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Overview of Wireless Power Transfer for Electric Vehicle Charging

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Abstract

This paper presents an overview of current wireless power transfer (WPT) technologies for the application of electric vehicles (EV) wireless charging. The basic principles of each technology are introduced. Followed by classification, the advantages and limitations of each technology for EV charging are discussed. Promising technologies such as coupled magnetic resonance and magnetic gear technologies are systematically reviewed. The latest development, key technical issues, challenges and state-of-art researches are introduced. The research trends are also been given.

Keywords: wireless power transfer, electric vehicle, wireless charging

1 Introduction

The growing EV market stimulates the demand for more convenient and reliable means to recharge the battery. WPT technique requires no physical contact between vehicle and charging device, therefore overcomes the inconvenience and hazards caused by traditional conductive method.

The initial objective is replacing conductive charging method by the novel WPT technology, while maintaining a comparable power level and efficiency. The long-term goal is to dynamically power the moving vehicles on road. This will lead to a much reduced battery pack but extended driving range. Then, the main concerns of EV, namely the high battery price and the range anxiety, will be addressed.

Great effort has been put on WPT technology. Feasibility of its application on wireless EV charging has been proved by institutes through various demonstrations. Leading manufacturers and major global automobile suppliers are seeking opportunities for commercialization. Nissan and Chevrolet have developed wireless charging system in corporation with Evatran for their EV models, the Nissan LEAF and Chevrolet Volt [1]. Meanwhile, Audi, Toyota, and Mitsubishi are integrating magnetic resonance WPT technology into their EV models in collaboration with Delphi, and WiTricity, using the technologies from MIT [2]. In 2011, Qualcomm acquired the former HaloIPT company owned by the University of Auckland and announced the biggest pre-commercial trial of wireless EV charging in Europe [3].

In this paper, current WPT technologies will be reviewed on the perspective of electric vehicle charging. For each technology, basic principle will be explained with summary of its potential and constraints on EV charging. For the two promising techniques, namely coupled magnetic resonance and magnetic gear; key issues, research challenges the latest developments will be noted. Finally, the technology trends will be introduced.

2 Classification of Wireless Power Transfer Technologies

For a better understanding of the power level, efficiency and application constraints of existing technologies, a classification should be carried out according to the physical mechanisms.

For the time-varying electromagnetic field, there are two main types of WPT technologies, the near-field and the far-field. The near-field is non-radiative and can transfer energy over a distance of less than one wavelength. Inductive power transfer (IPT) is a popular near-field technology which is widely used in induction motors. It has also been used in wireless charging electronics, such as electric toothbrushes and cell phones. However, the transferred power decays rapidly as the distance increases ($1/r^3$). Therefore, the efficient operating range is always limited to several centimetres. The near filed RFID system has a longer operating distance because only a small fraction of power is enough for functioning [4]. To obtain an extended operating range as well as sufficiently high efficiency, coupled magnetic resonance is proposed. It also belongs to near-field technology but is enhanced by resonance. Therefore the power transfer range is extended [5]-[7].

In contrast, far-field technologies are able to transfer energy from 2 wavelengths to infinity through propagation of electromagnetic waves. In space application, high directivity antennas and laser beam can transfer power at a high efficiency [8]; however, it demands a direct line-of-sight transmission path and complicated tracking strategies to maintain perfect alignment. While in the omnidirectional application, the power density decreases as well when the distance increases ($1/r^2$). For this reason, it's normally employed in signal broadcasting where the required power is on microwatts level. Moreover, for charging application, the antennas should be large enough to satisfy the safety standards on EM radiation regulation, which makes it unsuitable for vehicle application.

Capacitive WPT technology uses alternating electric field to transfer energy. It has a smaller EMI than traditional electromagnetic-field-based technologies, because the electric flux tends to travel within the conductive plates, while the magnetic flux tends to spread in all directions from the coils to make a closed flux loop. The other advantage includes the ability to transfer energy through metal barrier. The upper and lower surface of the metal barrier can act as conductive plates in an electric field. This effect will divide the original electric field but won't disturb the power transfer. [9]-[11] Despite its advantages, the capacitive WPT technology faces one big practical challenge, namely the small coupling capacitance. Because the permittivity of vacuum or air is quite small ($8.854*10^{-12}$ F/m), normally special and costly dielectric materials, such as BaTiO3 should be used to increase the capacitance [9]. Even though, any existing air gap or displacement of coupling plates will dramatically decrease the capacitance. This makes it impractical for wireless EV charging application where there must be a least 150~200 mm air gap and large displacement tolerance between the transmitting and receiving units.

