# Self-Resonant Coil Design for High-frequency High-Power Inductive Wireless Power Transfer

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***Abstract*—In this paper, the design methodology of a high-frequency, high-power, long-distance inductive wireless power transfer (WPT) is presented. The airgap (*d*) of a traditional high-power (>1 kW) WPT is limited to a few hundred millimeters, which is almost 1/4th of the coil diameter, *D*; *d ≤ D/4*. In this paper, the power transfer distance is significantly increased (*d ≥ 1.5D*) by adopting a high-frequency magnetic design and GaN-based power electronics. The material and design of the coil and shield are investigated using FEA and tested experimentally. A high frequency 6.78 MHz wireless charging system was built to transfer 1 kW power over 3 m airgap.**

***Keywords—Wireless Power Transfer, Long distance, inductive power transfer, GaN devices***

## I. Introduction

Wireless charging system has shown a significant promise of flexibility and reliability for electric vehicle charging. It has been demonstrated with high power and efficiency for electric drones, cars, buses, trucks, ships, etc. with high power and efficiency [1]. Drones, in general UAVs, are one of the most potential applications for the wireless charging system. The UAV application requires unattended, hands-free, automated, all-environment, and highly reliable charging infrastructure; which makes the WCS a highly fitting charging solution. While *d≈ D/4* has unlocked a large number of applications, such as cell phones and industrial robots, to electric vehicles, there is a tremendous opportunity of long-distance (*d>D*) WPT. For example, such long-D WPT would make the transmitter and receiver pad a few times smaller and lighter for the current high-power application, and unlock a new sets of applications such as hovering Drone, on-flight plane-to-plane, UAV-to-UAV, on-road EV-to-EV WPT, and many more. To achieve such target, a high frequency operation is essential, which requires to overcome many challenges through innovative magnetic and power electronics design.

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In literature, several high-power multi-megahertz wireless charging systems has been investigated for a few millimeters to few hundred millimeters and power rating up to few hundred watts [2-5]. In this work, we investigated the system design for the airgap higher than few meters and power rating of 1 kW and higher.

## II. Theory and Design

Fig. 1 shows the variation of the coupling coefficient with the normalized airgap (*d/D*), where *d* is the airgap distance and *D* is the diameter of the equally sized transmitter and receiver pads. Fig. 1 indicates that long-distance provides an extremely low coupling coefficient. At a low coupling coefficient, the amount of flux that needs to generate by the transmitter coil to induce the desired voltage at the receiver coils becomes extremely high, as only a small fraction (*k*) of that flux couples to the receiver. As a result, the power transfer capability becomes inherently low.

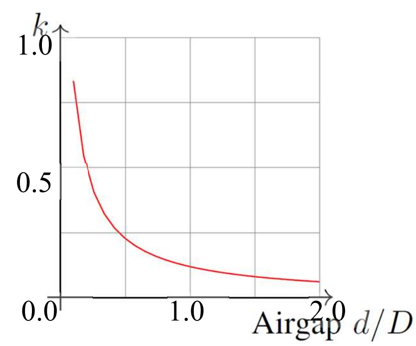



Fig. 1. Variation of the coupling coefficient with normalized airgap (*d=D*)

The fundamental power transfer capability for a coupled inductor can be expressed as

$$P = \omega\, M\, I_p I_s = \, 2\pi f k\, \sqrt{L_p L_s}\, I_p\, I_s \qquad (1)$$

where $P$ is the transferred power, $M$ is the mutual inductance, $I_p, I_s$ are the primary and secondary current, and $f$ is the operating frequency. For simplicity of analysis, we first assume that the number of turn is one for both the transmitter and receiver coil ($N_p$=$N_s$=1). Then, if the coupling coefficient gets smaller, either the frequency $f$, or the currents $I_p, I_s$, or both needs to be increased to maintain the power $P$ constant. Increasing both the frequency and currents are limited by the capabilities (size, cost, loss and thermal limit) of the semiconductor switches, coil, and magnetic material.

