Capacitive Power Transfer for Wireless Charging of a Smartphone

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Abstract  
This paper provides an overview of the work completed to produce a wireless power transfer system using a capacitive coupling circuit topology. A state of art circuit compensation network has been employed to evaluate the efficiency and possible applications for using capacitive power transfer for low-power applications rather than the already commercially available inductive power method. This paper provides an overview of the parameters required to design and build a capacitive power transfer device as well as some state-of-art research in the field. At the time of writing, the project is beginning its prototyping and testing.

1. Introduction  
Wireless power transfer (WPT) is a hot topic at present, with many multi-national companies heavily investing into research and development of low and high power systems for a variety of applications including; Smartphone charging, Portable/Personal electronics charging and most recently Electric Vehicle (EV) charging [1].

Most WPT methods are associated with electromagnetic induction which includes using inductors and/or capacitors to transfer some electrical energy wirelessly [2]. Inductive power transfer (IPT) is the most commercially available method of wirelessly transferring power and has been employed by major personal electronic companies such as SAMSUNG ELECTRONICS CO., LTD.[3] to enable wireless charging of their high-end smartphones.

Capacitive power transfer has only gained research and development momentum since 2008, but this method of WPT has several characteristics which supersede IPT capabilities including, its ability to transfer power through barriers such as metal without significant losses [4]. Traditionally, methods of wireless power transfer using capacitive coupling proved inefficient over large transfer distances while also requiring very high voltages to be applied on the coupling plates thereby, limiting the applications to be used commercially [4].

Figure 1 provides a graphical illustration of the transfer efficiency when comparing varying gap distances and power levels of both IPT and CPT methods. The circuit topologies associated with both IPT and CPT are quite similar, as they both require a resonant circuit to maintain a voltage which will be applied to the transferring coils/plates to generate either a magnetic or electric field.

This paper proposes a parallel plate capacitive power transfer circuit used for low power applications i.e. <10W. The purpose of this study is to investigate the efficiency of CPT for low power applications when compared to the commercially available IPT method. Analysis of different plate structures and compensation circuits will be analyzed for the given application, and a full breakdown of the proposed circuit designed for prototype demonstration will be discussed.

2. Capacitive Plate Design  
Capacitive power transfer can be modelled using various plate structures including; horizontal parallel plate, vertical parallel plate and series-series plate structures. Misalignment between the transmission and receiver plates reduces efficiency on the series-series and horizontal plate designs but has lesser effect on the vertical parallel plate design [5], [6].

For this project, the design focuses on a horizontal parallel plate design. Using the Maxwell finite element analysis tool, a simulation was produced to determine the various capacitances associated with a parallel plate design. A previous research paper completed in 2016 has a very clear mathematical and illustrative model of the capacitances associated with the design structure [5].

Figure 2: Capacitances associated with Horizontal Parallel Plate Design [5].

\[
C_{\text{in1}} = C_{23} + \left( \frac{C_{12} + C_{14}}{C_{12} + C_{14} + C_{23} + C_{24}} \right) \left( C_{23} + C_{24} \right)
\]
\[
C_{\text{in2}} = C_{24} + \left( \frac{C_{13} + C_{14}}{C_{13} + C_{14} + C_{23} + C_{24}} \right) \left( C_{13} + C_{14} + C_{23} + C_{24} \right)
\]
\[
C_M = \frac{C_{23} C_{24}}{C_{23} + C_{24}} + C_{13} + C_{14} + C_{23} + C_{24}
\]

Figure 3: Mathematical model of Mutual and Self Capacitances associated with CPT [5].

Figure 1: System output power versus air-gap separation distance [4].
3. Circuit Design

Following calculations of capacitances, the next step of the design process is to calculate a compensation circuit that will resonate high voltages onto the coupling plates thereby producing an electric field between the transmitter and receiver plates.

The most common resonant circuit is an inductor connected in series with the coupling capacitor, but if the self-coupling capacitances are very small, this will result in a very large inductor and switching frequency. Hence, an LC compensation circuit will be used where an external capacitor is added in parallel with the coupling capacitor, to increase the self-capacitance and thereby reduce the switching frequency and required inductor. The circuit model can be seen in Figure 4.

In summary, use equation (1) to calculate the total self-capacitance of the parallel plates. These results can then be entered in formula (2) to determine the coupling coefficient (Kc) of the plates. If Kc < 1 then the plates are loosely coupled. The resonant circuit model on both the transmitter and receiver side should be the same, and hence L1 = L2 and C1 = C2.

Equation (3) provides the resonant frequency of the system at a specified DC input and output voltage and a predefined output power rating. The equations provided below are adapted from reference [5].

\[
C_1 = C_{ext} + (C_{m1} - C_m) \quad (1)
\]

\[
K_c = \frac{C_m}{\sqrt{C_1 x C_2}} \quad (2)
\]

\[
W_c = \frac{V_{in} x V_{out} x C_m x (1 - K_c^2)}{C_1} \quad (3)
\]

\[
L_1 = \left( \frac{1}{W_c x \sqrt{1 - K_c^2}} \right) \quad (4)
\]

A DC input and output are required and hence an DC-AC inverter is required to apply a AC voltage onto the resonant inductor and a AC-DC rectifier is required on the receiver side to allow a DC voltage output to the load. The output signal from the inverter and input signal passed into the rectifier can be analyzed in Figure 5. The circuit model including the design specifications of the proposed circuit is provided in Figure 4 and Table 1.

![Figure 4: CPT Circuit Model [5]](image)

![Table 1: Circuit Model Specifications](image)

8. Conclusion

Using LTSpice software simulation tool to model circuit, it has revealed that using a higher switching frequency proves inefficient as it reduces the efficiency of the system, but using a switching frequency below 1 MHz results in a compensation network too large for a low power application as it results in air-gap voltage between the plates exceeding 1 kV.

Therefore, through various simulations, a medium was chosen that provided a switching frequency which provides >80% efficiency while also using a resonant circuit that is within the real-world limitations of air-gap voltage transfer to be used for a commercial product.

9. References


