# Capacitive Wireless Power Transfer System Applied to Low-Power Mobile Device Charging

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***Abstract*—Wireless Power Transfer (WPT) technologies are most popularly based on inductive coupling (IPT), using magnetic fields as transfer interface. Recently, studies have been published on capacitive coupling (CPT), through electric fields. CPT has small power density, due to low coupling capacitance, however, it also features reduced EMI shielding requirements, coupling through metal barriers, simpler coupling structure, lightweight and lower cost. This paper presents a mobile device charging application for the capacitive WPT technology. Using LC resonance, the system achieves 90% simulated efficiency with 5.7pF coupling capacitance. The power level for this application is 5W.**

***Index Terms*—capacitive power transfer, mobile device charging, wireless charging, wireless power transfer**

## I. INTRODUCTION

Wireless Power Transfer (WPT) has been gaining a lot of attention as an easy-to-use and effective way of delivering energy to devices without the use of cables. Reaching from low power applications (below 5W) to higher powers of charging electric vehicles, near-field WPT systems are either inductive or capacitive coupled. Most applications currently focus on the inductive technology and use magnetic fields between coils to transfer energy. Capacitive, on the other hand, couples through electric fields, allowing reduced EMI shielding requirements and the capability of transferring energy through metal barriers. In addition, there is no complex coil configuration or need for flux guidance materials, which makes the system less expensive and possibly more compact [1].

Previous research results show low-power transfer with higher coupling capacitance (above 60pF) and highlight difficulties when using small capacitive interfaces [2]-[4]. However, the approach described in this paper is based on a recent research that introduced a new capacitive WPT system and features 5.7pF coupling capacitance that would allow up to 30W transfer power [1].

Wireless power is especially appealing because it makes charging mobile devices as easy as dropping them down on a predetermined place, not requiring the user to have a cord to plug it in; especially if made cheap, efficient and effective. Therefore, capacitive WPT, opposed to inductive, is cheaper, simpler and more efficient.

Current similar commercial products use inductive technology and show around 85% efficiency using "Qi" standards [5] over a gap of typically 5mm to 40mm.

In this paper, a mobile device charging application will be presented for the recently introduced Capacitive Wireless Power Transfer System with low coupling capacitance [1]. That includes low power theory and software simulation aiming for the described power transfer density of 6.36kW/m ²and power transfer per unit capacitance of 5.52W/pF.

## II. COMMERCIAL INDUCTIVE WIRELESS POWER CHARGERS

Most current commercial products use the inductive approach, and consist of a transmitter and a receiver circuit, separated by an air gap, as the example shows in Fig. 1. Typically, the transmitter consists of a power supply (either AC or DC) followed by a power conversion unit that feeds a controlled frequency AC signal into a coil, generating a magnetic field. Secondly, a receiver coil must be aligned with the transmitter at a given distance in order to have electric current induced by that magnetic field. That current is once again converted into either AC or DC and filtered in order to provide an output voltage and current [6].

The transmitter and receiver must be aligned and should have some flux directing material, such as ferrite, to maximize magnetic coupling and power transfer. Shape and size of the inductors must also be taken into account for the same reason [7]. The receiver device must have the appropriate hardware to support wireless charging. A device without the appropriate coil cannot charge wirelessly. [8]

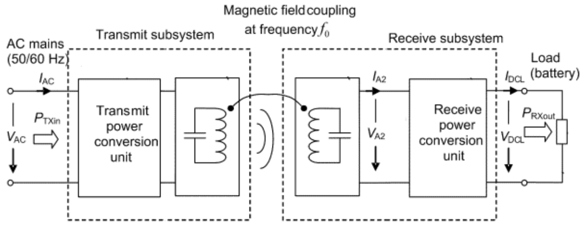


Figure 1. Wireless inductive power transfer example [9].

Furthermore, any metal object between the coils will disturb the power transfer and possibly disrupt it completely.

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Currently, similar versions of this architecture are being commercialized by major companies such as Microsoft, Samsung and LG, and use one of the three most common standards available: Qi, PMA (Power Matter Alliance) Powermat, and A4WP (Alliance for Wireless Power). Fig. 2 shows commercial examples of the inductive approach.