Increasing the switching frequency, $f$ to compensate the reduced coupling factor, $k$ has multiple limitations. Higher frequency increases the switching loss in the semiconductor switches, reduces the effective cross-section of the coil-conductor due to the skin effect. On the other hand, increasing the coil currents, instead of the frequency, has a different sets of limitations, such as, the increased volume of copper and ferrite requires to support the additional current and flux while maintaining high efficiency. Also, the increased current causes additional conductive and switching loss in the semiconductor switches. While these are the technical challenges, these choice also affect the cost of the system. In this paper, mostly the technical challenges are addressed.

### A. Selection of frequency

The selection of the operating frequency has the most significant impact on the electromagnetic design and component selection. In this study, a frequency range of 1 MHz to 10 MHz were evaluated to find the optimum operating frequency transfer the 1 kW to 10 kW power over 1 m to 10 m airgap using available conductor, magnetic materials, and semiconductor devices.

### B. Selection of the conductor

For high frequency design, Litz wire is one of the most potential candidates. Currently, most the higher power wireless charging systems for EV are operating at 85 kHz and using AWG38-40 strand based Litz wire. The high-frequency low-power wireless charging systems for cell phone applications uses both Litz wire and copper trace-based design. The selection of Litz wire or the copper foil depends on the operating frequency. The commercial litz wire are available up to AWG 46 strand, which are suitable up to 3MHz with ac/dc resistance ratio nearly 1: $R_{ac}/R_{dc} \approx 1$, and it can be utilized for even higher frequency with increasing $R_{ac}/R_{dc}$. One of the greatest benefits of the litz wire is its scalability for higher current rating.

**Litz wire**

For a single turn coil, the Litz wire mostly operate under its own field, as there are no additional field from the neighboring turns. Therefore, the Litz wire can be developed as a bundle of wire on a 2D surface. Assuming there are sufficient twisting and bundling in the Litz wire, the net current through each of the turn are the same, which is $I_{coil}/n$, where n is the number of strands and $I_{coil}$ is the total coil current. Fig. 2 shows the FEA based current distribution $|I_{coil}|$ for n=100, at $f$=10 MHz. The results shows that the outer strands experience much higher density than the inner strands due to proximity and skin effect. For simplicity of design, the system is modeled as rectangle coil. As the number of strands increases, the overall resistance of the coil will reduce. Fig. 3 shows the coil resistance vs number of strands plot for AWG44 and AWG46 strands at 10 MHz frequency. The highly extrapolated results indicate that, 10000 strands of AWG48, which is costly to build, would result in 0.5 Ohm coil resistance. Such high resistance results in a much lower quality factor. Therefore, Litz wire might not be an ideal candidate, and alternate coil options with copper tube and copper foil were explored.

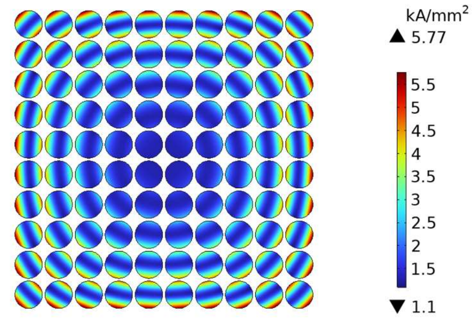



Fig. 2. Current distribution in the Litz wire strands for a single turn twisted litz wire.

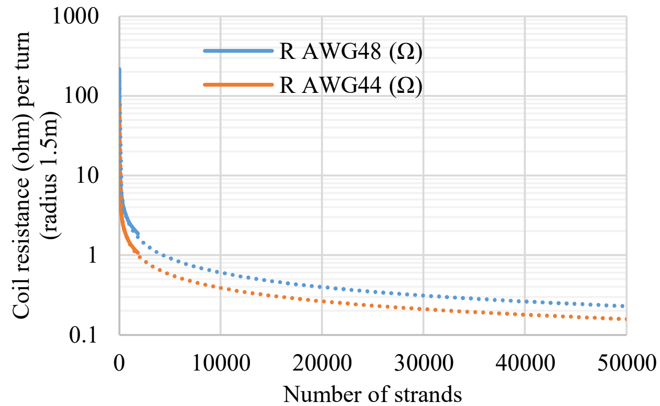



Fig. 3. Variation of the resistance of a single turn Litz wire with different number of strands

