Wireless Charging of Electric Vehicles

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Road transportation, which accounts for 23% of U.S. total energy consumption, 59% of petroleum consumption, and 22% of greenhouse gas (GHG) emissions (Davis 2016), is undergoing a major transformation due to the advent of ridesharing, autonomous driving, and vehicle electrification. Collectively these technologies, in conjunction with renewable sources of electricity, can dramatically reduce the negative impact of road transportation on the health of our planet. However, for the successful convergence of these technologies, electric vehicles (EVs) need to be low cost and fully autonomous—attributes that can be realized through wireless charging.

Consider a future, where a driverless ridesharing EV pulls over as you exit a building, takes you to your destination, and proceeds to drive passenger after passenger without ever needing to stop to recharge its battery. Instead, power generated by nearby wind and solar resources is delivered wirelessly from the roadway to the vehicle while it is in motion. Not having to stop and have a person plug-in a charging cable, makes the EV truly autonomous, and allows fewer vehicles to meet societal needs. EVs with in-motion (dynamic) wireless charging can have much smaller batteries, reducing their cost and accelerating adoption.

While the concept of medium range wireless power transfer (WPT), achieved using near-field (non-radiative) electromagnetic coupling, has existed since the pioneering work of Nikola Tesla over a hundred years ago (Tesla 1891), the technology to enable effective dynamic WPT for EVs is still in its nascent stage. Numerous challenges related to performance, cost and safety need to be overcome before the vision of wirelessly powered EVs can be realized.

Near-Field Wireless Power Transfer

Near-field WPT systems are of two types: inductive, which use magnetic field coupling between conducting coils, and capacitive, which use electric field coupling between conducting plates to transfer energy (see Figure 1). For medium range applications (in which the distance between the transmitter and the receiver couplers is comparable to the size of the couplers, as in EV charging), inductive WPT systems have traditionally been preferred. In the last decade, building on work done for material handling applications during the 1990s (Green 1994), tremendous progress has been made in inductive WPT technology for stationary charging of EVs (Bosshard 2016). Aftermarket stationary wireless EV chargers are already available, and some vehicle manufacturers have announced plans to introduce built-in stationary inductive WPT systems in their EVs as early as 2018.

An issue with inductive WPT systems is that for magnetic flux guidance and shielding, they require ferrite cores, making them expensive and bulky. Also, to limit losses in the ferrites, the operating frequencies of these systems are kept under 100 kHz; resulting in large coils and low power transfer densities. The high specific cost and low power transfer density is particularly problematic for dynamic WPT, as these systems need to have very high power capability to deliver sufficient energy to the vehicle during its short time over a charging coil. Hence, dynamic inductive WPT is yet to become commercially viable, although a few experimental systems have been demonstrated (Onar 2013; Choi 2015).