Magnetic gear technology uses mechanical force as the energy-carrying medium. It was first introduced to replace the conventional contacted

Table.1 Classification and Comparison of Different WPT Technologies for EV Charging

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

gear. Applications are seen in EV motor [12] and wind power generation [13]. It has also been applied in charging low power medical implants such as cardiac pacemaker [14]. Higher power applications for electronics and vehicles have also being studied. In 2009, 2 reported prototypes were able to transfer 1.6kW through 150mm and 60W through 100mm at the efficiency of 81%, as claimed [15].

A short summary is made to give a simple and clear classification and comparison of these WPT technologies, as seen in Table 1. For the EV charging application, only coupled magnetic resonance and magnetic gear are promising and practical in power, transfer range and efficiency aspects. The following sections will mainly focus on these two technologies.

3 Coupled Magnetic Resonance WPT

3.1 Basic Principles

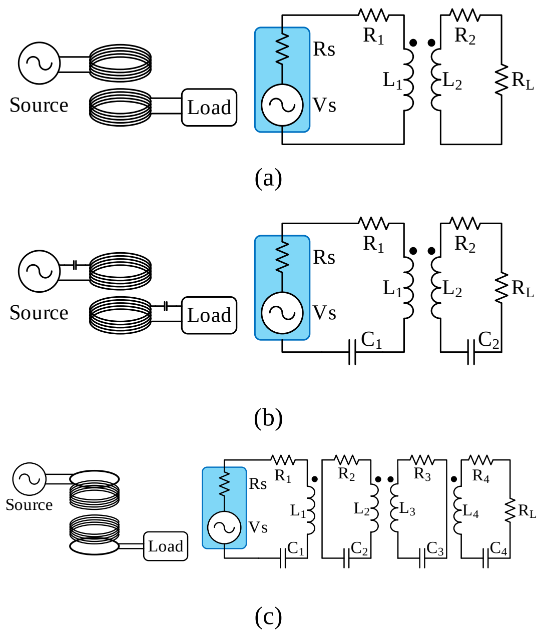

Figure 1: Topologies and equivalent circuit models of near-field wireless power transfer technologies: (a) traditional IPT; (b) coupled magnetic resonance; and (c) strongly coupled magnetic resonance.

Coupled magnetic resonance is a near-field WPT technology but with some differences from traditional IPT, as shown in Fig. 1. Two or more pairs of RLC resonators are used to enhance power transfer efficiency and extend transfer range. As shown in Fig.1. b. the two capacitors connected in series. However, both primary and secondary side compensation capacitors can be connected in series or parallel, which results in four different prototypes. Intensive research has been done on analysing and comparing those prototypes [16], [17]. Generally, the primary side is compensated to lower the reactive power and therefore lower the VA rating of the power supply. The secondary side is compensated so that the load acquires almost of the transferred power, enhancing the power transfer capability. The choice of topology is application oriented. Series compensation on secondary side is suitable for constant voltage application, while parallel topology is capable to support a constant current. The series-compensated primary can reduce the power supply voltage which is very attractive in long track application, while the parallel-compensated primary is capable to support a large supply current.

Especially, by using 2 loops and 2 coils, the internal resistance of voltage source R_S and the load resistance R_L are excluded from the RLC resonators, which results a much higher quality factor of circuit (Q) than conventional 2 coils resonators. This means with the same coupling coefficient, more energy could be transferred to the load. Additionally, to improve the transfer efficiency, the internal resistance of RLC resonators is further reduced by replacing lumped resonant capacitors by coil parasitic capacitance (C_2 and C_3 in Fig.1. c.). Therefore, with a highly reduced resistance, the resonators can transfer energy efficiently even when the coupling coefficient is low.

