User-Defined Power Distribution for Capacitive Wireless Power Transfer With Multiple Receivers

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***Abstract*—Capacitive power transfer allows for wireless charging of multiple devices at once. In a typical system, the amount of power delivered to the different devices is determined by their position and distance to the transmitter. However, it can be beneficial to prioritize the charging of the devices. For example, if a critical device has a low battery status, the system should be able to prioritize the charging of this specific receiver above other nearly fully charged devices, even if the position or distance of this receiver is not optimal. In this work, we present a methodology to realize a user-defined power distribution to an arbitrary number of receivers within a capacitive wireless power transfer system. It applies admittance inverters in each receiver to regulate the power delivery. The results are numerically validated in the simulation program LT Spice on an illustrative system.**

***Index Terms*—wireless power transfer, capacitive coupling, impedance matching, multiple receivers, power distribution**

I. INTRODUCTION

By means of capacitive power transfer (CPT), energy can be delivered wirelessly to electronic devices. It applies a high-frequency electric field as a medium to realize power transfer. The wireless link itself consists of conductive plates, which facilitate the charging of multiple receivers by a single transmitter [1].

To date, CPT systems are typically optimized for either maximizing the efficiency or maximizing the amount of power transfer to the receivers [2]. By impedance matching, the optimal load for each scenario can be selected [3].

However, in practical situations, the need can arise to diverge from the optimal efficiency or power scenario. For example, consider a CPT setup with multiple receivers. Some of the devices are almost fully charged whereas others are nearly depleted. In this case, it would be advantageous to prioritize the charging of the nearly depleted devices above the almost fully charged ones. In other words, a user (or control algorithm) should be able to impose a specific power distribution for the different devices. In this way, it is possible to prioritize the charging of certain applications above others in a multiple-receiver setup.

In this work, we apply an admittance inverter at each receiver to regulate the relative amount of power each device receives. Consider for example a CPT system with two receivers. By choosing a specific value for the characteristic admittance of the inverters, we can impose that the first device receives for example 30% of the power and the second device the remaining 70%. By varying the characteristic admittance of the inverter, another power distribution (e.g., 50%-50%) can be achieved. This has already been demonstrated for *inductive* wireless power transfer [4], [5], but to the best of our knowledge, no analysis for CPT has yet been performed.

First, we represent a CPT system with multiple receivers by its equivalent circuit. Next, we analytically prove our methodology for achieving user-defined power distribution. We obtain general equations that determine the values for the admittance inverters, given a required power distribution. This expression is a function of the coupling between the transmitter and each receiver, allowing imposed power distributions for varying couplings. Finally, our analytical results are numerically validated on an exemplary CPT system via the circuit simulation software LT Spice.

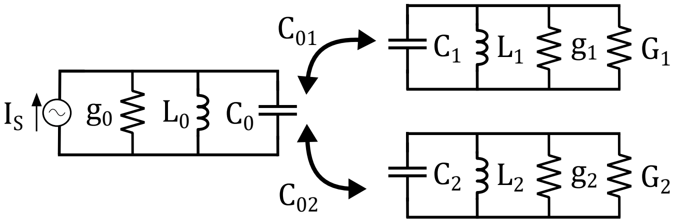

Fig. 1. Basic equivalent circuit of a CPT system with one transmitter and two receivers.

II. METHODOLOGY

A. Equivalent circuit

First, we demonstrate the methodology for achieving user-defined power distribution for *two* receivers. In the next section, we present the procedure for *any* number of receivers.

