A Literature Review in Dynamic Wireless Power Transfer for Electric Vehicles: Technology and Infrastructure Integration Challenges

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Abstract Dynamic wireless charging refers to the ability to charge a vehicle while it is in motion using resonant inductive power transfer. This is achieved by embedding source coils in the road and including a pickup coil inside the vehicle, these coils are coupled to get the maximum power transfer. From the point of view of the vehicle, dynamic wireless charging systems theoretically solve the Electric Vehicle (EV) battery problem by delivering unlimited range and making it possible to use smaller batteries, which reduce the cost and weight, however the implementation will be limited by the availability of the charging infrastructure, which in turn is limited by its cost. This paper presents a literature review on the recent advancements of stationary and dynamic wireless power transfer used for EV charging addressing power limitations, electromagnetic interference regulations, communication issues and interoperability, in order to point out the technology challenges to transition from stationary to dynamic wireless charging and the implementation challenges in terms of infrastructure.

1 Introduction

In 2012, the U.S. Energy Information Administration reported that the US imported about 45 % of the petroleum used in 2011 (U.S. Energy Information Administration 2012). The Department of Energy (DOE) has established as one of its primary goals to reduce the amount of oil used. Since transportation sector

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represents 70 % of the oil usage (Morrow et al. 2010), electric vehicles (EV) are becoming the path to reduce this amount, but costumer acceptance is closely related to their range and cost. The battery is one of the most important components in an EV and it is also the one that contributes the most to the range and cost problem, because an increment in battery size (more range) leads to an increment in cost and weight (Lorico et al. 2011), therefore, another solution needs to be proposed. Furthermore, DOE goals for EV adoption are to have a vehicle capable of fully charging in 5 min and having a 300 km range (US Department of Energy 2013a), this implies about 1 MW charging capacity in each charging station, batteries are currently not capable of absorbing that amount of power, this is something that will not be achieved in the near future (Slezak 2013).

Dynamic wireless charging (DWC), also known as in-motion charging, can be thought as a mean to address the problem of EV adoption by using the infrastructure as an extension of the power supply system of the vehicle. This is achieved by reducing the battery size and placing charging coils embedded in the road to transfer energy wirelessly using some variation of inductive power transfer. Although in (Musavi et al. 2012), it is pointed out 6 types of wireless power transfer (WPT) technologies: Inductive Power Transfer (IPT), Capacity Power Transfer (CPT), Permanent Magnet Coupling Power Transfer (PMPT), Resonant Inductive Power Transfer (RIPT), On-Line Inductive Power Transfer (OLPT) and Resonant Antennae Power Transfer (RAPT), for DWC purposes, only RIPT and OLPT are considered because they are the most promising technologies in terms of performance, their concepts, which are similar, are explained in the following section.

This paper presents the challenges to implement DWC, Sect. 2 presents the basic concepts of wireless power transfer and system components, Sect. 3 addresses technology challenges, safety issues and infrastructure topics to migrate to DWC, Sect. 4 presents the current standards roadmap and their scope and Sect. 5 summarize the contents of the paper.

2 Stationary Wireless Charging System

2.1 Basic Concepts

IPT refers to the action of transmitting power without using a medium other than the air. According to Lentz's law, a time variant current in a conductor creates a time variant magnetic field around it; this will be called the primary. And, from Faraday's Law, a secondary loop located in the vicinity will capture the magnetic field and it will induce a voltage in the terminals of the loop as shown in Fig. 1. A load can be connected to the terminals, the circuit will be closed and a current will flow, hence, power will be transmitted to the load connected in the loop (Witricity 2012; Kazmierkowski and Moradewicz 2012).

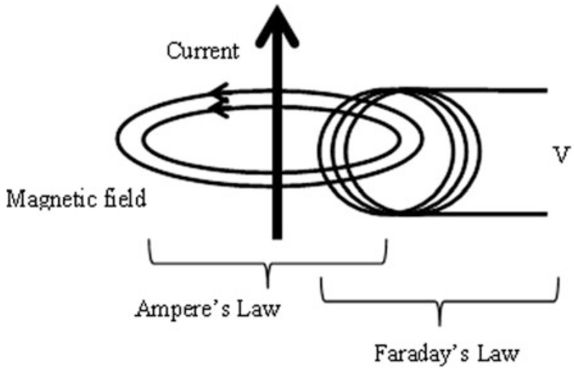

Fig. 1 Fundamentals of IPT (Covic 2013)

