Wireless Power Transfer in Electric Vehicles

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Abstract

A detailed accumulation of the methods of wireless power transfer (WPT) including short range as well as mid range transmission. The technology and the science behind WPT and the future scope is discussed in detail. While a lot of research has been done on this topic in the previous decade, a large part of it is yet to be explored. The topics further discussed are the Roadway Powered Electric Vehicles (RPEVs) and the Online Electric Vehicles (OLEVs). These vehicles can revolutionise the transport system. But they require high initial investment. Further discussion on the Solar Power Satellite (SPS) which aims at transmitting the solar energy and using it for wireless power transmission is done. The attempts to commercialise the vehicles that use WPTs are going on with full force and we also discuss the advantages and the disadvantages for the same.

Keywords: Inductive Power transfer (IPT), Wireless Power transmission (WPT), Online Electric Vehicle (OLEVs), Roadway Powered electric vehicle (RPEVs), Solar Power satellite (SPS)

1. INTRODUCTION

Due to limited availability of resources it has become essential to develop alternative methods to generate energy. Wireless Power Transmission (WPT) is thus an approach to noiseless, cost efficient and convenient charging. It is estimated that losses incurred due to wires is about 20-30%. [1] Hence WPT attempts to minimize these losses along with reduction in pollution levels caused due to resources used presently.

Wireless Power Transmission can be used to charge electronic portable devices. The Solar Power Satellites (SPS), which are expected to operate in 2025-2030, are
manufactured on the concept of capturing solar energy in space for utilization on Earth. The SPS designs are largely based on WPT.[1] However, the current major application is the charging of electric cars, fuel-less rockets, fuel-less planes, etc.

The basic working principle of inductive WPT Charging is that there are two parts of the inductor. One part of the inductor acts as a primary winding and the other half acts as a secondary winding of the transformer. The role of the charger is to convert the low frequency AC power to high frequency AC power. The high frequency AC is transmitted from the charger to the secondary side and then is converted to DC power and is supplied to the battery pack.[2]

\[ \text{Fig. 1 Schematic of a transformer where } Z_0 \text{ is the characteristic impedance and } V_1 \text{ and } V_2 \text{ are the voltages as shown [3]} \]

Various companies and groups which manufacture electric vehicles with wireless charging systems are:

- Tier 1 automotive suppliers including Delphi, Magna, Maxwell and Panasonic;
- Auto OEMs, including, GM, Audi, BMW, Chrysler, Daimler, Ford, Mitsubishi, Honda and Toyota.
- Present day active WPT suppliers include: WiTricity, Evatran, Conductix-Wampfler, LG and many more. [2]

The most famous wireless technology is the Tesla tower made by Nikola Tesla where he attempted wireless electricity transmission. He failed due to the phenomenon of diffusion in all directions. A similar spectacle is going to be tested by Japanese scientists at the Tokyo Tower. [1]

Early experiments in the field of WPT include the suspension of the light bulb in space at a distance of 2m from the transmitting coil. With advances in the field, a tram in the Seoul city tour is being run with the help of transmitting coils and wireless charging. [4]
Electric power for vehicles can be drawn by resonant coupling. The power of resonance can be explained by drawing a parallel with that of an opera singer. When the singer’s frequency matches with that of the natural frequency of the glass, the glass shatters into pieces due to the amplified vibration. A phenomenon similar to this is used for WPT called as magnetic resonance coupling.[4]

2. BASIC PRINCIPLES FOR WIRELESS POWER TRANSMISSION

There has been a widespread research on wireless power transmission in the previous decade. It can be categorised into radiative and non-radiative on the basis of energy transfer mechanisms. Radiative power is transmitted through an antenna in the form of an electromagnetic wave. But since electromagnetic waves travel in all direction,
the energy efficiency is low.[5,6] Non-radiative power is based on the magnetic coupling of the conducting loops. Non-radiative power transmission can be further divided into short range and mid range where the mid range WPT means transmission distance is greater than the resonating coil’s dimensions.

The three basic aspects of WPT are:

1. Inductive coupling between working and driving circuits.
2. Tuning in of circuits, that is “oscillation transformer”.

![Fig. 4: Magnetically coupled WPT system.][7]

The Tx coil gets excited due to the magnetic oscillating field produced by the RF amplifier which gives power to the drive loop. The Tx coil is a multiturn spiral coil next to the single turn drive loop. This system acts as a step up transformer. On the receiving side the similar arrangement now acts as a step down transformer due to the single turn load loop connected to the device. The Tx coil and the Rx coil share mutual inductance which is a function of the distance between them and their geometry. Power can be transmitted through large air gaps when the transmitting and the receiving coil is in resonance and have the same resonant frequency. The further approach and description through which transmissions can take place are:

2.1 Coupling theory:
This technology is based on the working principle of mutual inductance via a two part transformer such that change in current flow through one winding induces a voltage across the ends of the other winding through electromagnetic induction, as shown in Fig. 5. The inductive coupling between two conductors.

