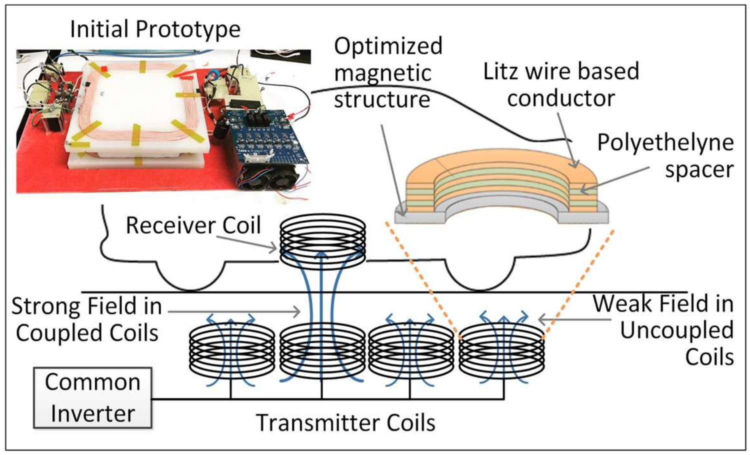
Introduction: The International Energy Agency estimates that by 2025, 70 million electric vehicles (EVs) will be on roads worldwide. As a result, research on increasing efficiency, reliability, and practicality of EVs and associated systems will be of increasing importance. Described herein is a wireless power transfer (WPT) approach for the dynamic charging of EVs. The goal is to address two challenges; reduction of component stress during high-power, high-frequency operation and electromagnetic field containment.



Literature Review: Dynamic charging, also known as roadway charging, consists of embedded roadway coils that transfer power to receiving coils on vehicles in motion (see figure) and has been demonstrated to increase the range of EVs. However, power transfer levels of 50-100kW are required to maintain the EV battery state of charge while the vehicle is in motion [2]. Another challenge is the health implications of electromagnetic fields emanating from the coils. The Society of Automotive Engineers (SAE) J2954 standard sets limits on stray electromagnetic fields [3]. Therefore, their reduction must be addressed if dynamic charging is to achieve mass adoption.

Objectives: To develop a high efficiency, high power multi-coil WPT system that will allow for localized electromagnetic field production between source and receiving coils.

Hypothesis: A reflexive WPT system comprised of: coils with embedded capacitors, saturable inductors and custom magnetic geometries, will enhance field containment capability and allow for efficient, high power dynamic EV charging with minimal electromagnetic field emissions.

Research Plan: *Stage I-Initial Investigations:* A WPT testbed based on a reflexive field containment compensation approach [4] will be fabricated. This topology achieves field containment by exploiting the receiving coil's reflected capacitive reactance to neutralize the source coil's inductive reactance. The source coil's current is thus attenuated when the coils are uncoupled, thereby reducing emanated fields. Based on my recent findings [5], saturable inductors will be used to enhance the field confinement effect. The goal of this stage is to achieve a power transfer of 10kW at an efficiency above 90% while maintaining a 30-fold field attenuation factor between uncoupled and coupled conditions. *Stage II-Coil Embedded Capacitors:* At power transfer levels of 50-100kW, the high voltages at the terminals of the inductor coils stress the resonant tank capacitors making the SAE J2954 mandated high frequency (~80KHz) operation challenging to implement. Previous studies have demonstrated this power transfer level only at lower frequencies [6]. Self resonant coils have been shown to eliminate the need for capacitors [7], however these are limited to use in MHz level resonant frequencies and lower powers. To address this, coil enclosures will be designed and built with polyethylene dielectrics spacers that allow for embedding large parasitic capacitances to reduce the voltage stress on the external resonant tank capacitors and allow for efficient high frequency operation. *Stage III-Additive Manufacturing Based Magnetic Structures:* Custom magnetic structures will be implemented in the coils to allow for optimum channeling of flux during operation to further reduce stray fields and improve coupling. This will be preceded by extensive finite element analysis of the desired magnetic structure geometry. The magnetic structures will be fabricated using an additive manufacturing process recently demonstrated at Oak Ridge National Laboratory [8]. A supplier for the required magnetic nano-alloy powder (FeNbSiCuB) and polyphenylene sulfide mixture has already been identified. *Stage IV-Optimization:* This stage will focus on the challenge of optimizing system performance at ~100kW for high efficiency operation, conformance to SAE standards and EV testing. Soft switching will be employed on the Silicon Carbide based inverter while processing minimal reactive power to improve efficiency. The test EV will be modified to carry the receiving coil and necessary power electronics to interface with its rechargeable batteries. Based on the SAE standards, shielding for the receiving coil will be designed to prevent fields from penetrating the EV cabin. An array of segmented source coils will be embedded on equal intervals of test track. As the EV drives along the track, the power transfer and field containment capability of the system will be characterized and compared to simulation figures.

