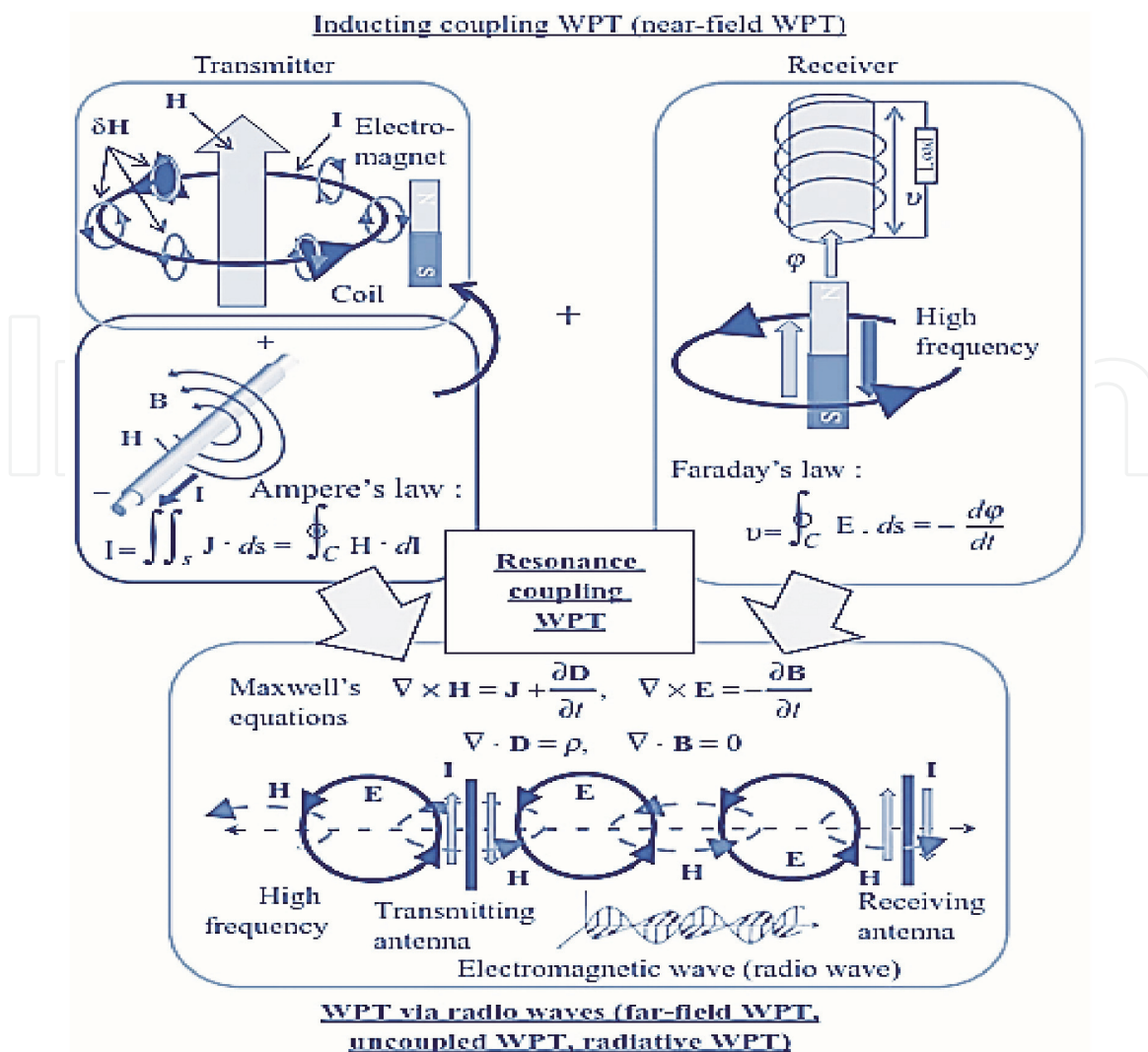
Figure 2.
Relationship between Ampere's law, Faraday's law, Maxwell's equations, inductive-coupling WPT, resonance-coupling WPT, and WPT via radio waves [13].

can help reduce the battery pack size and in turn make the EVs more proficient. However, all this cannot be knowledgeable by using traditional inductive chargers and WPT charging through large air gaps and least possible human interaction are required [12].