**Copper Tube and Foil**

Copper tube has been previously investigated for high frequency wireless charging systems. At high frequency, the currents in the copper tube gets concentrated on the surface due to the skin effect. Due to the proximity effect the current distribution gets further variation on the tube-surface. A 2D FEA model was developed to simulate the resistance of the copper tube for varying number of turns, and tube radius, as shown in Fig. 4. The results show that, the copper tube provide a relatively lower resistance than the Litz wire.

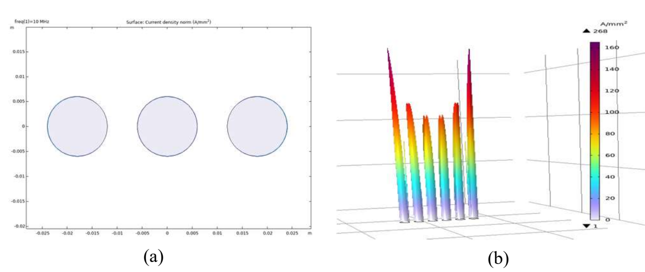



Fig. 4. (a) 2D FEA model of the copper tube with 3 turns, and (b) highly nonuniform current density plot on the copper tube with 5 turns.

As the tube radius becomes larger, it will require a large amount of copper to make the coil, while only a fraction of the copper tube surface will effectively conduct the current at 1-10 MHz Alternatively, a copper foil would provide the similar resistance with much smaller amount of copper and allowing much better design and prototyping flexibility.

The comparative study was conducted between the copper tube and copper foil, and finally the copper foil was selected. One of the most significant benefits of the copper foil is that it allows to make an integrated capacitor withing the coil winding, as shown in Fig. 6.

### *C. Evaluation of the Magnetic Material*

The Mn-Zn based power ferrites are widely used in the high-power wireless charging systems, which operates withing a few hundred kilohertz frequency. There are large number of materials available for that frequency and power range. For high frequency applications, especially above 1MHz frequency, the NiZn ferrites are more suitable. There are various classes of NiZn ferrites for different frequency range from 1 MHz to 10 MHz [6]. As the frequency increases, the loss density in the ferrites limits the maximum peak flux density the ferrites can be operated. Commonly, a loss density of up to 400 $kW/m^3$ can be thermally tolerated in the ferrite with natural convection. For that limit of loss density, the 4F1 materials can be operated for up to 10 mT, which is much lower compared to its saturation flux density of approximately 250 mT. Therefore, the use of ferrite for such high frequency high power system needs to be investigated more critically, considering not only the power requirement, but also for shielding requirement.

Fig. 5 shows the coupling coefficient vs coil radius plot for 10 m airgap and varying combinations of ferrite backing on the primary and secondary side. The plot indicates that if the coil radius is 1/4th or smaller than the airgap, the effect of ferrite is minimal, considering then enhancement of the coupling coefficient.

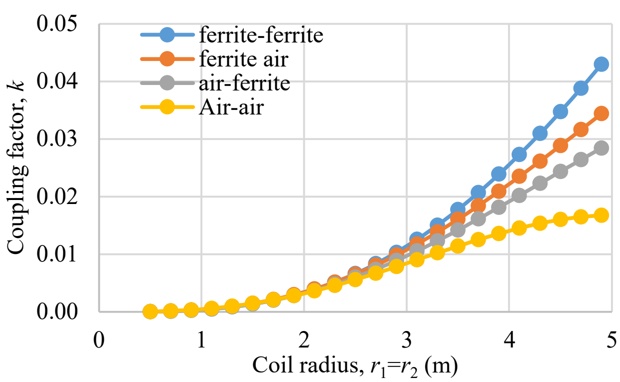



Fig. 5. Variation of the coupling coefficient against coil radius with and without ferrite cores.

