Three and Two Phase Rotating Field Inductive Couplers for Wireless Power Transfer with One Phase per Layer Windings

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***Abstract*—Multiphase inductive wireless charging coils have been proposed recently to improve coupler surface power density, reduce component stress and size, and provide near-constant power delivery to charge mobile electric systems. Several aspects for the fundamental characterization of multiphase coils are explored up to six phases including approximate mutual inductance with size and turn variation, induced voltage, and output power estimation. The relative component stress and size of passive components for resonant operation are compared between the multiphase variants. A combination of an experimentally validated 3D electromagnetic finite element analysis (FEA) and power electronic co-simulations are used to validate the estimated quantities approximated with a mixture of analytical equations and an artificial neural network model for mutual inductance. A novel three-phase transmitter, two-phase receiver coil pair is also proposed for electric vehicle charging to reduce the number of connections and compensation complexity on the vehicle-side with improved power output compared to a two-phase configuration.**

***Index Terms*—Wireless power transfer, inductive coupler, multiphase systems, electric vehicle (EV), wireless charging**

I. Introduction

Wireless power transfer (WPT) has been proposed for mobile electric systems, such as electric vehicles and cell phones, with unique benefits including charging without human intervention, potentially improved operational safety, and maximal ease of use. Wireless vehicle charging, for example, can enable, for stationary applications, improved access including curbside urban charger access, and operational safety, and, with dynamic on-road applications, considerably extended driving range or reducing battery size. Mobile electric systems typically have gravimetric and volumetric constraints, requiring a secondary-side coil as small and light as possible, while maintaining satisfactory efficiency at rated power.

Multiphase rotating field inductive couplers are an attractive proposition for high power density wireless charging with benefits including constant power output, reduced voltage stress, and potentially reduced compensation component size [1]. Implementation of multiphase coils aim for maximized surface power density and minimal circuit stress with a growing number of studies including, for example, alternative coil geometries [2], comparison to single-phase systems [3], improved efficiency with segmented couplers [4], and dynamic track implementation [5], [6]. Most recently, a three-phase topology has reportedly achieved record high power output (100kW and 270kW) with a 3-phase, 2-layer inductive coupler [7], [8]. Majority of studies so far have employed either single-phase, three-phase, or a mixture of both with selective coil excitation for cross-phase interoperability [9], [10].

Geometry of the inductive coil also significantly impacts coil performance with several studies comparing unipolar and bipolar coils as discussed at length, for example, in [11] and [12]. Several unipolar rotating-field coils have been prior studies,for example, such as the single layer three-phase coil [13] and unipolar half pitch coils [2] with advantages including angular misalignment tolerance, ferrite structure, and ease of design. Unipolar circular coils, often suggested as having the highest coupling capability, cannot be implemented with each phase on a separate layer, removing the potential for multiphase operation without increased surface area. Bipolar DD coils allow for multiple combinations of phase per layer coils for maximum surface power density with additional advantages including potential for improved misalignment tolerance, reduced ferrite size, and better efficiency vs mass [14]. A gap in the literature was found considering alternative phase combinations to single and three phase coils and the contributions of cross-phase mutual inductance to output power.

In this study, multiple phases and phase combinations are simulated for bipolar rotating-field inductive coil designs and compared in voltage stress, resonant compensation size, and mutual inductance. An example 85kHz stationary polyphase wireless charging implementation is depicted in Fig. 1 for electric vehicle applications. Finite element analysis (FEA) was used to simulate expected electromagnetic behavior for 1, 2, 3, 4, and 6 phase designs including mutual inductance, induced voltage, and output power. A mixture of analytical equations and an artificial neural network (ANN) are used for scaling electromagnetic attributes at varying outer diameter (OD) and number of turns. A reduced order model (ROM) was created to integrate coil electromagnetic properties into coupled power electronics simulations. The combined results from both models were used for the derivation of scaling equations capable of predicting a variety of aspects at varying outer diameters and turns. The combination of the FEA, analytical equations, and ROM are used for a comparison of multiphase coil system voltage stress and resonant compensation size.