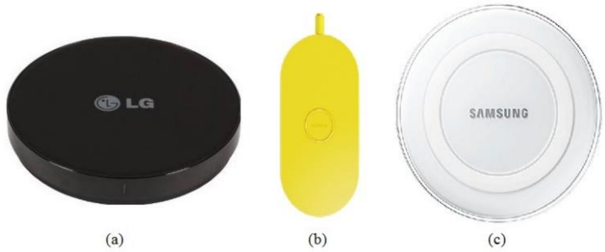


Figure 2. Examples of commercially available inductive chargers: (a) LG [10], (b) Nokia (Microsoft) [11], (c) Samsung [12].

All of the examples given above follow Qi standard. Microsoft states that its Nokia charger has standby power consumption of less than 30mW. Another product "QiPack" [13] declares 90 μW of standby power consumption.

## III. Capacitive Wireless Power Transfer Architecture and Limitations

Capacitive power transfer architecture is similar to the inductive. However, it uses parallel plates and electric field coupling between transmitter and receiver modules. That allows it to transfer power even if metal barriers are placed in the gap. In addition, less EMI shielding is necessary due to electric field's relatively directed nature. "Capacitive WPT systems are also potentially less expensive and more compact, as they do not require ferrite materials for flux guidance and can be operated at higher frequencies without excessive ferrite core losses." [1].

An extensive study of current capacitive systems is reported in [1]. It shows a maximum power per unit capacitance of 0.27W/pF, compared to 5.52W/pF of the proposed system.

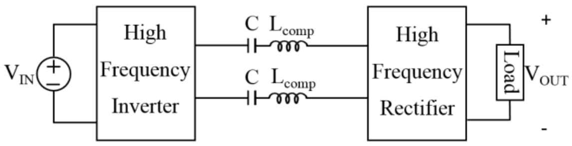


Figure 3. Conventional capacitive WPT system architecture [1].

As seen in Fig. 3, this topology consists of an inverter in the primary side, followed by compensating inductors and flat conductive plates as a transmitter. The secondary side also possesses conductive plates as receivers of the electric field, forming a coupling capacitance (1), followed by a rectifier.

The compensating inductors are designed to tune out the capacitive reactance in the resonant tank, therefore increasing power transfer capability. Neglecting fringing fields, the capacitance, $C$, of the coupling interface is given by:

$$C = \frac{K \cdot \varepsilon_0 \cdot A}{d} \tag{1}$$

here, $K$ is the relative permittivity of the dielectric (approx. 1 for air), $\varepsilon_0$ is the permittivity of space ($8.854 \times 10^{-12}$) [F/m], $A$ is the overlap plate area [$m^2$] and $d$ is the distance between the plates [m].

For a mobile device charging application, the surface available is limited by the size of the devices' surface. Also, in order to have truly contactless power transfer, this architecture requires two pair of plates (Fig. 3).

From [1], the maximum power transfer to be achieved by the system is given in (2), using fundamental frequency analysis and considering inverter operation close to the resonant frequency of the tank, for effective power transfer.

$$P_{max} = \pi \cdot \sqrt{2 \cdot K_{rec}} \cdot V_{OUT} \cdot C \cdot V_{C,max} \cdot f_s \tag{2}$$

In this equation, $V_{OUT}$ is the output voltage of the system, $f_s$ is the inverter switching frequency, $C$ is the coupling capacitance of each pair of plates, $V_{C,max}$ is the peak voltage across the capacitive interface and $K_{rec}$ is the resistance transformation ratio of the rectifier. The value of $K_{rec}$ depends on the type of rectifier. For a full bridge application, $K_{rec}$ is $8/\pi^2$. A derivation of this equation is available in [1].

It can be seen in (2) that the maximum power transfer of the system is directly related to the coupling capacitance of the plates, thus to the surface area available and the distance between transmitter and receiver. "Power transfer in such systems can be enhanced by increasing the switching frequency, or by using high output voltages. However, increased switching frequency can negatively impact system efficiency, and high input voltages are required if high output voltages are used. The combination of high input voltages and high switching frequencies can also make it harder to achieve soft-switching of the inverter switches." [1].

Power transfer is also limited by the maximum allowed coupling plates voltage, $V_{C,max}$. This value is determined by two factors: the magnitude of the electric field directly between the plates, limited by the voltage breakdown of the dielectric and the fringing fields, limited by safety regulations of electric field exposure [14]. Fig. 4 shows the electric field limit for a given frequency of operation.