2.1.1 Winding Structures:
The shape size and location of the magnetic core becomes important due to absence of metal-metal contact and hence windings play an important role in an efficient power
transfer. Recent development in magnetic circuits for coupling on-vehicle pads to ground based pads at higher efficiency have improved significantly. New polarized pads have been developed and exhibit superior performance when compared to earlier pads developed.

2.2 Inductive WPT:
Inductive power transfer (IPT) has been used successfully in several EV systems such as the GM EV1. The magne aka the primary is the charging paddle and the secondary are embedded in epoxy. The charging paddle is inserted in the centre of the secondary coil which begins the charging of the EV1 without any contacts or connectors at either 6.6 kW or at 50 kW. This system is connector-less but is not wireless.

![Fig. 5: Inductive interface (paddle) equivalent circuit.][2]

The equivalent circuit parameters at the charge coupling interface for an IPT charger are shown in Fig 6.

![Fig. 6: schematic of a series resonant converter circuit constructed around the coupling capacitor][2,8]

An universal IPT system using 10 kVA coaxial winding transformer for a 6.6 kW, 77 kHz, 200/400 V EV charger is presented in Fig 6 [8]. By utilizing a coaxial winding transformer benefits the ability to relocate all transformer core material off-board, and minimizes the sensitivity of on-board EV components to flux density and frequency. By using this method, transformer makes it feasible to implement a single loop, which can operate over wide frequency range and the ability to scale up to meet different power requirements. The design of the core of the transformer concerns over the impact of non-linear flux distribution which results in losses like eddy current losses...
and electromagnetic interferences. The losses mentioned above are dependent on the core size, increasing when the transformer is scaled up.

2.3 Capacitive WPT:
Recent technological venture of capacitive wireless power transfer has been proposed as an alternate contactless power transfer solution. The structure is same to the fig(5), with the CPT interface between a pair of coupling capacitors. Other parts such as the inverter and rectifier structures remains same. Since magnetics do not scale down as desired with decreasing power, at some power level. The cost and size of the galvanic isolation components can be minimized with a capacitive interface.[8] However, this solution is not preferred in High Power applications. And because of this most of the existing CPT solutions are applied in low power applications and portable electronic devices such as wireless tooth brush chargers, or wireless cellular phone chargers where the power transfer interface is implemented with capacitive coupled matrix pads.

2.4 Low frequency permanent magnet coupling power transfer (PMPT):
Low frequency PMPT is a combination of elements such as magnetic gears and synchronous permanent magnet electric machines. It consists of two main physical components and they are shown in the figure:

![Fig. 7: Use of a rotating magnet to enhance inductive power transfer between two coils][2]

2.4.1 PMPT transmitter:
A cylindrical, permanently magnetized rotor is either driven by an external, self-contained motor or directly by means of static windings that are positioned around the circumference of the rotor itself, separated by an air-gap and located either outside of the rotor, or inside if the rotor is hollow.
2.4.2 PMPT Receiver:

A similar rotor on the vehicle is positioned within 150 mm and parallel to the utility-side installation during charging. Owing to the coupling of the magnetic fields of the two rotors, the vehicle rotor will tend to rotate at the same speed as the utility-side rotor. This is the magnetic gear effect. [8]

2.5 Comparison between different WPT technologies:

A comparison of the WPT technologies discussed and is presented in Table 1. IPC (Inductive Power Coupling) is a mature and proven technology. Its only drawback is that it is only a contactless solution, and not a wireless solution.