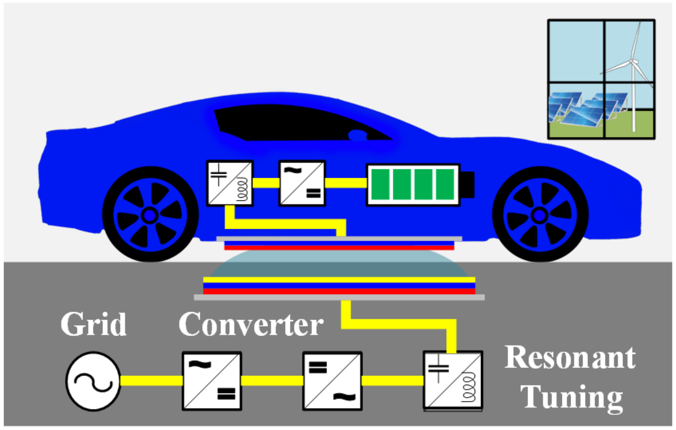

Fig. 1. Example application of stationary electric vehicle wireless charging with a two-phase receiver and three-phase transmitter inductive coupler pair.

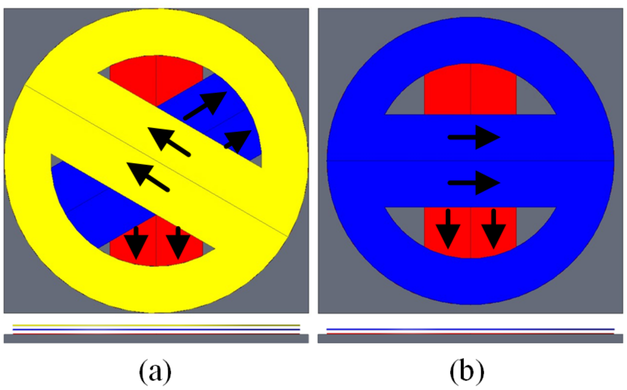

Fig. 2. Polyphase rotating-field bipolar inductive WPT coils in three-phase (a) and two-phase (b) variants with current excitation direction shown by the black arrows.

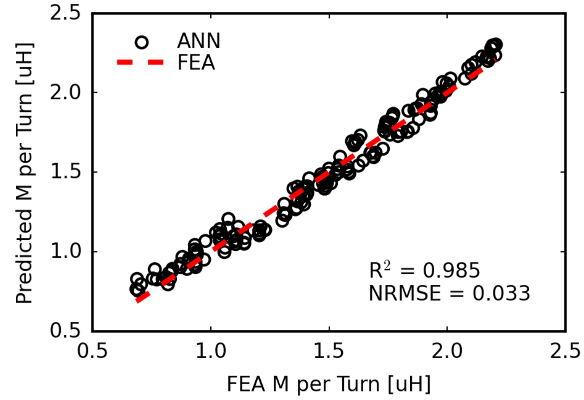

Fig. 3. Mutual inductance per turn prediction for geometry variation in a two-phase coupler design using an ANN meta-model trained on FEA results.

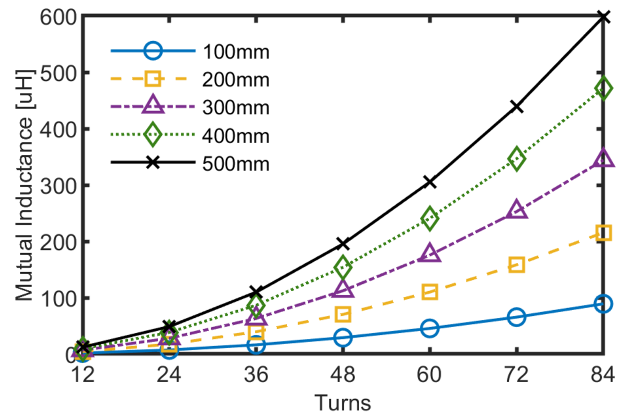

Fig. 4. Simulated mutual inductance between the primary and secondary with variation of turns and coil outer diameter.

