Review on the Wireless Power Transfer for the Application of Electric Vehicle

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Abstract. Wireless power transfer (WPT) technique will become a hot development trend of the energy supply system for electric vehicles (EV). Compared with plug-in hybrid electrical charging systems, WPT has superior characteristics in small size battery, lightweight, short charging time (charging-in-motion services), and long driving range, etc. This paper mainly introduces the basic frame and the classification of the WPT system and then reviews the basic principles of popular WPT technique, named electromagnetic resonant coupling transfer (ERCT) brief. The basic components of the ERCT, coil, compensation topology, power electronics converters and control methods are given a brief introduction. The real-world applications are shown through examples that the WPT system is feasible, but also meet unsolved problems or difficulties. At last, some superficial improved is presented.

Keywords: Wireless power transfer, electric vehicles, electromagnetic resonant coupling transfer, real-world applications.

1. Introduction
At present, the increasing pollution problems of the environment have perplexed the pace of human progress and has become the most severe and urgent problem of the global. The statistical data shows that exceed 25% ratio of environmental pollutants caused by conventional transportations heavily relies on internal combustion engines. Conventional vehicles are the primary emissions of greenhouse gases, such as CO₂, etc. To reduce the use of fossil fuels in vehicles, developing electric vehicle (EV) technology has been an increasing demand. However, the EV based on the Plug-in charging pattern has not yet been accepted by the consumer widely. At present, due to the limitations in current battery technology, the power density of current batteries is low. That means the weight of the onboard batteries which are necessary to supply sufficient power is heavy and the cost of the batteries is expensive. At the same time, the charging period is long because the grid connection has to be limited charging current to increase battery life and efficiency [1]. Moreover, the recharge is inconvenient because of a designated location is needed for recharge. Compared to traditional plug-in charging systems, a wireless charging system based on wireless power transfer (WPT) technique has shown superior performance and more benefits for better electric vehicle charging, such as small size, lightweight, short charging time(charging-in-motion services), and long driving range. So WPT has been attracted more and more
attention, not just in academic discussion, but also in industrial research to obtain an environmentally friendly future transportation system.

The rest of the paper is listed as follows: section 2 reviews the classification of WPT. Section 3 presents the basic principles of electromagnetic resonant coupling transfer briefly. Section 4 shows the real-world applications through examples that the WPT system is feasible. Section 5 shows the unsolved problems or difficulties. Some superficial improved propose is presented. Finally, the conclusion is given.

2. Review the classification of WPT

The WPT technologies transfer energy from the electricity grid to onboard battery chargers by using the electromagnetic field, or Electric field, or Mechanical force. The typical classification of WPT is based on its physical mechanisms [2].

### Table 1. WPT Classification of Different Energy-carrying medium

| Energy-carrying medium | Technology               | Power | Range | Efficiency | Comments                                      |
|------------------------|--------------------------|-------|-------|------------|-----------------------------------------------|
| Mechanical force        | Mechanical force         | High  | Medium| High       | Capable of EV charging                        |
| Electric field          | Capacitive power transfer| Low   | Low   | High       | Both power and range are too small for EV charging. |
| Near field              | Traditional Inductive power transfer | High  | Low   | High       | The range is too small for EV charging        |
| Far field               | Laser, Microwave         | High  | High  | High       | Need a direct line-of-sight transmission path, large antennas, and complex tracking mechanisms. |
| Radio wave              | High                     | High  | High  | Low        | Efficiency is too low for EV charging.        |

In table 1, the application of the electromagnetic field is suitable for EV charge. Based on the basic principle, the general Electromagnetic fields of WPT technologies are catalogued as following [2-5]: (1) electromagnetic radiation, such as microwave, laser or radio wave, WPT that is long-wave transmission and applicable for long-distance power transmissions, such as transmission between solar power satellites and the earth. Its primary frequency range focuses on 300Mhz ~ 300Ghz. The technologies of Laser, Microwave are presented in Table 1, are not suited for EV charge. And the efficiency of Radiowaves is too low for EV charging. (2) Electric induction WPT, it is known as capacitive coupling WPT that is for near field transmission [1]. Both the power and range of this technology are too small for EV charging. (3)Magnetic coupling WPT (inductive or resonant) for near field transmission does much less harm to the human body than electric induction/coupling. Electromagnetic resonant coupling transfer (ERCM) or coupled magnetic resonance technology which based on a coupled-mode theory proposed in [6]. This theory of coupled-mode can reduce power loss, provides a large air gap and no relevant location requirements. Due to its superior features, the efficiency of the device developed in [6]
is approximately 90% within 1 m. WPT can be also classified as stationary WPT charge or dynamic WPT Charge. It relies on the vehicle charge period whether the vehicle is in motion or not. Regardless of stationary WPT or dynamic WPT, WPT technology of ERCM for EV is competent.

3. Basic Principles of Electromagnetic resonant coupling transfer

Relevant literatures [1-4, 7-9] show the State-of-the-art research and technology development of WPT. Literature [3, 4] gives the overall frame of non-ionizing radiative wireless charging systems for EVs through near-field magnetic coupling. Its topology and control method is given in literatures [3, 9]. The connect grid contains the alternating current (AC) Input, the electromagnetic interface (EMI), rectifier, boost(AC/DC), buck(DC/DC), inverter (DC/AC) stage and primary compensation network. The vehicle side contains air gap, secondary compensation, rectifier AC/DC, filter network and battery pack. Each component consisted of the WPT system is mature technologies, except the compensation network. Many researches about long-wave are devoted to obtaining the better efficiency and mainly focused on three areas [3, 9]: (1) The detached transmitting and receiving coils, (2) compensation topologies, and (3) power electronics converters and control methods.