We consider a CPT setup (Fig. 1) with one transmitter (subscript 0) and two receivers (subscripts 1 and 2). The transmitter is powered by a current supply with peak current phasor I_S and operating angular frequency ω_0. Both receivers have purely resistive loads, represented by the conductances G_n (n = 1,2). It has been shown [6] that the wireless coupling can be depicted as capacitors C_i (i = 0,1,2) coupled by mutual capacitances C_{0n}. The coupling factor k_{0n} indicates the strength of the electric coupling. It is a dimensionless value between zero and unity, defined by:

$$k_{0n} = \frac{C_{0n}}{\sqrt{C_0 C_n}}. \tag{1}$$

We assume that the receivers themselves are uncoupled (i.e., C_{12} = 0). Indeed, in practical configurations, the receivers are each embedded in their own device and the mutual coupling between them will be significantly lower than their coupling with the transmitter.

In order to create resonance in each transmitter and receiver circuit, a shunt inductor L_n is inserted with value:

$$L_n = \frac{1}{\omega_0^2 C_n}. \tag{2}$$

The resistive losses of the transmitter and both receivers are represented by the shunt conductances g_n.

Note that this equivalent circuit approximates the physical reality [2], [6] and neglects for example the series resistances of the inductors. However, it provides a sufficient first-order approximation for the goal of this work.

B. Admittance inverter

An admittance inverter converts an admittance to its inversely proportional value. An example is given in Fig. 2. It is characterized by a susceptance B, that converts an output admittance Y_{out} to an input admittance Y_{in} by:

$$Y_{in} = \frac{B^2}{Y_{out}}. \tag{3}$$

B is called the characteristic admittance of the inverter.

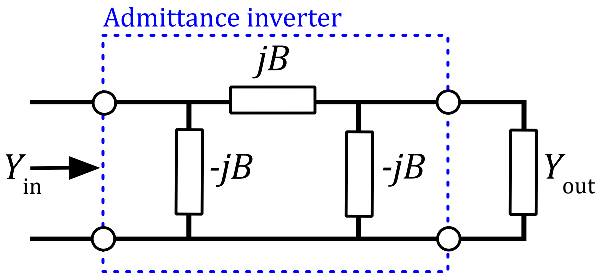

Fig. 2. Admittance inverter. All components shown in the circuit are admittances.

It is worth noting that the circuit of Fig. 1 is equivalent to Fig. 3 where the electric coupling is represented by the admittance inverters J_n with characteristic admittances $J_n = \omega_0 C_{0n}$ (n = 1,2).

C. Power distribution for two receivers

As indicated by Fig. 3 and Fig. 4, we can represent the transmitter and receiver by shunt admittances Y_0, Y_1 and Y_2. At resonance frequency ω_0, the transmitter admittance is given by:

$$Y_0 = g_0 \tag{4}$$

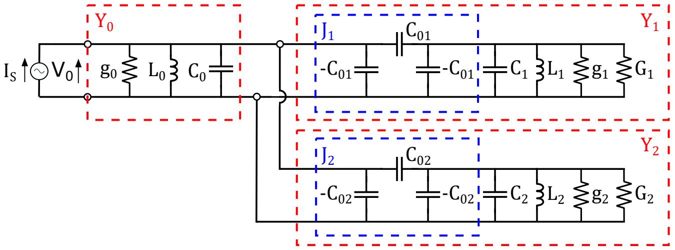

Fig. 3. Equivalent representation of a CPT system with one transmitter and two receivers. The electric coupling is represented by admittance inverters J_n.

and the receiver admittances equal:

$$Y_n = \frac{J_n^2}{g_n + G_n}. \tag{5}$$

Since the loads are purely resistive, the admittances Y_0 and Y_n are also real (i.e., conductances) at resonance frequency.

The maximum power transfer theorem states that maximum power is delivered from the transmitter to the receivers if

$$Y_0 = Y_1^* + Y_2^* \tag{6}$$

with Y^* the conjugate image of Y.

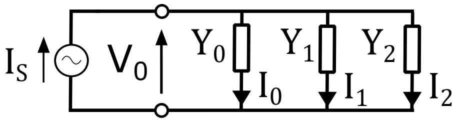

Fig. 4. The CPT network can be represented by a transmitter admittance Y_0 and receiver admittances Y_1 and Y_2.