This configuration is not efficient because the intensity of the magnetic field decreases with the distance and the air reluctance is high (Sadiku 2001). To improve power transfer, series or parallel resonance topologies are applied to the primary and secondary to create resonant magnetic coupling (RMC) (Qiang et al. 2012). RMC occurs when two objects exchange energy through their oscillating magnetic fields and the natural frequencies of the two objects are approximately the same (Witricity 2012). To make the system resonate, harmonic oscillators are built in each coil by adding resonant capacitors. The effect of tuning is increase power transfer; the output power of the tuned system is given by Eq. 1:

$$P = \omega I_1^2 \frac{M^2}{L_2} Q \tag{1}$$

where ω is the resonance frequency, $I_1$is the current in the primary side, M is the mutual induction coefficient, L_2 is the self-inductance of the secondary and Q refers to the loaded quality factor from the impedance matching. This equation shows that the output power depends in four aspects: first, the operation frequency; second, the source current; third, the magnetic coupling, and fourth, the tunning factor (Q).

To increase the amount of power transmitted the following needs to be considered: There exists a trade-off between the frequency and the losses. The higher the frequency, the better the coupling, but also, capacitive effects are created and in the turns of the coils and losses also increase (Dimitrakakis and Tatakis 2008), hence there is a limit to which the frequency can be increased and still have a good efficiency. Also, increasing of the current in the primary also increases the losses (I_1^2R loses), so there are two approaches to maximizing the efficiency: (1) to increase the magnetic coupling, that could be achieved by a design that ensures that the coupling factor k is both high and has minimum variation with changes in the air gap (Boys and Covic 2012) and (2) to increase the tuning factor, which can be thought as solving the impedance matching problem (Kurs et al. 2007).

2.2 System Components

As observed in (Musavi et al. 2012), RIPT systems maximize the transferred power and optimize efficiency, increase distances, reduce electromagnetic interference (EMI) and it works in the kHz order of magnitude. The components involved in WPT are: (1) Utility interface, (2) High frequency power inverter and controller, (3) Coupling coils, (4) Rectifier, filters and regulator, and (5) Communications between the vehicle and the road side unit (Kesler 2012). They are shown in Fig. 2.

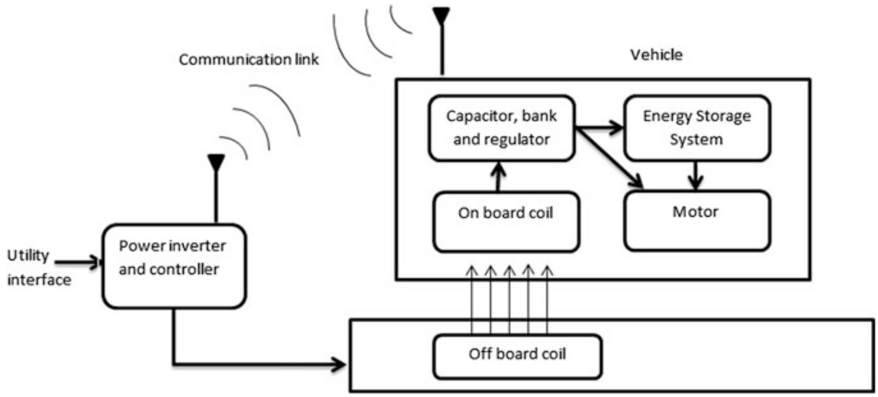

Fig. 2 Wireless power transfer system components

The system works as follows: The vehicle is located over the charging pad and when the identification process has taken place, the power inverter will convert the power from the utility to a high frequency alternating current, this will excite the resonant coils and the power captured in the on-board part will be rectified and sent to either to the battery or directly to the power train. To complete the loop a communication system is implemented to feedback the information from the vehicle to the grid side controller and vice versa. The overall system shall be capable of detecting any object between the coils and apply safety measures to avoid any incidents.

In order to have a successful implementation, the system needs to at least imitate the conductive charging solution, which has a high efficiency. To achieve this the vehicle should be correctly aligned, not represent harm for the user and the power levels should be at least similar to level 2 chargers (7.2 kW) (U.S. Department of Energy 2013b). Technology is mature in the stationary area, commercially available technology suppliers include: Conductix-Wampfler, Evatran, HaloIPT (Qualcomm) LG, Momentum Dynamics, and Witricity (Musavi et al. 2012).