3.2 Technology of Coupled Magnetic Resonant WPT for EV Charging

3.2.1 Stationary Charging

Auckland University has been researching on inductive power transfer technology since early 1990s. Its IPT® technology actually employs the coupled magnetic resonance as shown in Fig.1 b. Supported by this technique, some early achievements have been made by Conductix-Wampfler, such as the 20kW charging bay for 5 golf buses in New Zealand during 1997 to 2007 and the 60kW wireless charging urban bus fleets in Genoa and Turin, Italy in 2002 and 2003 [18]. The University owned company HaloIPT released a 3kW evaluation kits in 2010, which could achieve 85% overall efficiency through 180mm air gap. It was acquired by Qualcomm in 2011. In the same year, Qualcomm announced a pre-commercial trial in London, using similar kits but aiming to the mass consumer adoption of this technology [19].

Table. 2 Summary of Current Wireless EV Charging Projects.

Institute / corporation	Year of Installation	Location	Project Type	Vehicle Type	Power	Air Gap	Efficiency
Auckland University & Conductix-Wampfler	1997	Auckland	Public Demonstration (Stationary)	5 Golf buses	20kW	50mm	90-91%
	2002-2003	Italy		8-23 mini buses	60kW	30mm	-
Auckland University & Qualcomm Halo	2010	Auckland	Evaluation kits (Stationary)	Private vehicles	3kW	180mm	85%
	2012	UK	Public Demonstration (Stationary/ Dynamic)	-	-	-	-
ORNL	2010	US	Prototype (Dynamic)	-	4.2kW	254mm	92% (coil-to-coil)
	2012	US	Prototype (Stationary)	-	7.7kW	200mm	93% (coil-to-coil)
	2012	US	Prototype (Stationary/ Dynamic)	GEM EV	2kW	75mm	91% (coil-to-coil)
KAIST	2009	Korea	Prototype (Dynamic)	Golf Bus	3kW	10mm	80%
				Bus	6kW	170mm	72%
				SUV	17kW	170mm	71%
	2010	Korea	Public Demonstration (Dynamic)	Tram	62kW	130mm	74%
	2012	Korea		Bus	100kW	200mm	75%
MIT WiTricity & Delphi	2010	US	Commercial kits (Stationary)	Private vehicles	3.3kW	180mm	90%
Evatran	2010	US	Commercial Product (Stationary)	Private vehicles	3.3kW	100mm	90%

ORNL, mostly focusing coils design, announced two prototypes for Plug-in EV in 2012. The 7kW (SAE Level2) prototype has two identical 800mm diameter coils with Litz wire and soft ferrite plates could reach around 93% coil-to-coil efficiency. The 2kW prototype, using a different 330mm diameter coil design, was tested on a GEM EV powered by 72V lead-acid battery. Experiments have been done in both stationary and dynamic charging applications. The highest tested coil-to-coil efficiency is around 91% with an air gap of 75mm [20], [21].

Using the same technology, the Plusless Power produced by Evatran could transfer an output power of 3.3kW across 100mm. It has an over 90% plug-to-battery efficiency as claimed. It has already been successfully installed in Nissan Leaf or Chevrolet Volt. At the end of 2012, it announced a trial called Apollo Launch Program, aiming to the integration of this technology to current on-sale EVs across the United States [1].

MIT (WiTricity) and Delphi employs a different 4 coils design as shown in Fig.1. c. The strongly coupled prototype proposed by MIT in 2007 suggests a possible way to transfer energy through a relatively large distance (60W over 2m) [22]. In 2010, a set of 3.3kW development kits based on this technology was released. It has a very low profile on both primary and secondary sides, which could achieve an overall efficiency of 90% with 180mm air gap as claimed [23].

