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Leakage losses of a capacitive power transfer parallel four plate coupler

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Abstract

In spite of significant research on e.g. compensation circuits, capacitive power transfer is not able yet to match the same power densities as inductive power transfer.Not enough is currently known about capacitive coupling itself. One of the reasons that not much is known about capacitive power transfer with different media is because not much research has been done on it yet. This paper bridges the gap by introducing the capacitive coupling-induced leakage resistance.The leakage resistance is simulated using an analytical approach and with finite element simulations. The results of finite element simulations performed in a power electronics simulation circuit proof that losses in media should not be neglected. Furthermore, this paper shows that losses in polycarbonate are up to 30% of the total power.

1 Introduction

With wireless power transfer (WPT), no cables or connectors are needed to transfer power. This improves user-convenience, safety and robustness. Within near-field WPT, where distances between a few millimeters up to a few meters are covered,there are two main technologies: inductive power transfer (IPT) and capacitive power transfer (CPT). IPT is already widely adapted in the market. Next to IPT, there is CPT, that is barely commercialized. It is an upcoming technology which has advantages over IPT, such as its ability of transferring energy in the vicinity of metal objects. CPT systems currently exist as prototypes and are mainly investigated using air as a medium [1]. In literature, powers of up to 3.75 kW are achieved at frequencies between 600kHz and 13.56 MHz [2].

The CPT coupler is constructed of at least one pair of metal plates between which electric fields transfer energy. For the coupler research proposes different structures, in this paper the four plate parallel structure is used as showed in Fig. 1a [1,3,4]. Literature currently proposes a pi-model to analytically describe the capacitive coupling. This model consists of three ideal capacitors which represent electric coupling between the transmitter and receiver. It allows to determine the coupling coefficient but not to the energy losses in the medium [5]. As a consequence, it does not take losses into account, which makes it not possible to determine the coupling efficiency.

Depending on the application, media, such as water, can be placed between the conductive plates to obtain greater capacity and thus transfer more energy [6–8]. Here the question arises: Will any losses occur in the medium? To answer this question, this work presents and compares two approaches to model the resistive leakage losses of CPT. First, an analytical approach is presented that is based on the relative permittivity values of the dielectric. Next, a model that applies the admittance matrix of the wireless link is given. Finally, to indicate the importance of the influence of the leakage resistance, a power electronic simulation is done in PLECS which shows how much power is lost due to the medium.

2 Capacitive coupler model

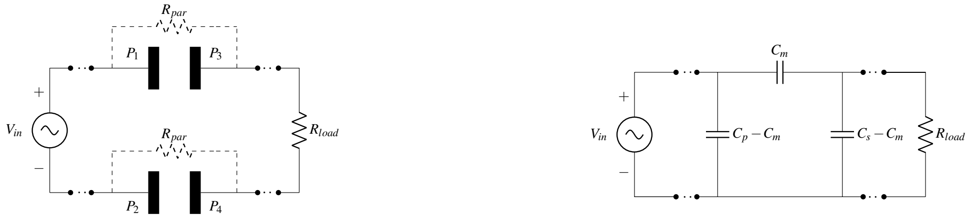
A basic CPT systems consists of a four parallel plate coupler (Fig. 1a). The circuit bears two capacitors in series. However, this is an idealized theoretic approach. In practice, parasitic capacitances occur between the plates. These capacitances are taken into account in the more detailed model proposed in [5]. This detailed model comprises, next to the main capacitance, the leakage capacitances and cross-coupling capacitances. According to [5], this configuration can be transformed to an equivalent pi-model as in Fig.1b. However, these models do not include resistive elements and are not able to estimate the transmission losses. A practical, non-ideal, capacitor is often presented in the literature as in the lumped element model of Fig.2a [9].

Since this study focuses on the leakage losses R_{par} caused by the dielectric medium, the parasitic elements C_{ser}, R_{ser} and L_{ser} are not considered as they depend on the system arrangement and are independent of the medium between the plates. Incorporating R_{par} into the idealized pi-model results in Fig.2b. For clarity: $C_{Tr} = C_p - C_m$ and $C_{Re} = C_s - C_m$, where Tr stands for transmitter and Re for receiver.