WPT systems are primarily classified as microwave, evanescent wave, magnetic resonance, electrical resonance, or electromagnetic induction methods. Scientists have newly proposed an electromagnetic induction method that is not premised on transformer coupling. It is revealed that the electric power transmission over a range including a magnetic field resonance method is enabled by adopting this method [13].

Ampere's law, Faraday's law, Maxwell's equations, the inductive-coupling WPT, the resonance-coupling WPT, and WPT via radio waves are the major theory that can describe the functionality of WPT technologies. **Figure 2** shows this relationship between these theories.

2. Basic theory of WPT system

When AC or DC electrical energy is transformed to high-frequency electrical energy by using a high-frequency inverter, the wireless feeding device (Tx.) releases electrical energy through a transmission device into space. Then, the

receiving system (Rx.) converts the electrical power into DC in the recipient electrical apparatus. In addition, the efficiency of the electrical power transmission, medical and environmental influence of electromagnetic waves, and improvement the facile high speed charging, safe security, and energy storage density are essential limits should be considered when WPT is designed for EVs.

WPT systems are classified as microwave, evanescent wave, magnetic resonance, electrical resonance, or electromagnetic induction methods. **Figure 3** shows the relation between transmitted power and transmitted length of these methods for WPT systems. Additionally, WPT can be classified to the kind of Type1,Type 2, Type 3 and Type 4 as shown in **Figure 4**. **Table 1** shows the relationship of Types 1–4 from the viewpoint of coupling mechanism, resonant mechanism, and feeding
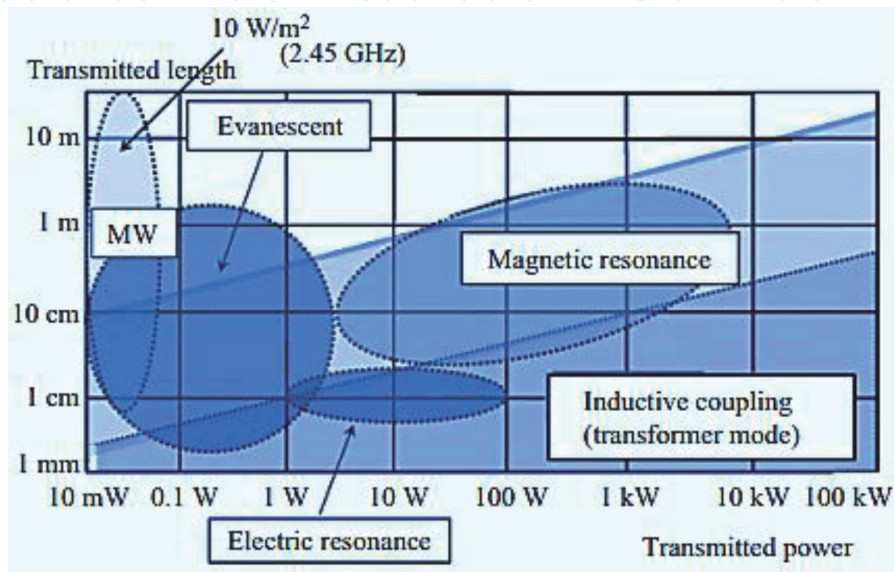