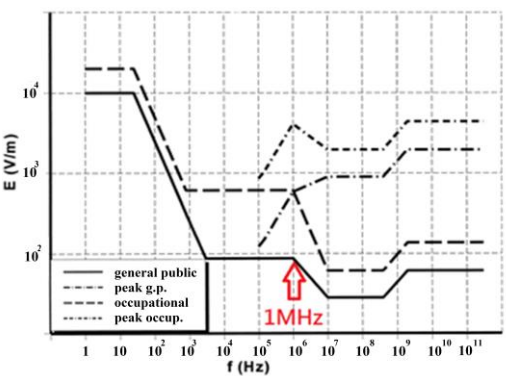


Figure 4. ICNIRP guidelines: for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)' [12].

## IV. Proposed Capacitive WPT Design for Mobile Device Charging Application

Fig. 5 shows the proposed circuit for this application.

This paper assumes an effective transfer surface area available of 50cm², plausible for a typical smartphone size. Therefore, the area of each pair is 25cm². Considering the plate separation to be the thickness of the smartphone casing summed with that of the prototype, the value used in this paper is 2mm.

Using (1), the coupling capacitance results in 11pF.

Inductors *L1* and *L2* are designed to resonate with the plates capacitances *C1* and *C2* (Fig. 5), creating a close to zero impedance loop, which increases the system efficiency and allows higher power output, allowing most of the voltage drop to happen on the load.

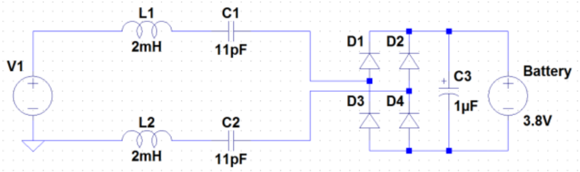


Figure 5. Main circuit structure proposed for a low power mobile device charging application.

Consider the angular frequency $\omega = 2 \cdot \pi \cdot f_s$. The impedance of the capacitor plates $Z_C$:

$$Z_c = \frac{1}{\omega \cdot C} = \frac{1}{2 \cdot \pi \cdot f_s \cdot C} \tag{3}$$

The impedance of an inductor $Z_L$:

$$Z_L = \omega \cdot L = 2 \cdot \pi \cdot f_s \cdot L \tag{4}$$

The resonant point occurs when the impedance of the capacitor plates $Z_C$ and that of an inductor $Z_L$ are equal in magnitude and cancel each other ($Z_C = Z_L$). Using (3) and (4):

$$\frac{1}{2 \cdot \pi \cdot f_s \cdot C} = 2 \cdot \pi \cdot f_s \cdot L \tag{5}$$

Solving for $L$:

$$L = \frac{1}{(2 \cdot \pi \cdot f_s)^2 \cdot C} \tag{6}$$

Following the application in [1], the switching frequency *fs* is 1MHz. Using (6), the value of the inductor can be calculated as 2mH.

Therefore, the circuit proposed is as follows in Fig. 5.

In this circuit, a rectifying bridge and filter are included to illustrate the application.

As seen in Fig. 5, the inverter is represented by a square wave generator $V_{in}$. It is configured to +12V and -12V in a 50% duty cycle with a switching frequency of 1MHz. The input voltage is connected to the compensating inductor *L1*, followed by capacitor *C1* that represents one pair of coupled plates, forming a resonant tank. The loop will be then closed with another resonant tank formed by *C2* and *L2*, representing the transmitter portion of the system. As a load, forming the receiver, a full bridge passive rectifier and a filter capacitor *C3* are connected parallel to the *Load* resistor.

## V. Software Simulation

Simulation software is designed to approach reality as much as possible, through accurate mathematical modeling of the components. Therefore, LTSpice is used for a first step validation of theory, providing useful information before designing and building a prototype.

Only the LC tanks and a load resistor (LCR), compose the circuit used for the first simulation (Fig. 6), in order to tune the switching frequency as close as possible to the resonating point. A 2200Ω resistor represents the load for all simulations. The frequency response analysis returns a resonating frequency of 1.066MHz. If the circuit is operating on any point below or above the resonating, the output response will drop dramatically (Fig. 7). That is due to a higher impedance of the LC tank, occurring in a higher voltage drop across those elements instead of the load. For the second simulation (rectified), the circuit is modeled with a full bridge passive rectifier and a filter capacitor *C3* as seen previously (Fig. 5). Table I shows the parameters used for the simulation.