3 Leakage losses models

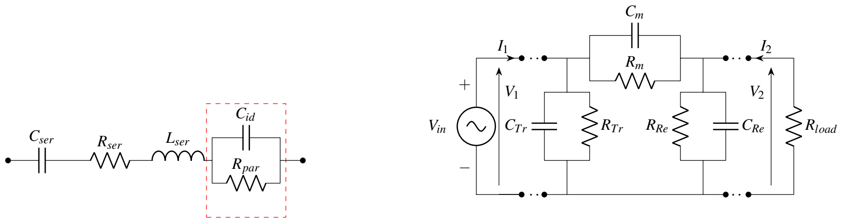
3.1 Permittivity based model

First, an analytical approach is presented that is based on the frequency dependent relative permittivity values of the dielectric. The capacitance C between two plates, housing



(a) **(b)**

Figure 1. (a): Simple CPT four plate structure; (b): Theoretical pi-model



(a) **(b)**

Figure 2. (a): Non-ideal Capacitor model; (b): Pi-model of the CPT system with non-ideal capacitors

a dielectric material between them, is described by [10]:

$$C = (\varepsilon' - j \cdot \varepsilon'') \cdot C_0 \text{ with } C_0 = \varepsilon_0 \cdot \frac{A}{d} \tag{1}$$

C_0 denotes the vacuum capacitance, and $\varepsilon = \varepsilon' - j \cdot \varepsilon''$ the complex relative permittivity of the dielectric material. The relative permittivity consists of a real part ε' and an imaginary part ε'', which gives an indication of how much the dielectric can be polarized.

The complex nature of the relative permittivity introduces a resistive loss R_C into the capacitor. The impedance Z_C of the capacitor is then given by:

$$Z_C = \frac{1}{j \cdot \omega \cdot (\varepsilon' - j \cdot \varepsilon'') \cdot C_0} = \frac{\varepsilon'' - j \cdot \varepsilon'}{\omega \cdot C_0 \cdot (\varepsilon'^2 + \varepsilon''^2)}, \tag{2}$$

with ω the angular frequency. The resistive loss R_C thus equals:

$$\Re(Z_C) = R_C = \frac{\varepsilon''}{\omega \cdot C_0 \cdot (\varepsilon'^2 + \varepsilon''^2)} \tag{3}$$

Note that R_C equals the series equivalent resistance of R_{par} in Fig. 2a.

A drawback of this method, based on Eqn. 3, is that the dielectric properties must be known. The parameter ε' and ε'' depend, i.a., on the frequency, humidity and temperature, therefore they are difficult to determine and the estimate of R_C is inaccurate. Furthermore, to our knowledge, it is cumbersome to gather data for ε' and ε''. The reason is that limited data is available in the literature for the required frequency range [11]. There is no data publicly availably for construction materials such as wood, bricks, insulation material. In this work, the ε' and ε'' data of polycarbonate ($C_{15}H_{16}O_2$), a suitable dielectric for CPT, is used from CST Studio Suite [11]. As can be seen on Fig. 3b and 3a, the parameters vary in function of the frequency which will affect the power losses in the medium.

3.2 Admittance matrix based model

This paper proposes an admittance based model as an alternate approach to consider the losses in the medium. This model applies the admittance matrix Y of the wireless link, which can be easily determined for a CPT setup by either simulation or experimental measurements. The peak voltages phasors V_i and peak current phasors I_i (i=1,2) are defined in Fig. 2b.