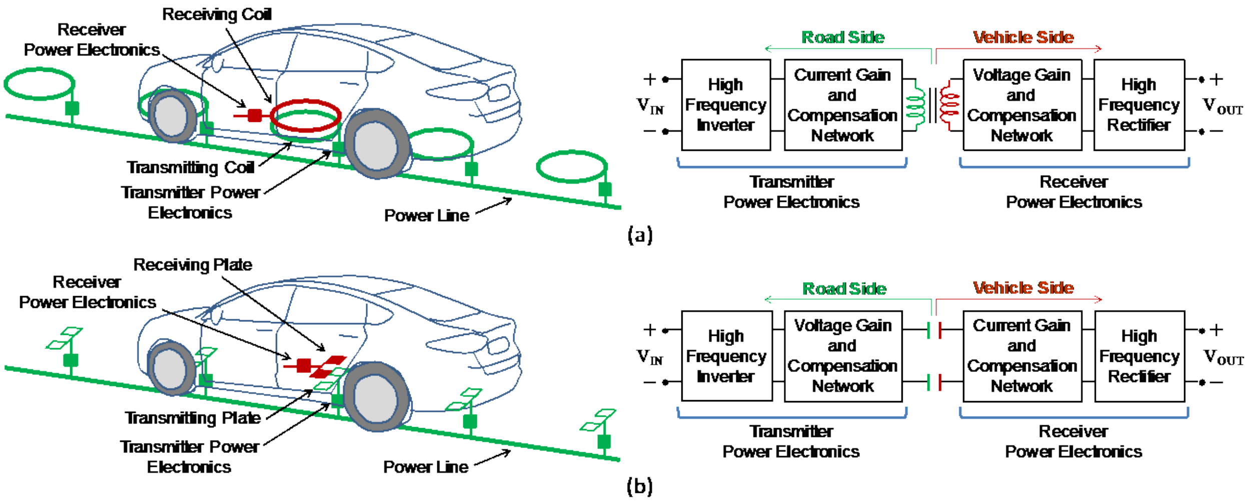

FIGURE 1: Physical implementation (left) and block diagram representation (right) of two approaches to deliver energy wirelessly to electric vehicles from an electrified roadway: (a) inductive wireless power transfer (WPT) using coils (embedded in the roadway and in the vehicle) which are coupled through magnetic fields, and (b) capacitive WPT using plates which are coupled through electric fields. In both cases, power electronics (comprising high frequency inverter and rectifier with semiconductor devices, and gain and compensation networks with inductors, capacitors, and/or transformers) is the enabling technology.

Capacitive WPT systems have potential advantages over inductive WPT systems due to the relatively directed nature of electric fields that reduce the need for electromagnetic field shielding. Also, since capacitive WPT systems do not use ferrites, they can be operated at higher frequencies, allowing them to be smaller and less expensive. Hence, capacitive WPT could make dynamic EV charging a reality. However, due to the very small capacitance between the road and vehicle plates, effective power transfer can only occur at very high frequencies, making the design of these systems extremely challenging. With the recent availability of wide bandgap (GaN and SiC) power semiconductor devices that enable higher frequency operation, high-power medium-range capacitive WPT systems are becoming viable (Zhang 2016; Regensburger 2017).

Two major challenges associated with capacitive WPT for EV charging are: (a) achieving high power transfer density at high efficiencies while meeting electromagnetic safety requirements, and (b) maintaining effective power transfer even as the couplers' relative position changes. These challenges have also been the focus of my group's recent efforts.

Achieving Safe and Efficient High Power Transfer

The size of the couplers in WPT systems can be reduced, with resultant increase in power transfer density, by designing them to operate at higher frequencies; in inductive systems the increase in induced voltage with higher frequency compensates for the reduced mutual inductance of the smaller coils, and in capacitive systems the increase in displacement current with higher frequency compensates for the smaller plates' lower capacitance. Higher operating frequencies also allow the power electronics associated with WPT systems (see Figure 1) to be smaller due to decrease in energy storage requirements.

However, achieving high efficiencies at high switching frequencies is very challenging. Also the fringing fields of WPT systems must be within safe levels, as defined by (ICNIRP 1998), in regions occupied by people and animals (i.e., the cabin and outside the perimeter of the vehicle chassis).

To achieve high power transfer densities at high efficiencies, while maintaining fringing electric fields within safe limits, capacitive WPT systems require circuit stages that provide appropriate voltage and current gain (to reduce displacement currents), as well as reactive compensation (see Figure 1). An active area of research is the design of these circuit stages (Theodoridis 2012; Lu 2015). Our work in this area has explored approaches utilizing multistage matching networks that can simultaneously provide gain and compensation (Sinha 2016). We have discovered that depending on the ratio of the system input and output voltages there is an optimal number of stages that maximizes efficiency. We have also identified the optimal distribution of gain and compensation among these stages.