### *D. Tuning and Capacitor Design*

Wireless charging systems include a transmitter coil, receiver coil, tuning capacitors and power electronics converters. These systems operate at high frequency at or near resonance to maximize power transfer distance. High voltages appear across the inductors and capacitors. Use of discrete components reduces efficiency, increases system complexity and in order to avoid these issues, in this work, the capacitor is integrated with the coil as shown in Fig. 6. A series-series tuning method was adopted for its simplicity of manufacturability with coil-integrated design. Both the primary and secondary coil and tuning are of same dimensions.

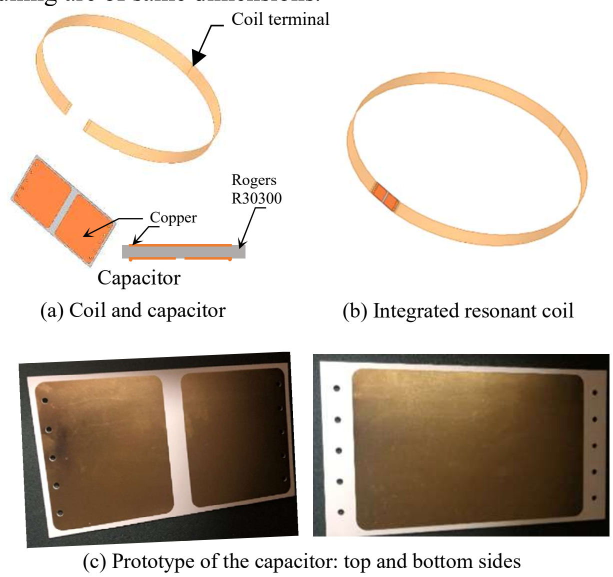



Fig. 6. (a) Coil and capacitor assembly, (b) integrated resonant coil and capacitors, and (c) prototype of the capacitor.

The coil turn is split into two half turns and the capacitor is connected to each half turn. This implements a series L-C system. The capacitor is made from Rogers R30300, with a dielectric constant of 3. In order to ensure a higher breakdown voltage, the capacitor is implemented so that the full voltage is applied across double the dielectric thickness. The fabricated capacitor is shown in Fig. 6(c). Measurements from the impedance analyzer agreed with the 3D finite element prediction of 130 pF.

### *E. Electromagnetic Field Emission*

Electromagnetic field emission is one of the main concern for such long distance magnetic field. Fig. 7 shows different standard limits on the magnetic field emission. In this study, the ICNIRP 2010 pubic limits are adopted, which shows a $27\mu T_{rms}$ limit for publicly accessible area. While the publicly accessible area depends on the application environment, in this study, a safety area is defined with the magnetic flux density is lower than 27μT. The FEA analysis shows that the flux density drops below that limit only 200mm away from the coil for 1 kW power transfer, as shown in Fig. 8.

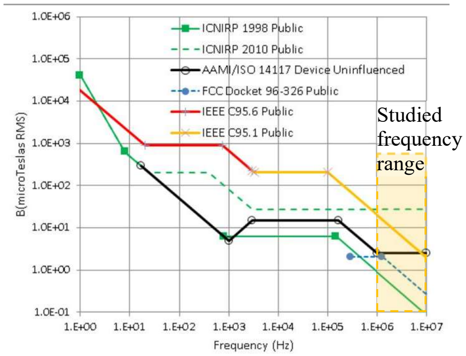



Fig. 7. Different standard limits for the magnetic field emission [7].

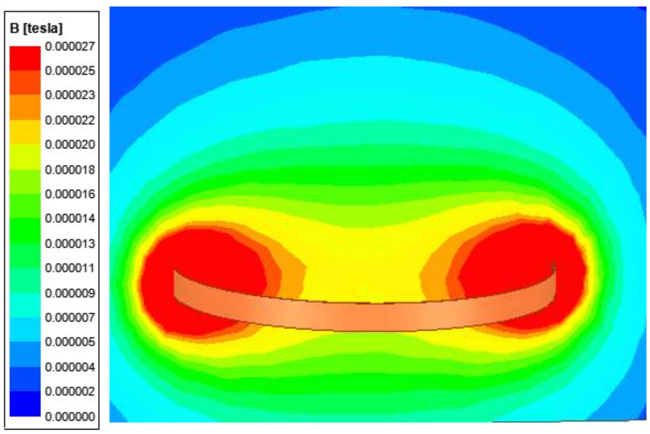



Fig. 8. 3D FEA simulation of magnetic field outside the coil. The flux density drops under 27uT from 200mm away from the coil.