3.1. Coils

In literature [8], it shows the single-sided polarized coils and the double-sided coils designed by the Auckland team. In literature [3] shows the Coil design for stationary charging systems and dynamic charging systems for EV. A single-coil design for the primary coil has some drawbacks. A new cross-segmented two pairs of power cables were proposed by controlling the current direction in the power cables. They were able to power the rails on and off selectively [3]. Cao et al. [4] present some methods to deal with the raise the coupling coefficient of the transformer.

3.2. Compensation topologies

In compensation topologies, four basic compensation topologies, named SS (series - series), SP (series - parallel), PS (parallel - series), and PP (parallel- parallel) are given in Figure 1 [3, 4, 7, 9, 10, 11, 14]. The primary compensation capacitance is given in Table 2.

![Figure 1](image_url)

**Figure 1.** Four basic compensation topologies. (a) SS. (b) SP. (c) PS. (d) PP.

**Table 2.** Primary compensation capacitance is

| Topology | SS | SP | PS | PP |
|----------|----|----|----|----|
| Primary capacitance $C_1$ | $\frac{C_2L_2}{L_1}$ | $\frac{C_2L_2}{L_1} - \frac{1}{1 - k^2}$ | $\frac{C_2L_2}{L_1} - \frac{1}{Q_s^2k^2 + 1}$ | $\frac{C_2L_2}{L_1} - \frac{1 - k^2}{Q_s^2k^2 + 1 - k^{2Q_s^2}}$ |

where $Q_s$ represents the quality factor, $k$ is the coupling coefficient.

In literature [12], Qin et al. employ the Pspice tool to simulate the SS mode to describe the resonant pattern in circuit mode. Ching et al. [7] give the oriented application of topology choice. A double-sided
LCL and LLC topology is analyzed in the literature [9]. These two topologies can achieve a significant efficiency improvement compared with the traditional LC parallel topology (PP). Meanwhile, LCC compensation topology is also proposed in literature [9] to obtain higher efficiency.

3.3. Power electronics converters and control methods

Power electronics converters and control methods are also key technical topics. The power electronics converters refer to indirect two-stage power conversion. Input 60 Hz utility AC power and rectify multi-inverter, and finally out the DC to charge batteries of EV. These complex processes refer to the low frequency to high frequency, AC to DC and DC to AC, etc. Literature [3] gives a detailed description of this field. Cao et al. [4] presents the typical control system: frequency converter controller system, constant Frequency System with pulse width modulation (PWM) and PWM + Phase Locked Loop (PLL) control.

4. WPT for the real-world application

Bi et al. [3] listed quite a few real-world applications in public transit buses, passenger cars and other applied fields, such as harbor, airport, rail systems, and theme parks, etc. Bi et al. [3] also make a summary of selected WPT electric bus projects in different zones from 2003 to 2014. In the research, it has been observed that the battery capacity using WPT could be reduced to below 20% of a conventional EV battery. WPT can enable significant downsizing of the onboard EV battery. These projects are in favor of facilitating technology development and establishing standards. Su et al. [8] makes a summary of the main milestones of the developments of the inductive power transfer systems (IPTS) and Roadway powered electric vehicles (RPEV). He gives a detailed description in 1 generation (Car), 2 generation (Bus), 3 generation (SUV), 3+ generation (Bus), 3+ generation (Train) and 4 generation (Bus). Furthermore, the 5 generations are establishing with more power (25kW/pick-up) and smaller rail (4 cm). It will bring much less cost and time to power rail construction.

5. Unsolved problems or difficulties

Now, the WPT system is attracted to more and more researcher’s attention. Bi et al. [3] have evaluated energy and environmental assessments, economic and policy analyses, and health and safety aspect. He presents the driving performance should be continuously improved and energy efficiency should be raised further. Dynamic WPT could be implemented to need a high initial infrastructure cost. Mobility of EV based on the coverage of dynamic WPT system. When EV is driving in remote areas, such as desert, wilderness, etc. How to charge the EV in this area? The EV is only restricted in urban living or municipal road or high way? Budget or financial costs may be a big problem. In the third world countries or developing countries, the financial costs could not be unbearable. Uddin et al. [13] point out that an efficient and valuable WPT system must satisfy the following criteria: high efficiency, large air gap, and high power. However, various analyses are performed in raising efficiency and obtained many fruits. Some integrated the compensated coils into the two-coil system [3] delivered 6.0 kW power with over 95% DC-DC efficiency at an air gap of 150 mm. However, due to its transmit loss, conversion loss, high-frequency circuit loss, the overall WPT system efficiency is still not high. There are still lots of work to do and make the WPT system have real-world application. Novel mathematics model for expression of compensation topology, proper resonant circuit design contained LCC or LCL, or further improved topologies for obtaining better optimum inverter topology, appropriate circuit parameter design, and duty cycle selection could be better raise the efficiency of WPT system. Raising the input AC voltage will reduce the loss of transmit process and enhance sustainable mobility. To make efforts to reduce the size of width of the power rail will cut construction costs of WPT drastically. Some global standards or uniformed criteria should be discussed and established.

6. Conclusion

At present, the count shows that exceed a 25% ratio of environmental pollutants is caused by conventional transportations mainly relies on internal combustion engines. There has been an increasing
demand for developing EV technology. However, the EV based on Plug-in charging pattern with many drawbacks has not yet been accepted by the consumer widely. A novel WPT technology has been developed to overcome the drawbacks of Plug-in charging pattern. This paper first introduces the basic frame and the classification of the WPT system and then reviews the basic principles of electromagnetic resonant coupling transfer brief. The real-world applications are shown through examples that the WPT system is feasible, but also meet unsolved problems or difficulties. At last, some superficial improved propose from my expertise is presented.

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