Figure 3.
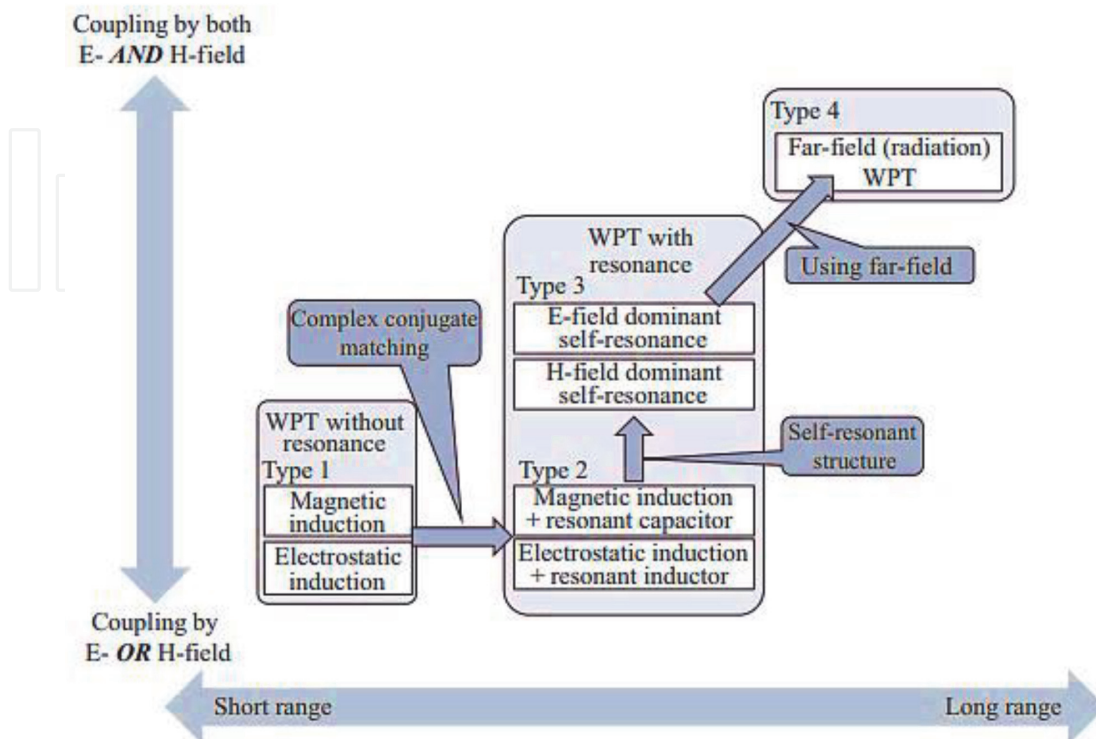*Transmitted power and transmitted length of noncontact WPT methods [13].*

Figure 4.
Relationship of different kinds of WPT scheme.

Type		Coupling mechanism		Resonant mechanism	Impedance matching mechanism (feeding mechanism)	Schematic
		E-field	H-field			
1	Electrostatic induction	Yes	No	Power factor compensation may be considered as a resonant circuit	Not active following for load impedance	
	Magnetic induction	No	Yes			
2	Coupled-resonant using electrostatic induction	Dominant	Negligible	Discrete reactance device is necessary for resonance	According to the load impedance or transmission distance, active following by circuit parameter in impedance matching circuit or transmission frequency is necessary to achieve simultaneous conjugate matching	
	Coupled-resonant using magnetic induction	Negligible	Dominant			
3	Coupled-resonant with self-resonant coupler (E-field dominant)	Dominant	Small, but not negligible	Coupler acts as resonator		
	Coupled-resonant with self-resonant coupler (H-field dominant)	Small, but not negligible	Dominant			
4	Far-field type (microwave WPT)	Coupling in far-field. Ratio of E-field to H-field is 377 Ω		Tx and Rx antennas resonate independently	Tx/Rx antennas are matched to the source/ load independently	