The schematic diagram of the studied system is shown in Fig. 9. The primary and secondary coils are series compensated. The self-inductance of both the coils is 4.39 µH and the resonant capacitance is 130 pF.

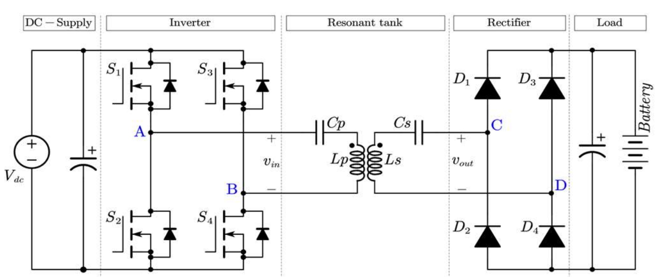



Fig. 9. Schematic diagram of the developed series-series compensated wireless power transfer system.

## III. Experimental Setup

A laboratory prototype was built to transfer 1 kW power at a distance of 3 meters, as shown in Fig. 10. The transmitter and receiver coil had a measured resonance frequency of 6.45 and 6.6 MHz. The inverter and rectifiers were built placed close to the coil to minimize the variation of the coil inductance and capacitance due to the additional lead-wire. Fig. 11 shows the GaN based inverter and the rectifier assembly with the liquid cooled copper heat-sink.

## IV. Conclusions

In this paper, the design method of a multi-megahertz high power inductive wireless charging system is presented. Different coil analysis shows that the copper foil shows better performance and material utilization than Litz wire and copper tube at such high frequency. The tuning design presents a highly integrated custom capacitor design. The experimental section presents the prototyped test setup including the copper foil-based couplers, and GaN based inverter, and rectifier.

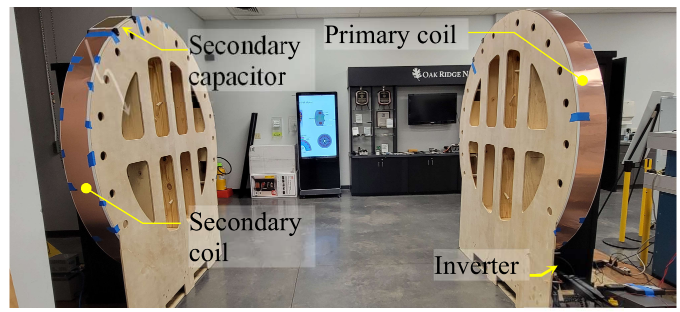
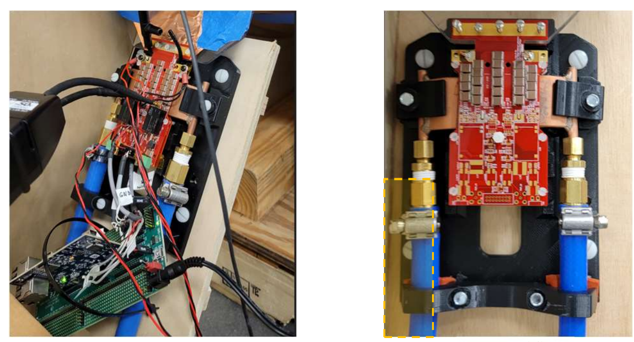



Fig. 10. The experimental setup with primary and secondary assembly with coils, compensation capacitors, inverter, and rectifier.



(a) Inverter (a) Rectifier

Fig. 11. GaN-based high-frequency power electronics assembly: (a) inverter and (b) rectifier.

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