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Design of a Capacitive Wireless Power Transfer Link with Minimal Receiver Circuitry

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***Abstract*— By applying capacitive coupling, wireless power transfer can be realized between a transmitter and a receiver. To maximize the power transfer, the default design is to construct resonant circuits by applying a compensation circuit, both at the transmitter and the receiver side. However, to obtain optimal power transfer at variable coupling, an impedance matching system or frequency tuning mechanism is necessary at the transmitter and receiver side, requiring data communication between both sides. We present a simple design of the capacitive link that reduces the receiver to the bare minimum: the capacitance plates and the load. All tuning for variable coupling occurs at the transmitter side, therefore lowering the costs and making data communication no longer necessary.**

Keywords*— *analog circuits, capacitive coupling, capacitive power transmission, electromagnetic coupling, wireless power transmission

I. Introduction

Wireless power transfer allows for the charging of electronic devices without the need of a power cord, from high power electric and automatic guided vehicles, to low power biomedical implants and consumer applications [1-3]. For the latter, the main advantage is the improvement of user-friendliness: the user can simply put the device on a charging pad without the need to connect a wire. Additional benefits are the improved, clutter-free aesthetics by using no wires, and increased durability, since the regularly connecting and disconnecting of the wire wears the cable down. For industrial uses, the most important benefit is the improved safety. Wireless charging is a spark-free and totally waterproof procedure, often desirable properties in hazardous or moist industrial environments.

Applications on the market that offer wireless charging are all based on inductive charging: the magnetic field between coupled inductors is used to transfer energy wirelessly. However, research and development on capacitive (or electric) coupling, that uses the electric field to transfer power wirelessly, is steadily increasing. Drawbacks are the higher voltages, frequencies and field strengths compared to inductive wireless power transfer [4,5]. However, it also has several competitive advantages, such as [5,6]:

- Lower power losses.
- Less heat production.
- Lower production costs.
- Less weight of the system.
- Reduced electromagnetic interference for short distances.
- Metal objects between the transmitter and receiver do not hinder the power transfer significantly.

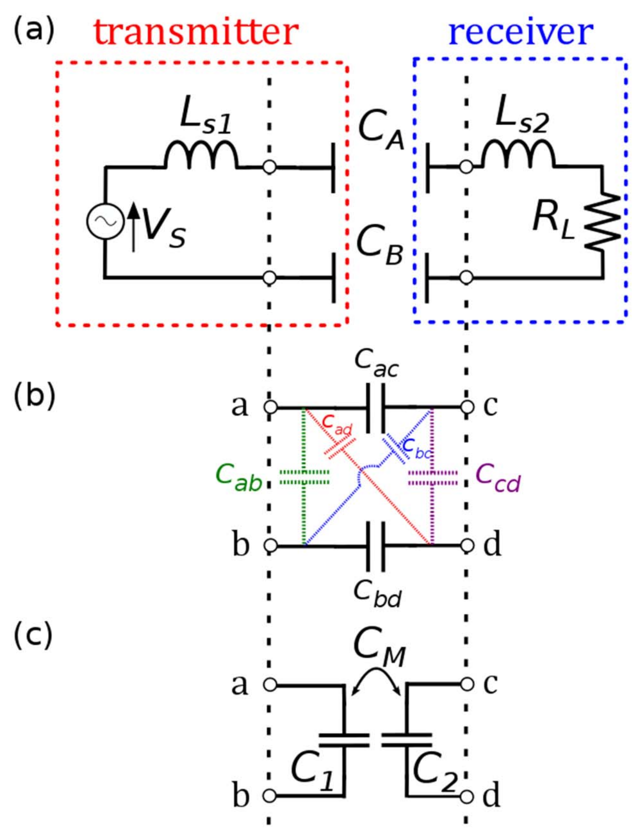

Fig. 1. (a) Overview of a general capacitive wireless power transfer system with capacitances C_A and C_B, time-harmonic voltage source V_S, compensating inductors L_{s1} and L_{s2} and load R_L. (b) Overview of the cross-capacitances (c) Equivalent circuit for wireless link.

A basic wireless capacitive link consists of two capacitances C_A and C_B (Fig. 1a). One plate of each capacitor is part of the transmitter, the other one belongs to the receiver part. Cross-capacitances are present between the plates as indicated in Fig. 1b and are named through their subscripts, e.g., C_{ab} is the capacitance between the two transmitter plates.

In order to obtain an efficient power transfer at the working angular frequency ω_0, the default strategy is to realize a resonant circuit, as well at the transmitter as at the receiver side [6-8]. Generally, this is done by adding a resonant coil in series or in parallel. More complicated compensation circuits include a PWM converter, a power amplifier, LC or LCLC based topologies [9,10].