To further reduce fringing fields in capacitive WPT systems various coupler design approaches have been considered. Approaches that utilize dielectric materials for field guidance introduce additional losses and have limited success in medium range applications. Our work in this area has been on exploring techniques traditionally used for beamforming in radars and other far-field applications (Hansen 2009). We have developed a near-field phased-array field focusing approach that uses multiple phase-shifted capacitive WPT modules to achieve dramatic reductions in fringing fields (see Figure 2). We have shown that with a 180°-outphased configuration there is a progressive reduction in fringing electric fields as the number of modules increases (Kumar 2015).

The area of phased-array field focusing provides various opportunities for innovation, including exploration of methods that incorporate parasitic interactions between multiple coupling plates into the design of the matching networks. Such phased array approaches could also be adapted for inductive WPT to help eliminate ferrites (Waters 2015).

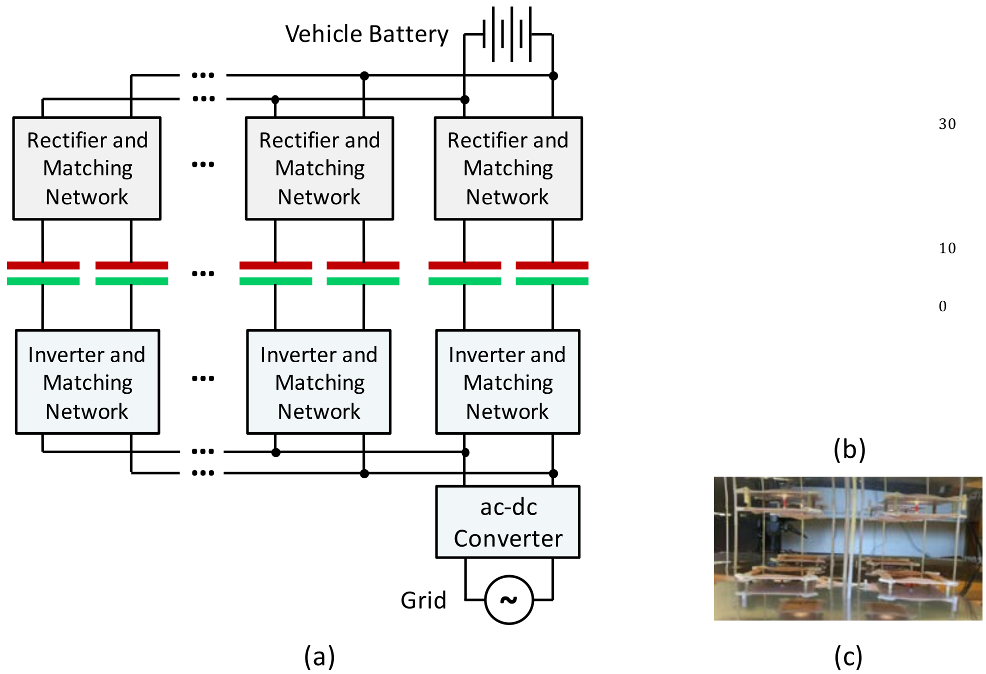

FIGURE 2: Multi-modular near-field phased-array capacitive WPT system: (a) block diagram representation, (b) simulated performance showing fringing field reduction with progressive increase in the number of modules, and (c) photograph of a prototype system.

Achieving Variable Compensation

To achieve effective power transfer, WPT systems need to operate close to the resonant frequency of the resonant tank formed by the coupler and the compensating network reactances. However, the coupler reactance depends on the vehicle's road clearance, and varies as the vehicle moves across the charger (see Figure 3). The drift between resonant and operating frequency causes a reduction in power transfer and efficiency of the WPT system.