II. Electromagnetic Characterization of Bipolar Rotating Field Inductive WPT Couplers

Electromagnetic properties of multi-phase coil designs, such as mutual inductance and induced voltage, can be characterized to determine an approximate power output for a maximum defined volume and supply current depending on thermal limitations. To explore the fundamental relationships effecting these parameters, a complex three-phase three-layer rotating field coil, shown in Fig. 2, was selected for this study using ANSYS Maxwell 3D FEA [15] assuming a macro coil model of many stranded Litz wire or printed circuit board (PCB) traces. The selected topology benefits from minimum leakage between poles with a 1/2 coil span and improved mutual coupling for high specific power compared to other variants. The simulated coils were designed as 85kHz 100mm OD small-scale laboratory prototypes with a 30mm airgap and 3mm thick square ferrite plates of 100mm width.

The flux linkage within the coupler pair, defined as mutual inductance, is the main magnetic characteristic defining coil performance and can be calculated through analytical equations or simulated with FEA, which often are computationally intensive. Recent studies have developed alternative methods to approximate mutual inductance with machine learning [16], [17]. An artificial neural network was created and trained on mutual inductance resulting from coil geometry parametric studies of a two-phase coupler design. The resulting prediction and FEA calculated mutual inductance per turn are depicted in Fig. 3 with prediction accuracy greater than 95%. Using these tools, the mutual inductance per phase can be approximated for many designs of varying sizes with a relatively small number of FE simulated studies.

Minimum spacing between phases and layers is limited to prevent flashovers and arcing at high voltage with limits of breakdown voltage, typically 40kV/mm in FR4 used for PCB insulation, and more conservative international safety standards like IPC-2221 [18]. A set of parametric studies were performed varying frequency, current, turns and outer diameter to approximate open circuit induced voltage at varying outer diameters, while maintaining a 0.3 ratio to the airgap. The results found that, as expected, induced voltage in the secondary with an equal turns ratio scales linearly with frequency and current matching the analytical equation: $V_{ls} = \omega I_p \hat{L_m} N_t^2$, similar to that defined in [19], where I_p is primary current, $\hat{L_m}$ is mutual-inductance per turn between coils, and N_t is the number of turns. Results from these studies also indicated that

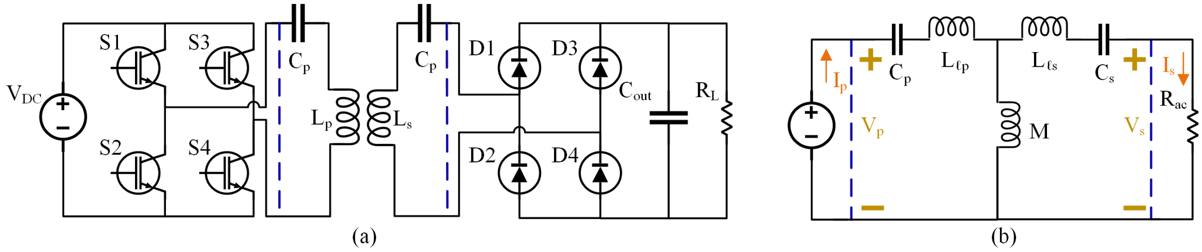

Fig. 5. Single-phase section of a series-series compensated inductive wireless charger (a) and a T-model representation of the coupler coil (b). The dashed blue lines indicate the section for transfer function derivation.