Table 1. Comparison of Wireless Charger Technologies[2,8]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Performance</th>
<th>Cost</th>
<th>Size/volume</th>
<th>Complexity of system</th>
<th>Suggested power level</th>
</tr>
</thead>
<tbody>
<tr>
<td>inductive power transfer (IPT)</td>
<td>medium</td>
<td>Medium</td>
<td>medium</td>
<td>medium</td>
<td>medium/ high</td>
</tr>
<tr>
<td>capacitive power transfer (CPT)</td>
<td>low</td>
<td>Low</td>
<td>Low</td>
<td>medium</td>
<td>low</td>
</tr>
<tr>
<td>permanent magnet coupling power transfer (PMPT)</td>
<td>low</td>
<td>High</td>
<td>High</td>
<td>high</td>
<td>medium/ low</td>
</tr>
<tr>
<td>resonant inductive power transfer (RIPT)</td>
<td>medium</td>
<td>Medium</td>
<td>medium</td>
<td>medium</td>
<td>medium/ low</td>
</tr>
<tr>
<td>on-line inductive power transfer (OLPT)</td>
<td>medium</td>
<td>High</td>
<td>Medium</td>
<td>medium</td>
<td>high</td>
</tr>
<tr>
<td>resonant antennae power transfer (RAPT)</td>
<td>medium</td>
<td>Medium</td>
<td>medium</td>
<td>medium</td>
<td>medium/ low</td>
</tr>
</tbody>
</table>
Further, WPT technologies are differentiated on the basis of strengths and weaknesses along with a few examples.

### Table 2: Comparison of strengths and weaknesses along with examples[2,9]

<table>
<thead>
<tr>
<th>WPT technologies</th>
<th>Strengths</th>
<th>Weaknesses</th>
<th>Example applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductive Coupling</td>
<td>Simple, high power transfer efficiency in centimeter range</td>
<td>Short charging distance, requiring accurate alignment in charging direction</td>
<td>Electric toothbrush, charging pad for cell phones and laptops</td>
</tr>
<tr>
<td>EM radiation Omnidirectional</td>
<td>Tiny receiver size</td>
<td>Rapid drop of power transfer efficiency over distance, ultra-low-power reception</td>
<td>Charging a WSN for environmental monitoring (temperature, moisture, light, etc.)</td>
</tr>
<tr>
<td>Unidirectional (microwave/laser)</td>
<td>Effective power transmission over long distance (kilometer range)</td>
<td>Requiring LOS and complicated tracking mechanisms, inherently large scale of devices</td>
<td>SHARP unmanned plane</td>
</tr>
<tr>
<td>Magnetic resonant coupling</td>
<td>High efficiency over several meters under Omni-direction, not requiring LOS, and insensitive to weather conditions</td>
<td>High efficiency only within several-meter range</td>
<td>Charging mobile devices, electric vehicles, implantable devices and WSNs</td>
</tr>
</tbody>
</table>

#### 2.6.1 Short Range Wireless Power Transmission

In 2005, Eric Lou[10] and his team had developed a wireless charger. They used Yagi antenna for the power transmission. The higher impedance and the gain of the antenna was the criteria for choosing it. But increase in the gain of an antenna also increases the cost and the size. [10]

In the recent years, further advancement in the technology has come up. Retrodirective arrays are of great interest these days since they are cost effective. Retrodirective arrays transmit the signal back to the interrogator’s position without any a priori knowledge of the incident angle.[11,12]

An electronic device is incident onto the array and a Van Atta array is used to amplify the radiation which falls onto it. This transmitted radiation signal received by the array which then sends a directed wireless power transmission beam in the direction of the electronic device. Many devices can be charged at the same time.[11]
2.6.2 MID Range Wireless Power Transmission

Attempts to transfer power to distances several times greater than the size of the resonators have been made.[13] This is mid range transmission. The mathematical model for mid range WPT can be designed using electric circuit theory. On assuming \( n \) number of magnetically coupled resonators.

\[
\begin{bmatrix}
R + j(\omega L - \frac{1}{\omega C}) & j\omega M_{12} & j\omega M_{13} & \cdots & j\omega M_{1n} \\
j\omega M_{12} & R + j(\omega L - \frac{1}{\omega C}) & j\omega M_{23} & \cdots & j\omega M_{2n} \\
j\omega M_{13} & j\omega M_{23} & R + j(\omega L - \frac{1}{\omega C}) & \cdots & j\omega M_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
j\omega M_{1n} & j\omega M_{2n} & j\omega M_{3n} & \cdots & R + j(\omega L - \frac{1}{\omega C})
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2 \\
\vdots \\
I_n
\end{bmatrix} =
\begin{bmatrix}
F \\
0 \\
\vdots \\
0
\end{bmatrix}
\]

(1)

where:

\( M_{ij} = k \sqrt{L_i L_j} \) (\( i, j = 1, 2, \ldots, n, i \neq j \)) is the mutual inductance between winding \( i \) and winding \( j \);

\( R_L \) is the load resistance which is connected to winding \( i \);

\( I_i \): Current in winding \( i \);

\( L_i \): Self-inductance of winding \( i \);

\( C_i \): Compensating capacitance of winding \( i \);

\( R_i \): Resistance of resonator \( i \) (including the resistance of winding \( i \) and the equivalent series resistance of the capacitor \( C_i \))

\( \omega \): Angular frequency
2.7.1 Roadway /online power transfer:

Online Power Transfer system has a similar concept to that of roadway power transfer. However, in the latter case a lower resonant frequency is used and in the OPT applications at high power levels can be done. In this case the primary coil is spread out over an area on the roadway and within this area the power transfer takes place.