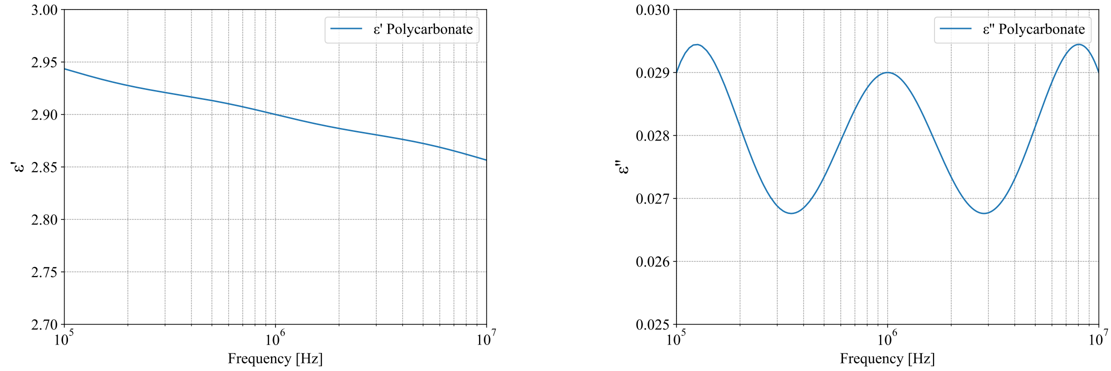
The admittance parameters of the model in Fig.2b result in Eqn.4. The admitances y_m, y_{Tr} and y_{Re} represent the parallel connection of the subscript matching resistor and capacitance in Fig.2b.

$$\begin{bmatrix} \overline{I_1} \\ \overline{I_2} \end{bmatrix} = \begin{bmatrix} y_{Tr} + y_m & -y_m \\ -y_m & y_{Re} + y_m \end{bmatrix} \cdot \begin{bmatrix} \overline{V_1} \\ \overline{V_2} \end{bmatrix} \tag{4}$$

For distances where the capacitive coupling coefficient is approximately equal to one, it can be said that y_{Tr} and y_{Re} are equal to y_m. small [1, 5]. As a result, the admittance matrix can be simplified to:

$$\begin{bmatrix} 2 \cdot y_m & -y_m \\ -y_m & 2 \cdot y_m \end{bmatrix} \Longrightarrow y_m = \frac{1}{R_m + j \cdot X_m} \tag{5}$$

Because of the assumption of a symmetric setup, the admittance of the parallel connection of R_{par} and the capacitance C_{main} between the plates P_1 and P_3, and P_2 and P_4 is called y_{main}. This simplification allows us to say that y_m equals



(a) **(b)**

Figure 3. (a): Real part ε' of the permittivity of polycarbonate ; (b): Imaginary part ε'' of the permittivity of polycarbonate

$\frac{1}{2} \cdot y_{main}$. This corresponds to what was proposed in literature C_m equals $\frac{1}{2} \cdot C_{main}$ but is extended here taking into account the parasitic leakage resistance R_m, which is equal Eqn. 3, caused by the material [5].

4 Simulation results

Based on the models, this section demonstrates the importance of determining the leakage impedance by means of simulations. A 1kW four plate CPT system with polycarbonate ($C_{15}H_{16}O_2$) medium is simulated for frequencies from 100 kHz up to 10 MHz for a distance between the plates of 5 mm.

4.1 Finite-element simulations

To compare the permittivity- and the admittance-model, finite element simulations are performed to obtain a result for the admittance model. Fig.4 shows the simulation used to determine the admittance parameters, and thus the mutual impedance of the capacitive coupler. There, two ports are used with an impedance of 50 Ω. A resistance is placed as a load on the receiver side.

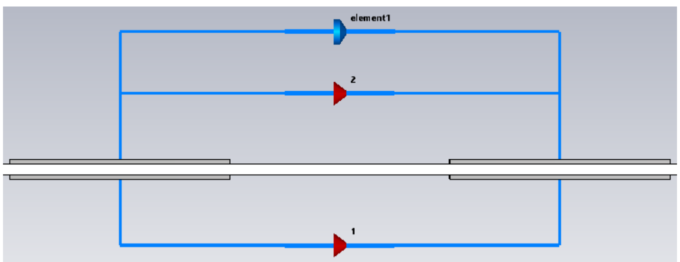


Figure 4. CST Studio model of four plate structure capacitive power transfer system with port 1 at transmitter side (in red), port 2 (in red) and the load resistance as lumped element (in blue) at receiver side

Fig. 5 shows the simulation results for the leakage resistance that equals R_C with open receiver side. For that, a practically infinite load resistance of 100 MΩ is employed. The simulation compares the permittivity based model, defined by Eqn. 3, and the admittance based model, defined by Eqn. 5. The grey area in the figures represent the practical used frequency range, between 600 kHz and 6.78 MHz, for CPT systems [1]. The maximum deviation between both models is 17.3%. However, this occurs at a frequency smaller than 500 kHz. For frequencies within the practical frequency range of CPT, the maximum deviation is around 13%. As the stated theoretical formula of the permittivity based is for single plate capacitors and given the assumptions made in this paper, these results are acceptable as indicating that the energy transfer cannot be considered ideal and losses occur.