Timeline and Collaboration: The proposed duration of the project is three years and will be performed under the supervision of Dr. Srdjan Lukic at North Carolina State University's (NCSU) NSF funded Future Renewable Electric Energy Delivery and Management Engineering Research Center (FREEDM ERC) in collaboration with Dr. Tim Horn of the Center for Additive Manufacturing and Logistics (CAMAL). Being one of the nation's leading centers for additive manufacturing, CAMAL's facilities have specialized equipment capable of fabricating magnetic structures from magnetic nano-alloy powders. The systems level integration will be performed on the EcoPRT EV mentioned in the personal statement.

Anticipated Results: Through the use of saturable inductors, custom magnetic structures, and coil embedded capacitors, high frequency power transfer at 50-100kW power levels with high field attenuation factor between uncoupled and coupled conditions will be demonstrated. Noting that a WPT system is a transformer with a large air gap, this project strives to meet a theoretical system efficiency of 98+%, or comparable to plug-in charging.

Intellectual Merit: This research plan focuses on developing novel WPT systems that enable dynamic charging and, more generally, on pushing the boundaries of high power WPT by developing better models of complex coil designs with integrated passives. Additive manufacturing will allow for novel magnetic structures that are optimized for specific applications, and this methodology can be utilized in other high power high frequency applications.

Broader Impacts: The mass proliferation of EVs is essential in addressing both climate change and the dependence on fossil fuels. Through the implementation of WPT systems for EV roadway use, the proposed project will assist in making feasible a system that will allow for the efficient and reliable increase in range and thereby practicality of EVs. I will regularly present findings from this research effort at scientific conferences and high profile journals. With NCSU being located in the Research Triangle area, I will share findings with industry to facilitate industrial proliferation of the technology.

(1) Clean Energy Ministerial, Electric Vehicle Initiative & International Energy Agency (2017). *Global EV Outlook 2017*. (2) Z. Pantic, et. al., "Inductively coupled power transfer for continuously powered electric vehicles," *2009 IEEE Vehicle Power and Propulsion Conference*, pp. 1271-1278. (3) *Wireless Power Transfer for Light Duty Plug-In Electric Vehicles and Alignment Methodology*, no. SAE Standard J2954, 2016 (4) K. Lee, et. al., "Reflexive Field Containment in Dynamic Inductive Power Transfer Systems," in *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4592-4602, Sept. 2014. (5) A. Dayerizadeh, et. al., "Saturable Inductors for Superior Reflexive Field Containment in Inductive Power Transfer Systems," *2018 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Accepted. (6) G. Jung *et al*., "High efficient Inductive Power Supply and Pickup system for On-Line Electric Bus," *2012 IEEE International Electric Vehicle Conference*, Greenville, SC, 2012, pp. 1-5. (7) A. Kurs, et. al., "Wireless power transfer via strongly coupled magnetic resonances," *Science*, vol. 317, no. 5834, pp. 83–86, Jul. 2007. (8) U.S. Department of Energy (2015). *Electric Drive Technologies: 2015 Annual Report.*