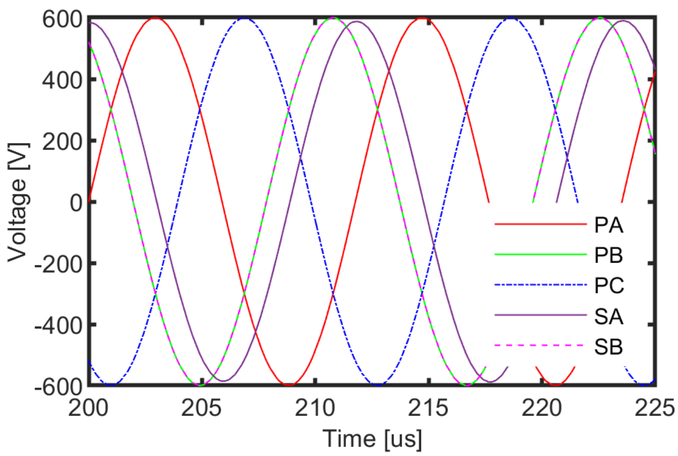

Fig. 6. Voltage waveforms from a co-simulation of a 3D electromagnetic model of the 3-phase transmitter, 2-phase receiver coupler with series-series compensation.

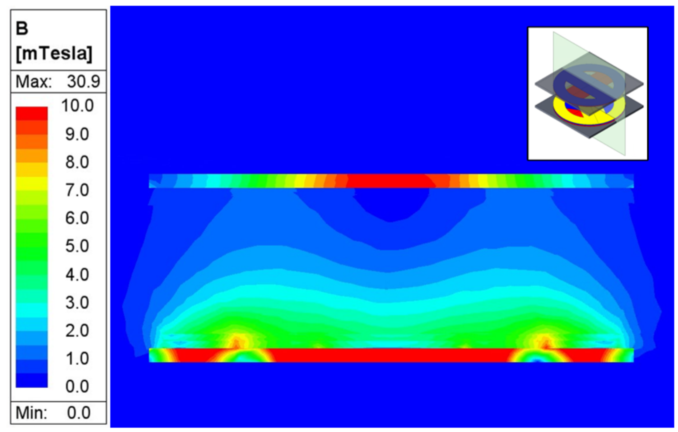

Fig. 7. Cross-sectional B-field results at the start of a period from a 3D electromagnetic model of a 3-phase transmitter, 2-phase receiver rotating field coupler.

inductance per turn and induced voltage increases linearly with OD assuming the same geometry. Induced voltage variation can then be estimated with a linear regression considering FE parametric study results for inductance per turn with variation of OD and number of turns.

Power between couplers can be calculated analytically as $P = |j\omega \overline{I_p^T} M_{ps} I_s|$, such as defined in [1], where M_{ps} are the mutual inductance terms between primary and secondary coils, and I_p and I_s are the complex vectors of primary and secondary currents respectively. Parametric study results for a variety of coil parameters suggest that outer diameter and the number of turns have the largest impact on mutual inductance, as indicated in Fig. 4 by a product and squared factor respectively. Limitations for power transferred coil to coil include size of compensation needed for the selected mutual inductance, maximum induced voltage, and current carrying capability for a set temperature rise.

Litz wire and printed circuit board (PCB) have both been proposed for high-efficiency operation at high-frequency to mitigate potential eddy current losses with many strands with cross-sectional area less than or equal to the skin depth. Additionally, variation in induced voltage due to proximity to ferrite core can cause significant circulating current losses and may be prevented either with transposed Litz wire or printed circuit board trace transposition and phase interleaving. Litz wire designs are limited in bend radius and volume but can carry very high current due to high strand counts and fill factor. Efficiency for PCB designs vary substantially due to conventional manufacturing practices, which limit fill factor, requiring optimal design for the strand number and connections for minimal AC and DC losses.