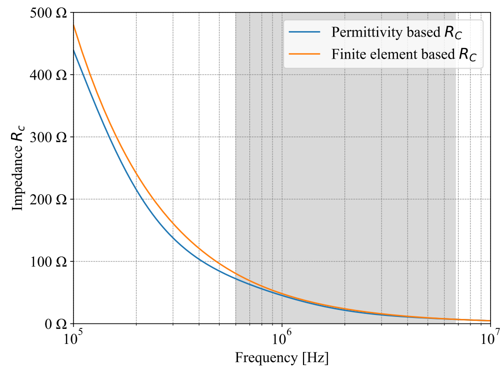


Figure 5. Permittivity based model vs finite-element simulation results for R_C

4.2 Power electronic simulations

To give an indication of how much power loss is involved for R_C at a practical frequency range, between 600 kHz and 6.78 MHz, CPT system, which aims to transfer 1 kW over 5 mm in polycarbonate, is simulated in a power electronics model in PLECS. To achieve an optimal energy transfer from transmitter to receiver using electric fields, the system must operate in resonance. To achieve resonance, a compensation circuit at transmitter or/and receiver side is needed. This model uses a primary induction compensation circuit and is represented in Fig. 6. During the simulation, the primary inductance adapts to the frequency of the electrical field so the system remains in resonance.

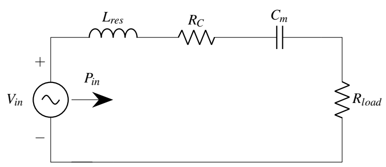


Figure 6. Power electronic simulation model in PLECS

Fig. 7 shows the input power and power loss by the leakage resistance R_C. It shows that at lower frequencies, the power loss across the leakage resistance is 30% of the total power. As mentioned earlier, as the frequency increases, the leakage resistance decreases, resulting in lower losses for polycarbonate. At higher frequencies from 5 Mhz onwards, the losses in the medium will be less than 6%. The increase of the used system frequency cannot continue indefinitely as the switching losses in the inverter become too large as indicated in [6]. In practice, an optimum must be sought where switching losses are limited while minimizing losses in the medium.

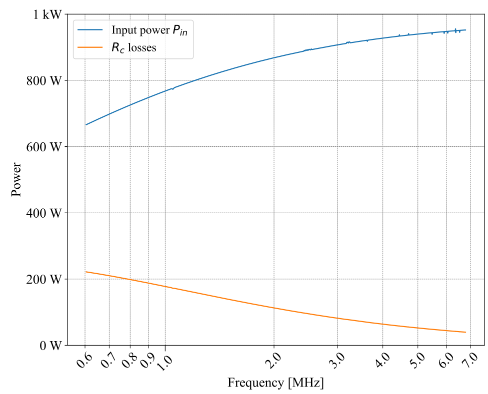


Figure 7. Input power versus power loss caused by leakage resistance

5 Conclusion

During this research, it became clear that, to the best of our knowledge, there is currently insufficient information regarding the electrical properties of materials that could serve as a medium for capacitive power transfer. Nevertheless, two models, based on analytical expressions, are proposed that exceed the state of research by considering losses in the medium. The models are compared to each other, which results in a maximum deviation of 12% in the practical frequency range. In the simulations, it becomes clear that as the frequency increases, the leakage resistance decreases and thus losses also decrease. A use case of a 1 kW capacitive power transfer system reveals that the losses caused by the medium depend on the frequency and range from 30%, for low frequencies, to 5%, for higher frequencies, of the total power input. This raises a new research question: How much of these losses can a medium handle? Further investigation should be done by doing a thermal assessment of a capacitive power transfer system.

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