Table 1.
Coupling mechanism, resonant mechanism, and impedance matching mechanism for various kinds of WPT.
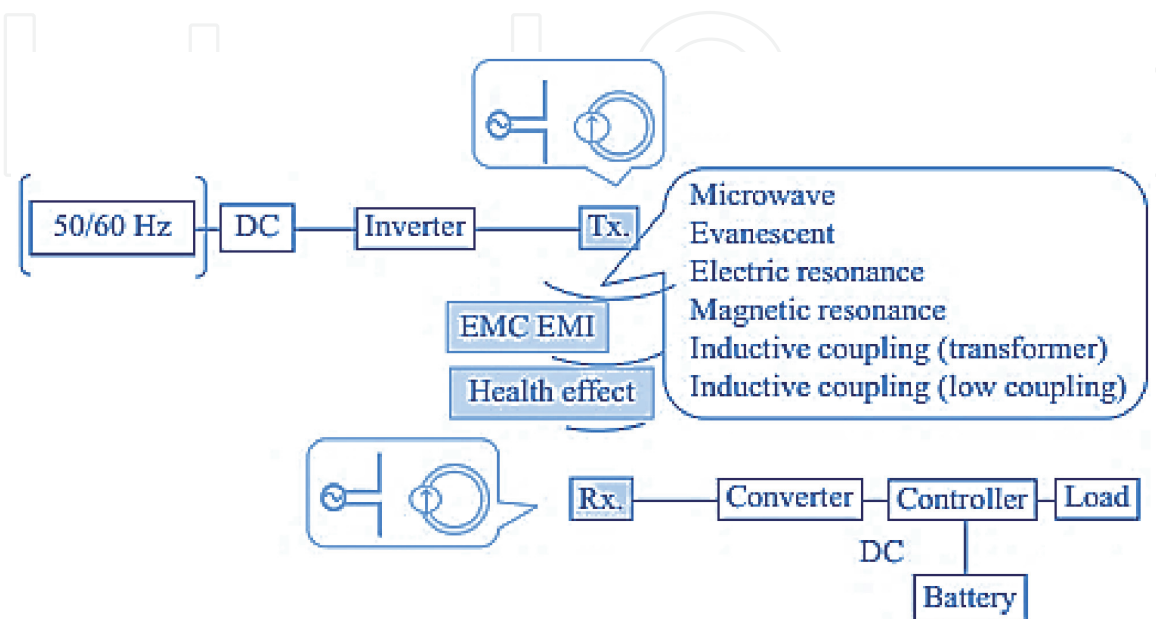

Figure 5.
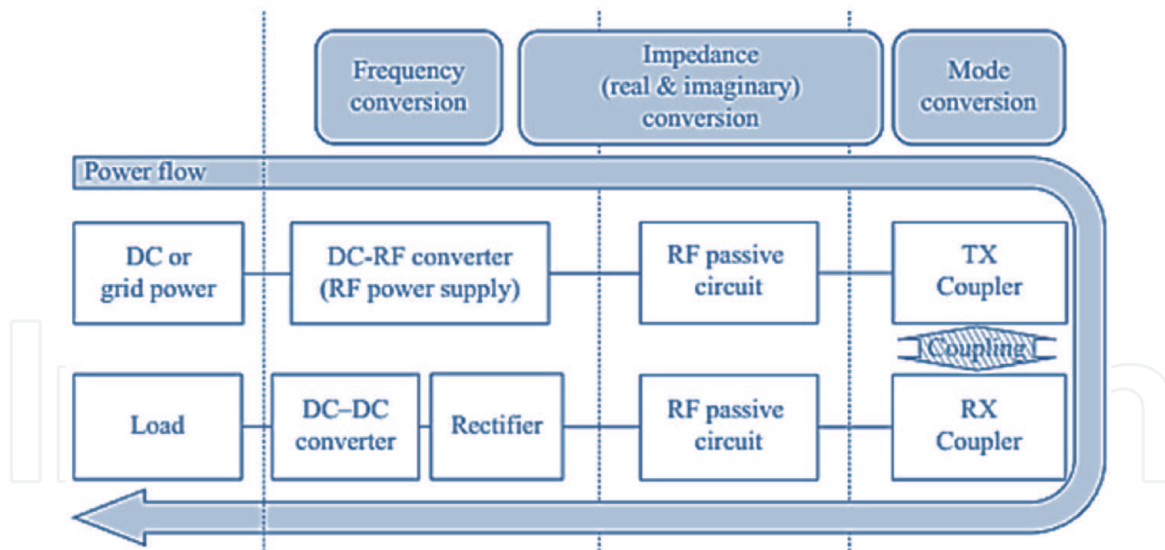*Block diagram of WPT system.*

Figure 6.
Power flow in WPT system.

mechanism. **Figure 5** shows the general Block diagram of wireless power transfer system [13].