III. Multi-Phase WPT Coupler Coil Simulation

Inductive couplers for wireless charging utilize resonance to maximize power transferred to the load, improve system efficiency, and regulate supply current and induced voltage. Series-series (SS) compensation was employed for this study, as shown in the single-phase example of Fig. 5 (a), for resonant operation with worst-case scenario passive component stress. The sizing of compensation components in SS wye connected systems is $C_i = \frac{1}{\omega^2 (L_i - M_{ij} + M_{jk} - M_{ki})}$, as detailed in [1], to consider interphase couplings, which can greatly impact capacitor ratings. A first harmonic approximation of the single-phase SS compensation, depicted in Fig. 5 (b), was used for steady-state analysis of voltage gain given an ideal 85kHz excitation and an equal number of turns in the primary and secondary. Example voltage waveforms of a 3-phase transmitter, 2-phase receiver coupler pair is shown in Fig. 6 with a near unity voltage ratio. Results from the transfer function matched electromagnetic coil FEA models with SS compensated power

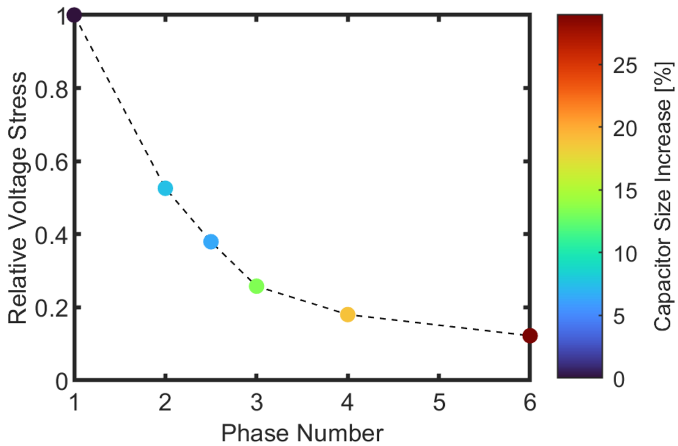

Fig. 8. Relative voltage stress and size increase for passive components in systems of varying phases with the same outer diameter, airgap, and power output.

Fig. 9. Experimental setup for the measurement of inductances between the primary and secondary coils with a three to two phase 100mm OD PCB prototype.

electronic co-simulation using a reduced order model (ROM) of the simulated coil in ANSYS Simplorer.

Five variants of multi-phase sequentially layered DD coil systems were simulated ranging from 1 phase to 6 phases, each with a phase per layer, geometrically and electrically shifted by either $\theta = \frac{360}{m}$ for 3-phase or $\theta = \frac{180}{n}$ for 2-phase reducible systems. An example depiction of the magnetic field between the primary and secondary coils is visualized in Fig. 7 for a cross-section of one of the studied coil geometries. Layers were sequentially stacked for the simulation of magnetic quantities such as mutual inductance, which would ideally be transposed and interleaved to mitigate imbalances between phases. Notably, the simulated two-phase coil designs had naturally balanced mutual inductance with no cross-coupling between phases within the primary or the secondary, simplifying series compensation. Resulting power followed $P = K\omega M_{ps} I_p I_s$, from [17], where M_{ps} is the maximum mutual inductance between couplers, I_p and I_s are maximum excitation current, and K is a constant dependent on the number of phases.

Designs with phases greater than two had significantly increased K relative to the number of phases, which is due to cross-phase coupling or coupling between phases B in the primary and C and A in the secondary, etc. The contribution of cross-phase coupling to power can be isolated analytically by solving for power with the following calculation: $M_{ps}^{cc} = M_{ps} - (M_{ps} I_n)$, where I_n is the identity matrix. This indirect coupling was found to contribute as much as 30% of total output power in the 3-phase coils. Compared to the dual three-phase coil designs, the dual single phase and two-phase designs would need four and twice as much current respectively for the same rated power. These power differences were validated with ANSYS Simplorer and in line with expectations based on previous prototypes.