In WPT systems operating at frequencies below 100 kHz, where bandwidths are not restrictive, the traditional approach to dealing with variations in coupling is to change the operating frequency to track the resonant frequency (Covic 2013; Shehkar 2013). However, in high-frequency WPT systems the operating frequency must stay within one of the designated industrial, scientific and medical (ISM) bands (e.g., 6.78 MHz, 13.56 MHz and 27.12 MHz) which have very restricted bandwidths (FCC 2014). One solution that is employed in low power inductive WPT systems is to use a bank of capacitors that can be switched in and out of the compensating network, so as to keep the resonant frequency roughly unchanged as the transmitter and receiver move relative to each other (Lim 2014). However, this is not an effective approach for higher power WPT systems as the switches have to be much bigger and more expensive to keep the system efficient. Also this approach is less suited to capacitive WPT, as it requires multiple switchable compensating inductors which are bigger than capacitors. Other adaptive impedance matching techniques have also been employed, including the use of saturable and variable inductors (James 2005). However, these techniques reduce system efficiency and do not scale well with power.

We have developed new high-frequency rectifier and inverter architectures that compensate for coupling variations while operating at fixed frequency and maintaining high efficiency. An example is the active variable reactance (AVR) rectifier of Figure 3 (Sinha 2017). By appropriately controlling the output voltages of its two coupled rectifiers, the AVR can provide continuously variable compensation while maintaining optimum soft-switching, ensuring high efficiency. This compensation architecture ensures that the output power of the WPT system is maintained at a fixed level across wide variations in coupling, and is applicable to both capacitive and inductive WPT systems.

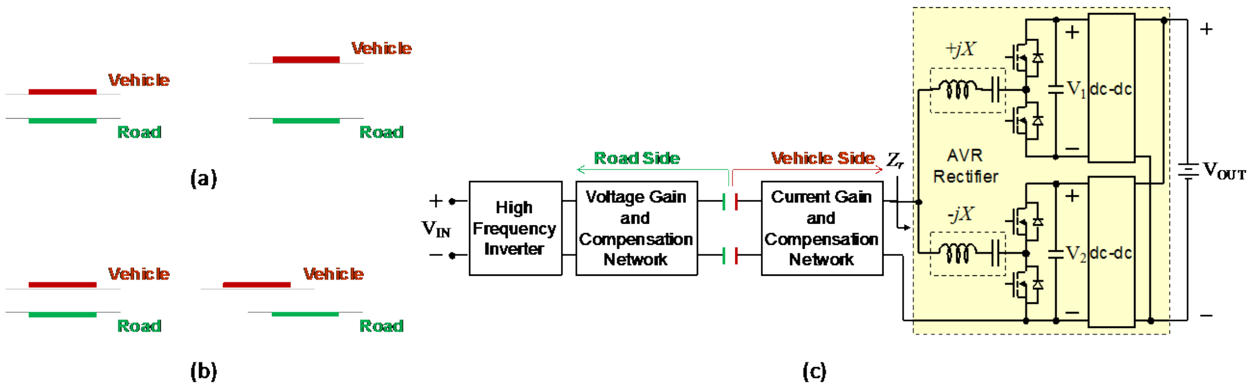

FIGURE 3: Coupling variations and an approach to compensate for these variations: (a) variation in coupling due to different vehicle road clearances, (b) variation in coupling due to change in vehicle position as it drives over the charger, and (c) a capacitive WPT system with an active variable reactance (AVR) rectifier that can provide continuously variable compensation by controlling the voltages V_1 and V_2.

Conclusions

High performance, safe and cost effective dynamic EV charging has the potential to revolutionize road transportation. What combination of capacitive and inductive WPT will enable this revolution is an open question. Both offer tremendous opportunities for research, especially in high frequency power electronics and near-field coupler design. Work is also needed in studying: health effects of long term exposure to weak electric and magnetic fields; mechanisms to detect living and foreign objects in the proximity of WPT systems; methodologies to determine optimal charger power levels and spacing for cost effectiveness; techniques to embed WPT technology into roadways; and approaches to analyze impact of large-scale deployment of dynamic WPT systems on the electric grid.

The technologies developed for dynamic EV charging are foundational, and would also enable wirelessly powered biomedical implants, humanoid robots and supersonic hyperloop transport. The technological challenges are exciting and the possibilities are endless.

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