## 3. Power flow in WPT system

The block diagram of the Power flow in WPT system becomes as shown in **Figure 6**. RF inverter converts the frequency of the power. Typically, RF inverter also converts the voltage of the power. Considering that the power is P = VI and the impedance is Z = V/I, the RF inverter also converts the impedance of the power. The rectifier in Rx side also changes the frequency of the power.

## 4. WPT-systems for charging EVs

Figure 7 depicts the base components of a WPT system for EV charging. It consists of two prime sub-systems, one of which is existing underneath the road surface and the second is found into the vehicle underbody [14]. The first subsystem includes the source of energy, rectifier and high frequency inverter, primary compensation network and the primary/transmitter coil (Tx). The built subsystem in EVs, has the secondary/receiving coil (Rx) and secondary compensation network composes a resonance circuit that supplies into a high frequency rectifier, filter and the battery. The sub-systems are separated by an air gap. The distance between the two systems depends on the type of vehicle, ground clearance and road conditions such as pavement thickness. Usually the air gap is smaller than 0.4 m. Additionally, both sub-systems share information via a communication link.
The system given in **Figure 7** includes:

- Distribution network in the road has low-frequency AC power for various loads [15, 16].

- Rectifier and power factor correction (PFC).
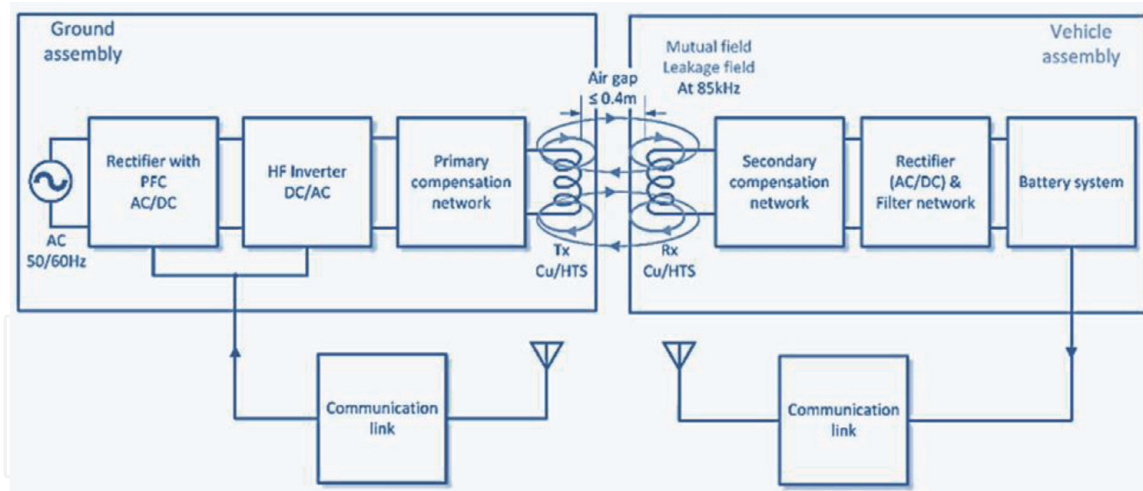
(a)
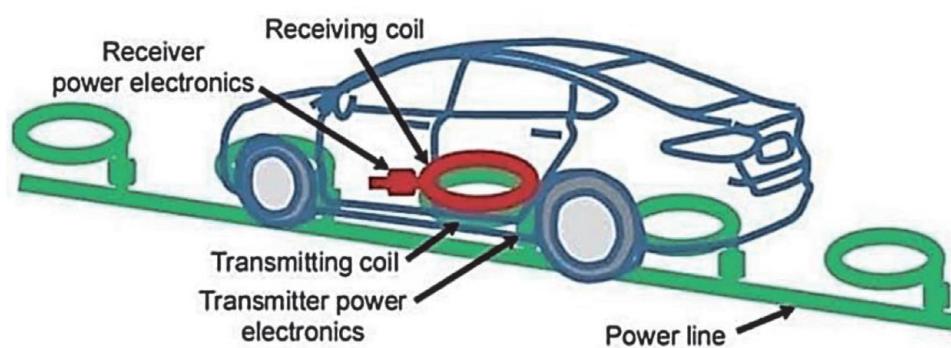
(b)