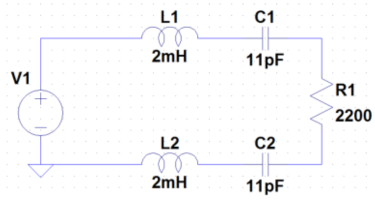


Figure 6. LCR circuit simulated to verify resonating frequency.

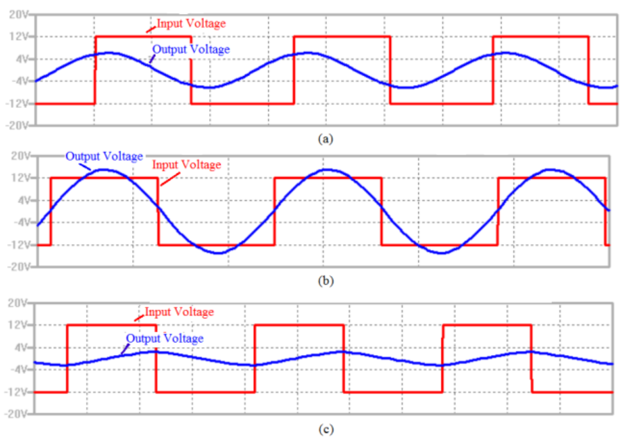


Figure 7. Voltage waveforms as output vs. input for LCR circuit at frequencies: (a) 975kHz, (b) 1.066MHz and (c) 1.4MHz.

TABLE I. Simulation Results

| Parameter | Value | | Unit |
|---|---|---|---|
| Circuit | LCR | Rectified | |
| Plates Voltage ($V_{C,max}$) | 94.3 | 105 | V |
| Switching frequency ($f_s$) | 1.066 | 1.066 | MHz |
| Input Voltage | 11.99 | 11.99 | V |
| Input Current | 4.79 | 5.42 | mA |
| Input Power | 51.64 | 56.7 | mW |
| Output Voltage ($V_{out}$) | 10.55 | 10.59 | V |
| Output Current | 4.79 | 4.81 | mA |
| Output Power | 50.57 | 51 | mW |
| Efficiency | 97.9 | 89.9 | % |

## VI. Prototype Design and Execution

A simple small prototype built to validate each previous theory and simulations consists on the elements previously mentioned. First, two compensating inductors *L1* and *L2*, two capacitors *C1* and *C2* simulating coupling capacitance and a load resistor (Fig. 8).

Figure 8. Prototype LCR circuit with load resistor.

However, due to component availability at the time, the inductors used have 1mH inductance and the capacitors are 12pF. That influences the resonating frequency, according to (5) and solving for $f_s$. After sweeping using the frequency generator, the value for optimal output was 1.018MHz.

Component size and soldering techniques must be observed, since the switching frequency is close to 1 MHz and long conduction paths may cause significant parasitic inductance.

The same frequency variation comparison is made on the prototypes for comparison purposes and shows how the output power responds to frequency variations without (Fig. 9) and with rectifier (Fig. 10).

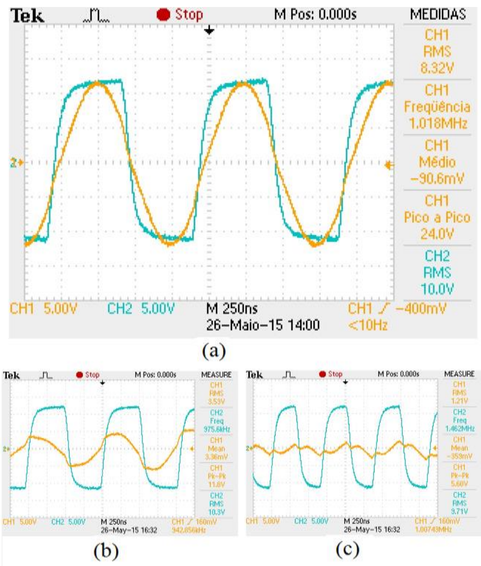


Figure 9. Voltage waveforms as output vs. input for LCR prototype at frequencies: (a) 1.018MHz, (b) 975kHz and (c) 1.4MHz.

The square wave represents the input voltage, as the orange sine-like wave is the output load voltage.

After acquiring the waveforms for the first case, another prototype is built with a rectifier and C filter (Fig. 11). The diodes used in the rectifier are 1N4148.

For this prototype, the frequency response is as follows (Fig. 10). With the addition of the rectifier and its elements, the resonant frequency shifts slightly to 1.137MHz.