Fig. 1a shows the circuit where an inductor is added in series at the transmitter and the receiver side to construct the resonant circuits. In practice, a real capacitive wireless power transfer system will include other network elements as e.g., a rectifier-stabilizer, supply regulator, power conditioner,... For this work, we neglect those systems because we want to study the properties of the wireless power transfer link itself, without the influence of other network elements. For an excellent overview of the different compensation techniques that takes into account the remote electronics, we refer to [9,10].

At variable coupling, either due to varying vertical distance or due to lateral alignment changes, the value of the compensation network or operating frequency would have to change for each position to obtain optimum power transfer at the transmitter and the receiver side. This not only requires an impedance matching system or frequency tuning mechanism at the transmitter and receiver side, but also data communication between both sides.

The design would be greatly simplified if at varying coupling only modifications at the transmitter side were necessary, so that the receiver can stay invariable and no data communication is necessary between transmitter and receiver. Moreover, since more receivers as transmitters are fabricated for most wireless power transfer systems, the simpler design of the receiver could for certain applications lead to a lower system cost, in particular for multi-receiver applications [11]. We present a design that simplifies the receiver to the bare minimum: the capacitance plates and the load. All tuning for variable coupling occurs at the transmitter side.

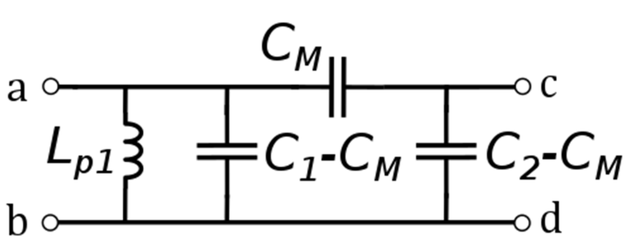

Fig. 2. Step 1: the parallel circuit of L_{p1} and C_1-C_M which is, at resonance frequency ω_0, equivalent to an open circuit.

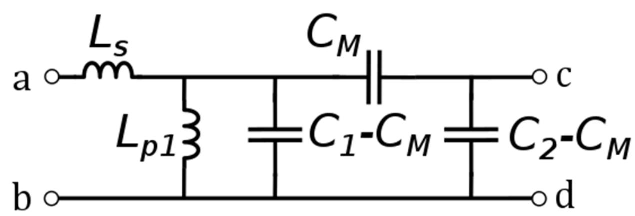

Fig. 3. Step 2: the series circuit of L_s and C_M which is, at resonance frequency ω_0, equivalent to a short circuit.

II. METHODOLOGY

An analogous simplified design, but for inductive wireless power transfer, was developed by Costanzo et al. [12]. They realized a matched wireless power transfer link for a lossless configuration by using a single inductive coil at the receiver side. All required compensating capacitances for this inductive link are located at the transmitter side, allowing for a simpler design and the non-necessity of data communication between transmitter and receiver when tuning is required due to variations in the coupling.

Here, we follow the same methodology, but first replace the wireless link of Fig. 1a and 1b by its equivalent circuit of Fig. 1c with C_1 and C_2 the capacitance of transmitter and receiver, respectively, and C_M the mutual capacitance. The relation between the configuration of Fig. 1b on the one hand, and C_1, C_2 and C_M on the other hand is well described [13]. The coupling factor k of the wireless link is defined as:

$$k = \frac{C_M}{\sqrt{C_1 C_2}} \tag{1}$$

We replace the wireless link by its equivalent pi circuit. In the first step, we compensate the capacitance C_1-C_M by adding in parallel an inductance L_{p1} (Fig. 2) given by

$$L_{p1} = \frac{1}{\omega_0^2 (C_1 - C_M)} \tag{2}$$

The parallel circuit of L_{p1} and C_1-C_M is, at the resonance frequency ω_0, the equivalent of an open circuit. This allows us as a second step to easily compensate the reactance of the capacitance C_M by adding an inductance L_s in series (Fig. 3):

$$L_s = \frac{1}{\omega_0^2 C_M} \tag{3}$$

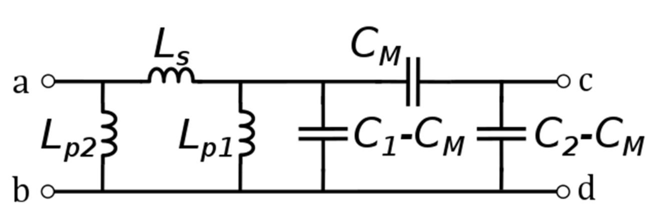

Fig. 4. Step 3: the parallel circuit of L_{p2} and C_2-C_M which is, at resonance frequency ω_0, equivalent to an open circuit.