Typically, the combination of the input side of the resonant converter and the distributed primary windings collectively is known as the track and the secondary coil is known as the pickup coil, which is in the vehicle. The system is supplied by a three phase AC system, or high voltage DC system.

The Online Electric Vehicle (OLEV) developed by the Korea Advanced Institute of Science and Technology (KAIST) is an innovative transportation system. In 2010, it ranked amongst the top 50 innovations in the TIME magazine. The KAIST OLEV uses the conversion of 60Hz frequency to 200kHz using an inverter which makes 200A of current flow through it with up to 80% efficiency transmitted wirelessly. When a vehicle is operating on a road with power transmitters installed in it, the power transmitter collects electricity from underneath the ground and distributes it either to the motor or the battery depending on the requirement as shown in the figure 4. If there are no power transmitters then the OLEV runs on the battery. Hence this technology enables the OLEV to be mobile during charging.[14]

If the short range of the EVs and the associated cost of infrastructure is considered, the feasibility of these charging system might be unfavorable. However, one benefit is that due to frequent and convenient charging, vehicles can be manufactured with a minimal battery capacity (about 20% compared to that of the conventional battery-powered EVs), which can consequently minimize the weight and the price of the vehicle. A charger with narrow rail width, 10 cm, and large air-gap, up to 20 cm, was proposed. An efficiency of 74% was reported at 27 kW output power for a three-phase supply input of 440 V, and 20 kHz switching frequency.

![Diagram](image)

**Fig. 9:** (a) WPT without transmitters (b) WPT with transmitters[14]
In comparison to pure battery EV and battery replace EV, Hybrid EV, Plug-in hybrid EV and Roadway power EVs do not require innovations in battery for commercialization; as in these EVs can be readily available in markets using currently affordable EV batteries. When the power supply rails for transmitting power to RPEV are fully deployed under the road, RPEVs need not require battery energy storage for their traction because they directly get required power from the road while they are moving on it.

Hence, RPEVs are most free from the battery-related problems among EVs and quite promising for future transportation of small cars, passenger cars, taxies, buses, trams, trucks, trailers, and trains, even in competition with internal Combustion engines.

Despite the fact that RPEVs are free from battery problems, RPEVs are not being widely used. The drawback of this technological solution is the high power transfer from the road efficiently, within the bounds of economic status and safely. The power transfer is either wired or wireless. Earlier, the former method was preferred because of no advancement in wireless power transfer. The highest speed train is powered through pantographs, which are a sort of wired power transfer device. Because of the wearing of pantographs and due to the maintenance problems, wired power transfer is gradually replaced with wireless one as hundreds of kilowatts of power become available. Thus, various wireless power transfer systems (WPTSs) have been widely developed for RPEVs.

Important technical issues in the developments of inductive power transfer systems (IPTSs), the majority of WPTSs, are addressed, and major milestones of the developments of RPEVs are summarized, focusing on the developments of on-line electric vehicles (OLEVs) that have been recently commercialized.

2.7.2 Fundamentals of WPTS for RPEV:

**Overall Configuration of the WPTS:** The requirement for WPTS in RPEVs is that a high power should be efficiently delivered via a moderate air gap to avoid collisions
between the RPEVs and the road. The WPTS are composed of two subsystems:

1) Roadway subsystem for providing power, which includes a rectifier, high-frequency (HF) inverter, primary capacitor bank, and power supply rail.