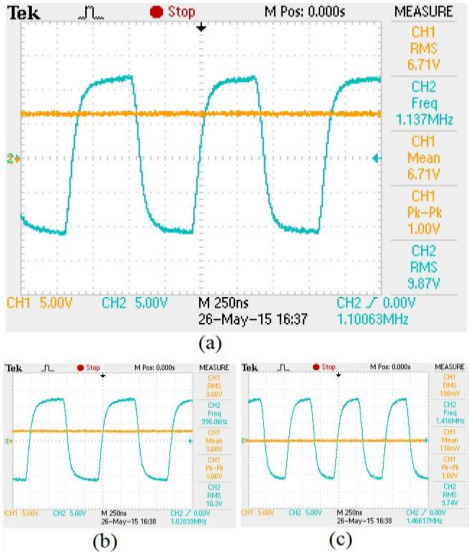


Figure 10. Voltage waveforms as output vs. input for LCR prototype at frequencies: (a) 1.137MHz, (b) 996kHz and (c) 1.4MHz.

Figure 11. Prototype LCR circuit with Load resistor, rectifier and C filter.

## VII. Conclusion

This paper presents a specific application for a newly introduced capacitive power transfer system technology. In comparison to the inductive systems already commercially available, it shows a potential of achieving higher efficiency levels, as well as allowing reduced EMI shielding requirements and the capability of transferring energy through metal barriers, amongst other advantages.

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## REFERENCES


[1] C. Chang, G. G. Da Silva, A. Kumar, S. Pervaiz, and K. K. Afridi, "30W capacitive wireless power transfer system with 5.8pF coupling capacitance," in *Proc. IEEE Wireless Power Transfer Conference*, Boulder, CO, May 13-15, 2015.

[2] M. Kline, I. Izyumin, B. Boser, and S. Sanders, "Capacitive power transfer for contactless charging," in *Proc. IEEE Applied Power Electronics Conference and Exposition*, March 2011, pp. 1398-1404.

[3] L. Huang, A. P. Hu, and A. Swain, "A resonant compensation method for improving the performance of capacitively coupled power transfer system," in *Proc. IEEE Energy Conversion Congress and Exposition*, Pittsburgh, PA, September 2014.

[4] M. Kline, "Capacitive power transfer," Technical report, University of California, Berkeley, 2010.

[5] Wireless Power Consortium. Inductive power transmission. [Online]. Available: http://www.wirelesspowerconsortium.com/technology/basic-principle-of-inductive-power-transmission.html

[6] A. T. Waters, "Wireless charging system using inductive coupling," Honors Baccalaureate of Science in Electrical and Computer Engineering, Oregon State University, University Honors College, USA, 2010.

[7] S. Y. R. Hui and W. W. C. Ho, "A new generation of universal contactless battery charging platform for portable consumer electronic equipment," *IEEE Transactions on Power Electronics*, vol. 20, no. 3, pp. 620-627, 2005.

[8] C. Hoffman. (May 6, 2013). No more cables: How wireless charging works and how you can use it today, *How to Geek RSS*. [Online]. Available: http://www.howtogeek.com/162483/no-more-cables-how-wireless-charging-works-and-how-you-can-use-it-today/

[9] N. P. Cook, L. Sieber, and H. Widmer, "Wireless power transmission for portable wireless power charging," Patent US20100127660 A1, May 27, 2010.

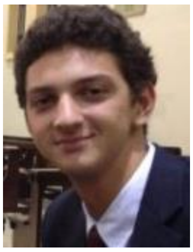
[10] *LG WCP-300 Technical Specifications*, LG USA, 2015.

[11] Microsoft. (2015). Nokia wireless charging plate - Detailed specification. *Microsoft Mobile Devices*. [Online]. Available: http://www.microsoft.com/en/mobile/accessory/dt-900/specifications/

[12] Samsung Electronics America. Wireless charging pad, black sapphire. *Samsung Mobile Accessories*. [Online]. Available: http://www.samsung.com/us/mobile/cell-phones-accessories/EP-PG920IBUGUS

[13] J. Allen, "Road warrior: Retooling the mobile lawyer," *Gpsolo*, vol. 31, no. 4, 2014.

[14] ICNIRP, "Guidelines: For limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300GHz)," *Health Phys.*, vol. 74, no. 4, pp. 494-522, 1998.

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