3.2.2 Dynamic Charging

KAIST has made great achievement on EV dynamic wireless charging in the last few years, which is called on-line electric vehicles (OLEV). The OLEV project was launched in 2009. In the same year, 3 generations of prototypes were reported with power ranger from 3 to 17kW [24]. The first demonstration, a 2.2 km tram loop, was installed in Seoul Zoo on March 2010. This 62kW wireless powered tram has a 40% smaller battery package than normal battery powered trams. At Expo 2012, an OLEV bus system was demonstrated which was able to transfer 100kW (5*20kW pick-up coils) through 20cm air gap with average efficiency of 75%. The battery package is further reduced to 1/5 [25]. KAIST is ready to apply its OLEV technology on over 300km/h, 180kW high speed high power rail way at the end of 2013 [5].

3.3 Key Challenges of Coupled Magnetic Resonant WPT

3.3.1 High Efficiency

The basic coupled magnetic resonance WPT system is consisted of 4 power stages, namely the power factor correction (PFC) converter, the RF amplifier, the coils or resonators, and the on-board rectifier. Fig. 2. shows the system schematic of a 4-coil strongly coupled magnetic resonance wireless EV charging system with uncontrolled pick-up. To archive 90% overall efficiency, both of the PFC and RF amplifier stages should have 97% efficiency at least, with the coil-to-coil efficiency higher than 96% and the rectifier efficiency close to 99%.

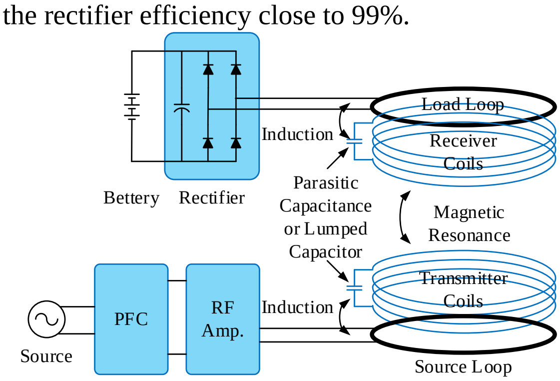

Figure 2: Schematics of strongly coupled magnetic resonance wireless EV charging system.

The coil design is the most important part in the whole system. The dimension of coil will defines the upper limit of the power capacity, and the efficiency will be affected by the quality factor of coils. For vehicle application, the coils normally consist of two parts, the wires and the magnetics. The coils will be operated from 10 kHz to several hundred Hertz. Under such high frequency, the skin effect will cause a very high AC resistance. So, Litz wire is often used [21]. Moreover, the alternating current flowing in one strand will generate an alternating magnetic field which will induce eddy current in its adjacent strands. This is called proximity effect and will also increase the AC resistance. When operating under MHz, a solid copper wire may have higher efficiency than Litz wire [26]. That's because the AC resistance may be dominated by proximity effect under such frequency. To eliminate this effect, wire coated with magnetic thin film is proposed to give shielding for the alternating magnetic flux and eliminates eddy current [27]. Some solutions turn to non-metallic materials such as graphene and carbon nanotube to completely eliminate the skin effect and proximity effect [28].

The magnetic structures are used to enhance coupling, reduce flux leakage and shape the magnetic field. There are two major types of magnetic structures, the track type and the lumped pad type [20], [25]. The track type can provide an evenly distributed magnetic flux, which reduced the design and control complexity of the following stages. KAIST The magnetic field shape can be controlled by the configuration of the ferrite core in power supply and pick-up sides, as well as the distance and coils turns. So the Shaped Magnetic Field in Resonance (SMFIR) technology is proposed to offers a tool to optimally solve functional requirements and design parameters using an axiomatic approach, as defined in [29]-[31]. The lumped pad is mostly used for stationary charging because when the displacement occurs, the mutual inductance of the primary and secondary coils will change, which will cause a fluctuation of the magnetic flux. And when it's used in dynamic charging there should be a control strategy which will tolerate or correct the flux fluctuation. And if the technique permits, this kind of structure will offer less restriction on vehicle movement and make the driving more freely.

3.3.2 Alignment Tolerance

Alignment tolerance is another important issue in EV charging application. One of the solutions is to adjusting configuration of the ferrite cores. By using a fish bone shaped primary core and flat E shaped pick-up, the alignment tolerance is nearly doubled than the former design in KAIST first few OLEV prototypes [24]. The Auckland proposed a new polarized coupler topology called DD or DDQ structure. By rearranging the ferrite bars, the newly proposed structure has 5 times larger charging zone than traditional circular pad without increasing the materials [6], [32]. Another solution is to use multiple charging pads. This solution has the potential to offer the maximum alignment tolerance. However, as said before, technique is required to control the flux fluctuations.