Figure 7.
(a) The base components of a WPT system for (b) EV charging system.

- High-frequency inverter converts the DC power to high frequency AC in the primary side. On the secondary side, the high-frequency AC energy is rectified to DC power and filtered to create a ripple free current that can charge the battery of EVs. The resonant frequency of the compensation topologies and coils determine the required switching frequency of the inverters. Usually used resonance frequencies for WPT EV-chargers are within a range of 20–100 kHz [17].

- Compensation networks are located between the high-frequency inverter and the primary coil in the ground assembly (GA), while between the secondary coil and the rectifier in the vehicle assembly (VA). **Table 2** summaries these networks and their efficiency. Power transfer efficiency with mutual inductance relationships for the basic compensation topologies SS, SP, PS, and PP are given in **Figure 8**. An optimal selection operation of the compensation topology based on the economics of the system is proposed in [18]. It concludes that SS and SP-compensation networks are the most appropriate topologies for high-power WPT systems. In addition, SS compensation needs less copper than the other compensation networks.

- Communication links. Evenly important to the power transfer system is the communication link between GA and VA. This also contains the communication to the GA grid connection to manage demand upon grid status.

Topology	Circuit	Power transfer efficiency at resonance $\eta = P_{out}/P_{in}$
SS		$\dfrac{R_L}{R_2+R_L+R_1\left(\frac{R_2+R_L}{\omega M}\right)^2}$
SP		$\dfrac{R_L}{R_2+R_L+\frac{R_2R_L^2}{(\omega L_2)^2}+\frac{R_1R_2^2}{(\omega M)^2}+\frac{R_1\left(L_2\omega^2+\frac{R_LR_2}{\omega^2L_2}\right)^2}{(\omega M)^2}}$
PS		$\dfrac{R_L}{R_2+R_L+R_1\left(\frac{R_2+R_L}{\omega M}\right)^2}$
PP		$\dfrac{R_L}{R_2+R_L+\frac{R_2R_L^2}{(\omega L_2)^2}+\frac{R_1R_2^2}{(\omega M)^2}+\frac{R_1\left(L_2\omega^2+\frac{R_LR_2}{\omega^2L_2}\right)^2}{(\omega M)^2}}$

$\omega = \sqrt{\frac{1}{L_1C_1}} = \sqrt{\frac{1}{L_2C_2}} = \sqrt{\frac{1}{LC}}$ M: mutual inductance, ω: resonance frequancy

Table 2.
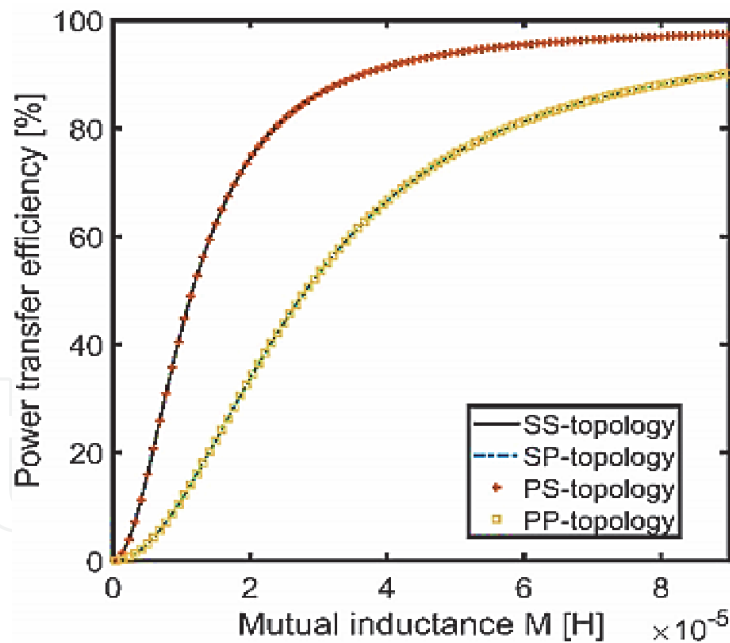*SS, SP, PS, PP compensation topologies.*