2) On-board subsystem for receiving power, which includes a pick-up coil, secondary capacitor bank, rectifier, and regulator for battery, as shown in the fig(9) [15]

![Diagram of WPT technology](image)

**Fig. 11: Roadway powered electric vehicle.**[15]

The roadway subsystem should be so robust and cheap that it may withstand severe road environments for a long time and should be economic to install over a long distance, whereas the on-board subsystem should be compact in size and light in weight so that it may be adopted into the RPEV.[15]

3. ADVANCEMENT IN WPT TECHNOLOGY:

The first ever demo of WPT was given by Kurs *et al* in 2007, since then there have been lots of developments in magnetic resonant coupling to make use in commercial applications. In 2008, Fig(10B), Intel modified the magnetic resonant coupling using flat coils which were easier to fit in a mobile device rather than the helix coils.[9]

Kurs *et al*[8] started up a company known as Witricity Corp. and the TED Global 2009 conference, together they demonstrated WPT for portable devices such as cell phones. Afterwards, Kurs *et al* developed an enhanced technology by properly tuning coupled resonators which can lead to energy transfer to multiple coils at the same time which was used in home and office applications like laptops, tablets, cell phones simultaneously.[9]

In 2010, home appliances manufacturer Haier exhibited an all wireless HDTV without any power cords and signal cables. Recently several automobile companies like Rolls-
Royce, Audi, Nissan, Toyota and Mitsubishi were working on powering electric or plug-in hybrid vehicles wirelessly.

In 2011, Rolls-Royce manufactured electric version of its Phantom car. The development of WPT technology allows these electric vehicles to be charged while they are parked along the street or in a garage without any power cord. This WPT technology, once fully mature, could help boost the electric car industry.

Wireless electricity is a technology based on the strongly coupled magnetic resonance. At a distance of seven feet from the power source, a 60 Watt bulb was illuminated with a 40% power transfer efficiency with the help of two identical resonating coils.

![Fig. 12: a) Magnetic Resonant Coupling was first demonstrated by Kurs et al.; b) Intel developed wireless power system by using flat coils; c) Witricity demonstrated this power transfer technology for cell phones](image)

The Solar Power Satellite (SPS) is believed to be the future of technology. Hence wireless power transmission is very important for the transmission from the geo stationary orbit to the ground. Power transmission using microwaves have been demonstrated for over 40 years but still requires research. To choose a frequency in the medical and scientific band (ISM) 2.45 GHz was selected earlier but 5.8 GHz is now considered more desirable due to the recent advancement in C-band RF technologies.
Sasaki[19,20] and his team would decide the more desirable medium among the microwaves or the laser and with the selected medium they will conduct a 100kW class experiment in the space before 2020. Depending on the expected power costs, 2 MW and 200 MW would be tested before 2030. This scenario would guarantee the construction of 1 GW class commercial SPS in 2030’s.[19]

4 COMMERCIALLY AVAILABLE SYSTEMS:
So far only a few of the wireless charger systems are available. These systems are only in pre-commercial trials and none of them are in mass production. WiTricity Corp. is active and has collaborative ties with Delphi Electronics, Mitsubishi Motors Corporation, Audi and Toyota Motor Corporation. Plug-less power (manufactured by Evatran) is another active player in collaboration with Nissan and GM to support the Nissan Leaf and Chevy volt products. Mercedes Daimler and Conductix-Wampfler have a wireless charging research project. Finally, Qualcomm Inc. (acquired HaloIPT) has announced a wireless EV charging trial in collaboration with the UK Government, and Transport for London.[8]

5. CHALLENGES:
- The most prominent drawback of all WPT systems is the fact that low efficiency energy is transferred. Most of the losses takes place during the energy transfer from coil to coil.
Furthermore, installation cost of WPT charging systems will be more than plug-in charging methods due to many factors, which includes but is not limited to, increased infrastructure, goods and safety/shielding requirements. Hence, WPT might be disadvantageous to EV consumers as it is not cost effective.

WPT technological systems leads to various health hazards due to the exposure to RF radiation. In various countries the regulations is decided beforehand by the organization to limit the exposure of humans to RF frequency. In Canada, these regulations are set by Canadian Safety Code 6. In the United States, the rules are regulated by the IEEE C95.1 standard whereas in Europe the organization using WPT technology have to follow the standard regulations set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). In Australia, the same is being done by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) on RF exposure.

The International Committee on Non-Ionizing Radiation Protection (ICNIRP) limits the exposure to magnetic field. ICNIRP also regulates the exposure of time dependent EM fields on humans. According to ICNRP regulations, the limit on exposure of average flux densities to human body should not exceed 6.25 μT in the frequency range of 0.8–150 kHz.

6. CONCLUSION

In this article we reviewed the different technological solutions for WPT, their limitations and different applications. It also includes the advances made in the field such as RPEV, OLEV and SPS. RPEV and OLEV are still used at a lower scale and SPS will be fully functional by 2040. There has been a lot of research on short range power transmission but research is still going on to limit the losses in mid range power transmission. Hence, WPT will lead the world to an advanced, greener and a sustainable future.

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