3 Dynamic Wireless Charging System

Dynamic wireless charging (DWC) refers to the ability to charge a vehicle while it is in motion using resonant inductive power transfer. The implementation will inherit the problems from the stationary case, where the vehicle is parked, and it will introduce new ones. First, the vehicle will be in motion, thus the amount of time that the coils will be interacting is significantly smaller than in stationary case, this leads to the necessity of high power devices and also forcing the system to have high alignment tolerances to keep high efficiencies.

3.1 Technology Challenges

Using a Nissan Leaf as a benchmark, whose battery capacity is 24 kWh with a range of 74 miles (Leaf owner's manual 2012), it is necessary to define what type of service dynamic wireless charging will provide. Will it be designed to fully charge the vehicle or just an external range extender? The former case, as stated by Landreman (Landerman 2012), will require 30 miles of resonating coils to take the vehicle from 0 to 80 % of the full charge while driving at 60 mi/h, assuming that the fastest technology currently available is being used, and taking into account that Lithium Ion batteries get damaged when using fast charging. The latter case, assuming that the system is designed to add 30 miles of range, which is the average daily commuting distance (9.6 kWh), driving at 60 mi/h in a one-mile length charging lane, assuming 90 % of overall efficiency, it will require a power supply of almost 650 kW.

Another approach is that the vehicle is charged in a distributed manner, i.e. usage of several charging locations to extend the range instead of only one to balance the amount of power taken from the batteries and from the infrastructure. For this approach, the discussion about charging spots location and length is addressed by Pantic et al. in (Pantic et al. 2009). Three driving cycles were considered (UDDS, HWFET and VAIL2NREL), and three type of vehicles (compact car, large car and SUV). Several power levels for the charging station were tested (up to 60 kWh); the results are the optimal length of the charging lanes, location in the drive cycle and battery size. It was concluded that when minimum DWC track length is the only optimization criterion the DWC track length becomes very short. Therefore, it is beneficial to size the batteries to easily meet the peak power requirements. Since passenger vehicles usually do not follow a specific drive cycle in their normal operation, this approach is more suitable for transit vehicles because their route, stops and velocity profile are known.

All the scenarios presented before require a steady amount of power delivered and high power levels. Currently, scholars are investigating how to address this problem; the proposed approaches include but are not limited to: Magnetic field shaping (Ahn et al. 2012), dynamic parameter identification (Xin et al. 2010), reactive VAR compensators (Dixon et al. 2005), active rectification (Onar 2013), soft switching topologies and fast dynamic controllers (Wu 2012).

3.2 Safety

WPT systems are essentially resonant antennae, since they're devices for radiating and receiving radio waves (Merriam-Webster 2013). The transmitter transforms electric power into radio waves that are captured by the receiver, which means that the system intentionally generates and radiates energy. WPT operate in the near field of the magnetic field; research efforts should be aimed to works in the non-radiating reactive zone (Miller 2012). Due to the power amount that is transmitted, the fact that this system is not designed to transmit information and that it works in the near field zone, common regulations for antennae cannot be applied to them (Intertek Laboratories 2012).

Exposure to radio frequency magnetic fields is harmful for humans because it might induce current in tissues (ICNIRP 2010), and as it is observed in Fig. 3, exposures in the near field are more difficult to specify because the field patterns are more complicated and both electric and magnetic fields must be studied or measured separately (Hai et al. 2012). The following comparison is made to have an idea of the magnetic field levels when charging EVs, the experiment that MIT researchers presented in (Kurs et al. 2007), transmitting power to a 60 W bulb using a system that works at 10 kHz, produced a magnetic field of 1–8 A/m. For the implementation of DWC to be worthwhile, the system must supply at least the amount of power to move the vehicle over the charging lane, for a Nissan Leaf, 25 kW are needed for driving at 60 mi/h. This power amount will create a magnetic field approximately 30 times bigger than the one measure by MIT researchers.