3.3.3 Dynamic Charging Control

Different charging control strategies are proposed, such as control on both primary side and secondary side with the help of wireless communication. However, this solution is not universal to all vehicle types, because the road side and on-board system has to be designed at the same time. A more promising solution for the future application is to use only road side control, as proposed by ORNL, although the wireless communication is also included [21]. This solution enables the on-board pick-up rectifier to be compact and reliable, and make the charging device universal to all types of vehicles.

4 Magnetic Gear Wireless Power Transfer

Fig. 3 represents the typical schematic of a magnetic gear WPT system. Quite different from the inductive technology, this technology uses interaction between two synchronized permanent magnets (PM) as its main coupling mechanism. Unlike its common application in EV and wind generation, the two PMs are placed side by side rather than coaxial [12], [13].

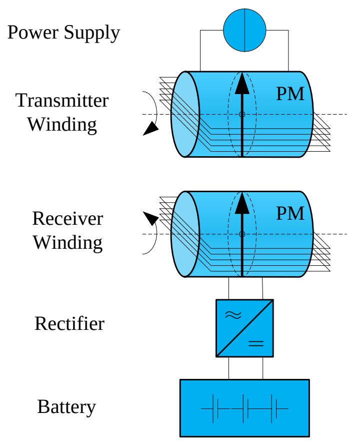

Figure 3: Schematics of magnetic wireless EV charging system.

The power is fed from a current source into the transmitter winding, producing a mechanical torque on the transmitter PM and making it rotate. Then, the magnetic interaction induces a torque on the receiver PM and makes it rotate synchronically with the transmitter PM. The receiver works in generator mode and delivers the power into the battery charging rectifier.

In WPT area, this technique was first used in powering medical implants. However, the power level and air gap are both small. In [14], the maximum transferred power is 6.6W and the maximum power at 1.0 cm is 1W. This is due to the limited space in human body application. By applying the same technique, researcher has scaled up the power level to 1.6kW with an air gap of 15cm, which is quite capable for vehicle charging application [15].

Although the technique is quite promising, several technical challenges need to be addressed. First, the transferred power is controlled by speed of the rotators. And there is a definite upper power limit when the rotators lose synchronization, which is 150Hz in [15]. So in real EV charging application, the speed needs real time adjustment with the feedback from the battery side. Another issue which may cause application challenge is the alignment. Similar to the inductive techniques, the power transfer capability of magnetic gear WPT will also decrease when the axis-to-axis separation increases. And it may be even worse because the PM dimension is quite small: 5cm*10cm in 1kW power level. Finally, this technique is not suitable for dynamic charging.

5 Industry Trends and Vision on WPT Developments

In EV wireless charging area, great achievements have been made on various pre-commercial demonstrations and some ready commercial kits. The very short term development will be focused on mass adoption of existing stationary or semi-dynamic charging techniques into market available EVs. High power, high efficiency, misalignment tolerance and optimized charging control will still be emphasised issues. Researches include magnetic structure design, high efficiency RF amplifier and converter control strategy design. Besides, international standards and safety regulations are also speed up for the future application.

In the long term, the final objective of this technique is to allow wireless charging the EVs with freely driving on road. The multiple placed charging tracks is under demonstration. More attractive is the multiple lumped charging pad structure. Because every single pad can be separately turned on, this will leads to higher system efficiency and maximum driving freedom if control technique enables.

6 Conclusion

In this paper, different wireless power transfer techniques are reviewed on the perspective of EV charging application. A classification is made first by energy carrying mediums and then by technologies. The coupled magnetic resonance and magnetic gear technologies are chose out for detailed review, because their suitability for EV charging application in both power and range level. The basic principle of each technology is explained. The latest development and research are summarized, with an especial emphasis on coupled magnetic resonance technology. Technical challenge and future development trends are also introduced.

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