Figure 8.
Power transfer efficiency characteristics under varying mutual inductance [26].

- The core components of the WPT system are two coupled coils that allow power transfer via magnetic field [19]. Electric current flows through the primary coil and produces a time-varying magnetic field around it. In the nearness of the primary coil, the secondary coil intercepts the magnetic field, which induces a voltage. The value of induced voltage depends on the air gap length between these coils, the number of turns and the value of dφ/dt; φ is the magnetic flux.
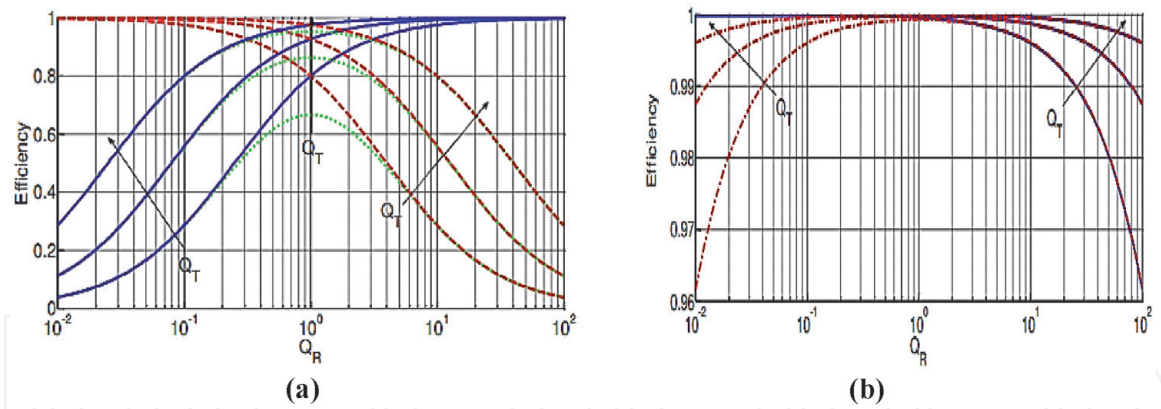
Figure 9.
Efficiency of resonant WPTSs with SS, SP, PS and PP topology [12].
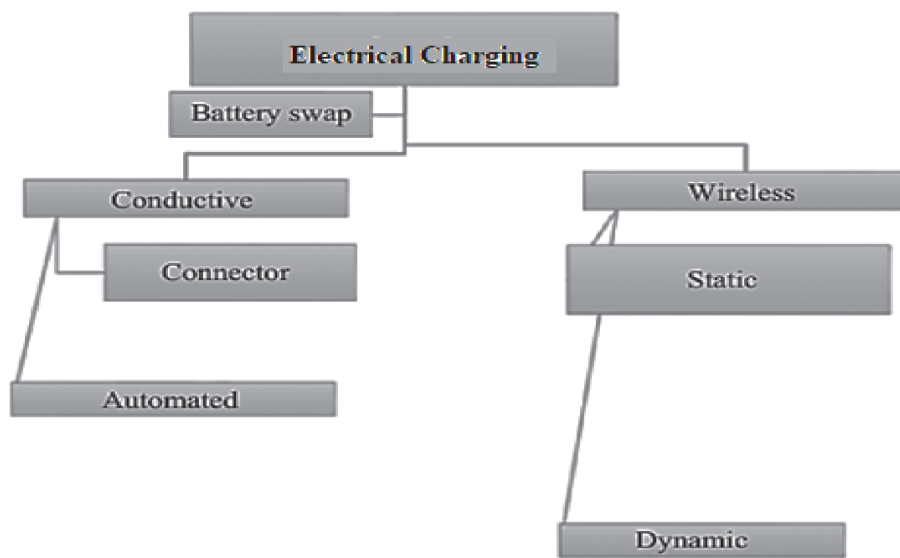