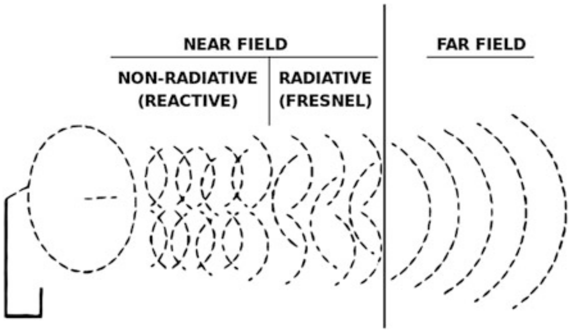

Fig. 3 Near field and far field regions of a time varying electromagnetic field (Djuknic 2003)

IEEE has determined that the maximum permissible exposure of magnetic field for controlled and uncontrolled environments is 163 A/m from 3 to 100 kHz, which are the frequencies at which the stationary systems work (IEEE 2006), from the calculations presented above, DWC would violate the permissible exposure if no active shielding is performed. The regions in the system that need to be analyzed are, in between the coils, around the coils and around the vehicle. The first two are not normally exposed to humans or animals but the last one is (Hai et al. 2012). Even if the vehicle is appropriately shielded and people inside the vehicle are safe, pedestrians, motorcycles and road workers and other people external to the system that can be in the vicinity are not protected reason why there is a need for safety measurements that take these actors into account (Landerman 2012).

3.3 Infrastructure

In addition to safety other challenges need to be considered. Since coils will be part of the road surface, they need to follow the same regulations as the road. The design of a road includes, among others, choosing the pavement material and how to handle rainwater and utility lines (U.S. Department of Transportation 2004). The coils need to be (1) as elastic as the pavement material, because they will support the weight of the vehicles, (2) waterproof, in case a crack lets water reach the coils, (3) reliable, to lead to zero maintenance, (4) noninterfering with periodic maintenance of the road and 5) coordinate with the existing utility lines to connect with the grid. The last characteristic also implies that there is a need for an upgrade in the distribution system because current designs are not prepared to handle the amount of power that the wireless charger will withdraw from the grid (Green II et al. 2011). Studies realized to stationary wireless charging of EV ensure that the distribution grid is capable of handling EVs charging between 1 and 6 kWh, but that the introduction of EV would force the grid to operate nearly at full capacity at all hours of the day, leading to deterioration of distributions transformers. Smart charging and smart grid are suggested as possible solutions to overloaded distributions systems (NY 2009; Kintner-Meyer et al. 2007).

Also, new infrastructure solutions are needed in the communication area. Vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication play an important role to determine the position of the vehicle in the lane and the presence of obstacles, also to monitor the charging process. In 1999, Federal Communication Commission (FCC) allocated 75 MHz of spectrum at 5.9 GHz to be used exclusively for V2V and V2I communication in the U.S. called Dedicated Short Range Communication (DSRC) (Federal Communication Commission 1999). DSRC technology is the preferred solution because it provides fast network acquisition, low latency, high reliability when required, priority for safety applications, interoperability and security and privacy (U.S. Department of Transportation 2012). Even though ad hoc network is a mature problem in the communication field, and several solutions already exist, there is still a need for research that evaluates how the network performs in terms to latency, bandwidth, such that no important information is lost, the control strategy behaves as expected and the system does not become a threat due to miscommunication.

4 International Standards

Currently there exist several commercial stationary charging technologies, most of them are incompatible with each other because the absence of standards by the time they were developed. There are several active groups working now in standardization of stationary wireless charging, as SAE J2954 and UL 2750. And other related standards as SAE J2847/6, SAE J2931/6 and SAE J2836/6 (Taiber 2013). Currently IEC subcommittee TC69 is working on developing a new standard for EV wireless power transfer systems, which is intended to be published as IEC 61980 (IEC 2013).

The topics to standardize in performance are: Alignment methods, interoperability, frequency, power levels, location of the coils in the vehicle. In terms of safety: Obstacle detection, communication, magnetic field levels, maximum temperature, and electric shock, among others (Schneider 2013). Recently, This IEEE Standards Association Industry Connection Activity approved a working group for pre-standardization in dynamic wireless charging; these efforts address the range limitation of EV as well as the cost aspect of the vehicle energy storage and complement the current standardization activities of the SAE J2954. This is currently the only group working on DWC; this activity will be expected to be finalized by June 2015 (Taiber 2013).

5 Summary

A review of the wireless power transfer concepts for EVs was presented. This paper investigates the technology challenges to transition from stationary to dynamic wireless charging. The purpose was to present the key technological components that need to be analysed in order to provide an overview of the problem of dynamic charging and to determine the feasibility of implementation. For that purpose, power transfer challenges, safety issues and infrastructure needs topics were addressed and discussed; in addition, an overview of the standardization activities for stationary and dynamic wireless charging was presented.

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