At ω_0, this series circuit is the equivalent of a short circuit. In the third step, we compensate C_2-C_M by adding an inductance L_{p2} given by (Fig. 4):

$$L_{p2} = \frac{1}{\omega_0^2 (C_2 - C_M)} \tag{4}$$

At the resonance frequency ω_0, the circuit behaves (Fig. 4)

- as a short circuit between node a and c, and between node b and d.
- as an open circuit between node a and b, and between node c and d.

Fig. 5 shows our proposed design: all the reactances of the wireless link are compensated by inductances which are located only at the transmitter side. The receiver only consists of the capacitance C_2 and the load R_L. In this way, all tuning can occur at the transmitter side when the coupling between transmitter and receiver is variable.

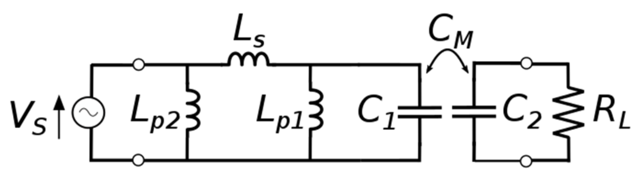

Fig. 5. Simple receiver design of capacitive wireless power transfer system.

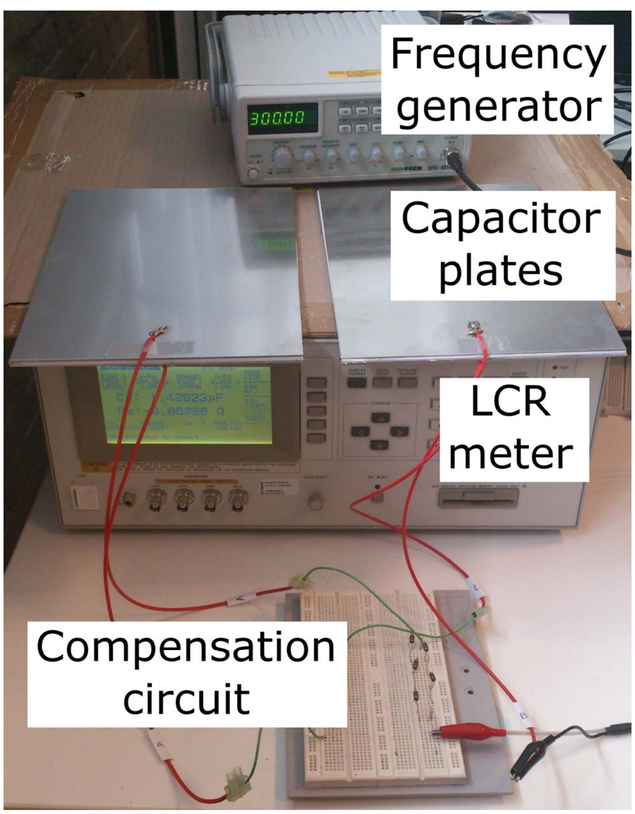

Fig. 6. Experimental setup of a basic capacitive wireless link.

TABLE I. MEASURED QUANTITIES OF THE EXPERIMENTAL SETUP.

Quantity	Value
C_{ab}	2.3 pF ± 0.5 pF
C_{ac}	462 pF ± 0.5 pF
C_{ad}	2.7 pF ± 0.5 pF
C_{bc}	2.7 pF ± 0.5 pF
C_{bd}	415 pF ± 0.5 pF
C_{cd}	2.4 pF ± 0.5 pF
V_S	20.0 V ± 0.05 V
V_{OC}	16.4 V ± 0.05 V
f	300 kHz ± 0.5 kHz

III. CASE STUDY

As case study, we start from a capacitive wireless link with capacitances C_A and C_B (Fig. 1a) with four aluminum plates, each 200 mm x 300 mm x 1.2 mm (Fig. 6). In order to create a dielectric gap of 2.5 mm, we use a plate of polyvinyl chloride. The measurements of the passive components are performed with an Agilent 4285A LCR meter at 300 kHz. The results are listed in Table I, with reference to Fig. 1b.

The open circuit voltage at the receiver, V_{OC}, is measured when applying a harmonic voltage source of V_S = 20.0 V ± 0.05 V peak to peak at a frequency f of 300 kHz ± 0.5 kHz.

From the measured values, the equivalent circuit of Fig. 1c can be constructed, by applying the following equations [6,13]:

$$C_1 = \frac{(C_{ac}+C_{ad})(C_{bc}+C_{bd})}{C_{ac}+C_{ad}+C_{bc}+C_{bd}} \tag{5}$$

$$C_1 = \frac{(C_{ac}+C_{bc})(C_{ad}+C_{bd})}{C_{ac}+C_{bc}+C_{ad}+C_{bd}} \tag{6}$$

$$C_M = \frac{V_{OC}}{V_S}(C_2 + C_{cd}) \tag{7}$$

We find C_1=C_2=220 pF ± 2 pF and C_M=182 pF ± 3 pF. From (1), the coupling factor k can now be determined, resulting in k=82.9 % ± 1.8 %. An overview of the calculated quantities can be found in Table II.