Figure 10.
Classification of charging method for EVs.

Moreover, different types of coil design are used in WPT, such that Circular, Flux pipe/flat solenoid, Bipolar, Tripolar, Zigzag, DD and DDQ [20–26].

Efficiency of resonant WPT with SS and SP topology, and of an inductive WPT vs. Q_R for different values of Q_T is reported in **Figure 9a**, while the efficiency of resonant WPTS with PS and PP topology is given in **Figure 9b**.

$$Q_{T,R} = \frac{\omega L_{1,2}}{R_{1,2}}$$

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

$Q_{T,R}$: Transmitting and the receiving quality factor, respectively. k: Coupling coefficient. L1 and L2 are the s self-inductances of the transmitting and the receiving coils, M is their mutual inductance, and R1 and R2 are the coil resistances.

To charge or transfer energy into the vehicle electric storage device, many electrical charging methods are established and standardized. This methods are given if **Figure 10**.

Furthermore, there are many other many electrical charging methods uses different converters among different renewable sources [27, 28].

5. Major IEC/ISO standards for WPT for EV

1. **SAE J2954**: Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology.

2. **SAE J2894/1**: Power Quality Requirements for Plug-In Electric Vehicle Chargers.

3. **SAE J2847/6**: Communication between Wireless Charged Vehicles and Wireless EV Chargers.

4. **SAE J2931/6**: Signaling Communication for Wirelessly Charged Electric Vehicles.

5. **ICNIRP 2010**: ICNIRP Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz − 100 kHz).

6. **ISO 14117:2012:** Active implantable medical devices – Electromagnetic compatibility – EMC test protocols for implantable cardiac pacemakers, implantable cardioverter defibrillators and cardiac resynchronization devices.

7. **ISO/PAS 19363:2017**: Electrically propelled road vehicles – Magnetic field wireless power transfer – Safety and interoperability requirements.

8. **ISO 15118:** Road vehicles – Vehicle to grid communication interface.

9. **IEC61980–1:** Electric vehicle wireless power transfer (WPT) systems – Part 1: General requirements.

6. Conclusion

In this chapter, several WPT technologies are presented and explained the importance of WPT. In recent years, WPT technology gains enormous attention due to its advantages. WPT systems are classified as microwave, evanescent wave, magnetic resonance, electrical resonance, or electromagnetic induction methods. Moreover, the prospective EV wireless charging applications are also highlighted, and different coupling techniques are discussed in this chapter. Inductive coupling, magnetic resonance coupling, and microwave are the main EV wireless charging techniques. The chapter also provided detailed information on the manufacturing and configuring the magnetic resonance coupling based wireless charging system. This chapter deals with the basic overview of the present and future scenarios of EVs. After discussing the scenarios, various concerns regarding battery types and charging methodologies are discussed as well.

Wireless Power Charging in Electrical Vehicles
DOI: http://dx.doi.org/10.5772/intechopen.96115

Author details

Nassim Iqteit[1*], Khalid Yahya[2] and Sajjad Ahmad Khan[3]

1 Department of Electrical Engineering, Palestine Polytechnic University, Palestine

2 Department of Mechatronic Engineering, Istanbul Gelisim University, Turkey

3 Department of Electronics and Communication Engineering, Istanbul Technical University (ITU), Turkey

*Address all correspondence to: nassim_eng83@ppu.edu

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