Alternative geometries and configurations were also simulated for a comparative study of mutual inductance and power with the same surface area. With a fixed OD of 100mm, a 30mm airgap, 0.67 coil span, and current per phase of 8Apk, a single-phase unipolar circular coil and single-phase bipolar DD coil were compared as well as three-phase three-layer DD coil and three-phase two-layer one-third layer configurations. When comparing simulation results for the same number of series turns per pole, the circular single-phase coil had 20% less power than the DD single-phase coil. For the 3-phase configurations, the three-layer configuration had 70% higher power output but with the added caveat of significantly more volume and coil coverage than a two-layer configuration. As reported in multiple previous studies comparing coil geometries and configurations, results vary significantly depending on the study parameters and assumptions with these results being just one example.

IV. Electric Vehicle Charging Case Study

Design for mobile applications involves the sizing of both the coil couplers and the interconnected passive components to minimize size and weight. Voltage ratings for circuit components typically dictate system size and larger capacitance values typically require more surface area or a greater number of layers. Relative voltage stress and capacitor size for the simulated designs is plotted in Fig. 8 assuming the same rated power output compared to a single-phase system. The mixture of increased phase number and cross-phase coupling reduces the voltage stress for a rated power. As the number of phases increases, the coupling coefficient decreased for the same OD and airgap, requiring larger passive components for compensation. A trade-off is then necessary between voltage stress, the necessary size of SS compensation capacitors, and the volume and complexity of additional phases.

Designing for maximum efficiency or maximum surface power density at minimum volume requires a trade-off between mutual inductance, including outer diameter and the number of turns, and total current. Maximization of current can increase transferred power by a power of 2 but can substantially increase losses within the coil. If designing with a fill factor restricted medium in mind, such as PCBs, mutual inductance can be maximized with a set outer diameter by increasing the number of turns. Implications of a high mutual inductance include much smaller capacitance, which could require specialized manufacturing, increased induced voltage by a power of 2 compared to the linear impact of increased current, and substantial impact on system voltage gain.

A novel three-phase transmitter, two-phase receiver coupler pair is proposed based on the results for voltage stress and capacitor size at the same rated power for minimal volume while benefiting from cross-phase coupling. Simulation results indicate that the three to two phase coil can output 1.5 times the power of the two-phase to two-phase version with simplified compensation on the secondary side as there is no coupling between the two phases. For electric vehicle application, this allows for reduced volume and connectors in the secondary side, naturally balanced inductances, and easier manufacturability at the cost of specific power but may be better for systems without cooling. Ideal implementation to minimize volume and manage losses is proposed as a PCB two-phase coupler on the secondary-side with a Litz wire three-phase coil on the primary-side with high input current and high output voltage. A prototype, shown in Fig. 9, was developed with 100mm OD PCB coils and mutual inductance was measured across a 30mm airgap with an LCR meter resulting in satisfactory agreement between FEA and ML results with less than 15% error.

V. Conclusion

Multiphase rotating field bipolar coils are electromagnetically characterized and compared using a mixture of ANSYS Maxwell 3D FEA, power electronic co-simulation, and analytical equations. Mutual inductance, induced voltage, and transferred power are evaluated for designs from single phase to six phase for comparison of transferred power and passive component sizing. A reduced order model of selected multiphase designs was integrated into a coupled power electronics circuit for voltage-driven operation to evaluate effectiveness of analytical equations for output power and scalability with geometry. Analytical isolation of cross-phase coupling in coils with more than two phases revealed significant power increase compared to the expected increased scaling with the number of phases. A novel three-phase transmitter, two-phase receiver coil pair is proposed for electric vehicle charging to reduce receiver volume, the number of connections, and compensation complexity on the vehicle-side, while providing improved power transfer compared to a similar 2-phase design.

Acknowledgment

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. 2239063 and the NASA National Space Grant College and Fellowship Program and the Kentucky Space Grant Consortium under NASA award number 80NSSC20M0047. The support of ANSYS Inc., the Lighthouse Beacon Foundation, and the University of Kentucky, the L. Stanley Pigman Chair in Power endowment is also gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the sponsoring organizations.

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