TABLE II. CALCULATED QUANTITIES OF THE EXPERIMENTAL SETUP.

Quantity	Value
C_1	220 pF ± 2 pF
C_2	220 pF ± 2 pF
C_M	182 pF ± 3 pF
k	82.9 % ± 1.8 %

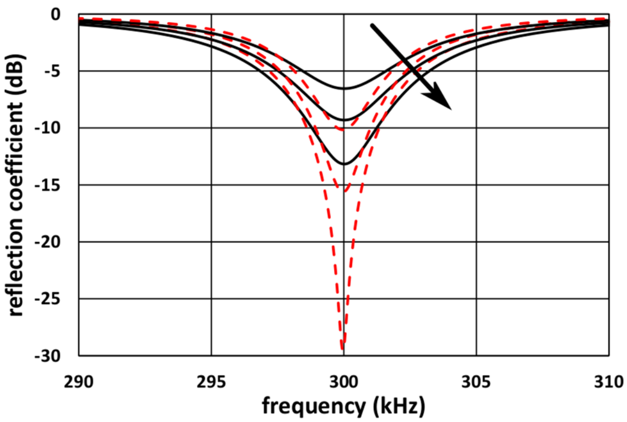

Fig. 7. The reflection coefficient S_{11} for the default (full line) and simple (dashed line) receiver design, for three different coupling factors: k=60, 70 and 80% (arrow indicates increasing coupling factor k).

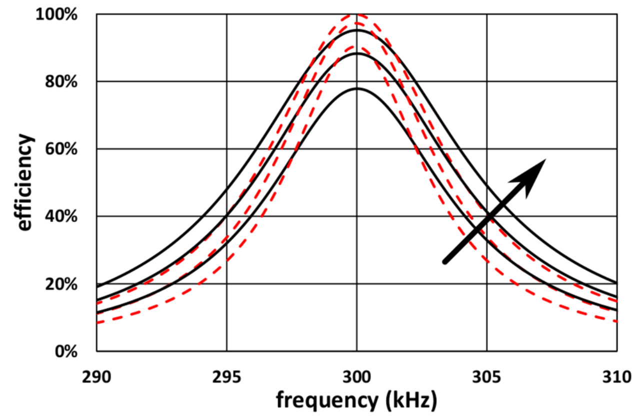

Fig. 8. The efficiency $|S21|^2$ for the default (full line) and simple (dashed line) receiver design, for three different coupling factors: k=60, 70 and 80% (arrow indicates increasing coupling factor k).

We simulate two lossless configurations using the representative values of the wireless link from this case study:

- the "default receiver design" with a compensating series inductance of 1.28 mH at the receiver, corresponding with a resonance frequency ω_0 of 300 kHz.
- our proposed "simple receiver design" of Fig. 5 with all the compensating elements at the transmitter side.

Our goal is to compare the bandwidth and efficiency as function of the coupling for these two configurations. By applying equations (2), (3) and (4) for a working frequency ω_0 of 300 kHz, we find for our example set-up L_s=1.55 mH, L_{p1}=7.41 mH and L_{p2}=1.28 mH.

Fig. 7 shows the reflection coefficient S_{11} for three different coupling factors for both the default and simple receiver design. At first, we notice that the resonance frequency for both configurations is 300 kHz. The higher the coupling factor, the higher the bandwidth. The resonance is more distinct for the simple receiver design.

Fig. 8 shows the power conversion efficiency $|S_{21}|^2$ of the wireless link with a reference impedance R_L and internal voltage source resistance of 50 Ω. As expected, the higher the coupling factor k, the higher the efficiency at each frequency.

As already mentioned, our proposed simple receiver design has the advantage of reduced cost and the non-necessity of data communication between transmitter and receiver. This case study highlights another advantage. We notice that in the lossless case, the simple receiver design attains slightly higher efficiencies as the default receiver design. This is attributed to the fact that our default receiver design only has a resonance compensating inductance at the receiver side and not at the transmitter side. Indeed, at high coupling factors, an additional compensating inductance at the transmitter side would for this case study lead to frequency bifurcation [14], resulting in a lower efficiency at the working frequency of 300 kHz. The undesirable frequency bifurcation is not present here at high coupling when using the simple receiver design. A more detailed study on frequency splitting for near-field non-radiative coupling is out of the scope of this work and we refer to the literature for more details, e.g., [14-17].

IV. Conclusion

We presented a simple design of a capacitive wireless link that reduces the receiver to only the capacitance plates and the load. The advantage of this design is that all tuning for variable coupling can occur at the transmitter side. The receiver can stay invariable, making data communication between transmitter and receiver no longer necessary.

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