Condition (6) will maximize the total power transfer from transmitter to receivers, but the power division between the receivers themselves will be dependent on the values of the loads.

By inserting an admittance inverter into each receiver (Fig. 5), the power distribution to each receiver can be adjusted by varying the value of the characteristic admittance B_n of the inverter. Bear in mind that the admittance inverter of Fig. 2 is equivalent to a circuit with one capacitor C_{Bn} and two shunt inductors L_{Bn} given by:

$$B_n = \omega_0 C_{Bn} = \frac{1}{\omega_0 L_{Bn}}. \tag{7}$$

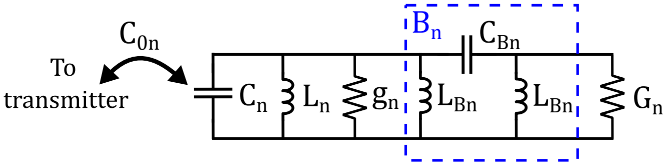

Fig. 5. An admittance inverter B_n (n=1,2) is inserted into the n-th receiver to realize power distribution.

By inserting the admittance inverter B_n, the receiver admittance Y_n is changed to Y_n':

$$Y_n' = \frac{J_n^2 G_n}{G_n g_n + B_n^2}. \tag{8}$$

In practice, the power dissipated in the n-th receiver at resonance frequency ω_0 corresponds to the output power dissipated in the load since g_n is typically much smaller than G_n. We obtain:

$$P_{out,n} = \frac{1}{2}\Re(V_0 I_n^*) = \frac{1}{2}|V_0|^2 Y_n'. \tag{9}$$

I_n and V_0 are the peak current and peak voltage phasors respectively, as indicated in Fig. 4. Note that we have taken into account that Y_n' is real at resonance frequency ω_0.

It follows from (9) that the output power ratio between both receivers equals:

$$\frac{P_{out,1}}{P_{out,2}} = \frac{Y_1'}{Y_2'}. \tag{10}$$

It is clear from (8) and (10) that the power distribution between the receivers can be determined by choosing an appropriate value for the characteristic admittance B_n.

Since only the ratio of the characteristic admittances of the receivers determines the power division, we have an extra degree of freedom to implement another condition: by imposing (6), we can use the maximum power transfer theorem to maximize the amount of power delivered to the receivers, given a predefined power division. Combining (6) and (8) results into the condition for impedance matching:

$$\frac{J_1^2}{G_1 g_1 + B_1^2}\frac{G_1}{g_0} + \frac{J_2^2}{G_2 g_2 + B_2^2}\frac{G_2}{g_0} = 1. \tag{11}$$

Thus, each receiver will take a percentage $\%P_n$ of the total dissipated power in the receivers given by:

$$\%P_n = \frac{J_n^2}{G_n g_n + B_n^2}\frac{G_n}{g_0}. \tag{12}$$

D. Power distribution for N receivers

We illustrated how targeted impedance matching allows for user-defined power division for two receivers. We now detail the procedure for a CPT system with an arbitrary number of receivers N and given coupling factors.

First, the user (or a control algorithm) defines for each receiver n the percentage of total power $\%P_n$ it should get, for example depending on the current charge status of the receiver. Obviously, it holds that:

$$\sum_{n=1}^{N} \%P_n = 1. \tag{13}$$

Second, the characteristic admittance B_n of the inserted inverter is determined from (12):

$$B_n = \sqrt{\frac{J_n^2 G_n}{\%P_n \cdot g_0} - G_n g_n} \tag{14}$$

with $J_n = \omega_0 C_{0n}$.

Finally, the values of the capacitor and inductors in the inverter can be determined by (7).

III. NUMERICAL VALIDATION

We validate the analytical derivation in the circuit simulation software LT Spice. We consider an illustrative CPT system with one transmitter and two receivers (Fig. 1). There is no cross-coupling between the receivers themselves.

The values of the system are indicated in Table I. They are based on [8] and are typical for a CPT system consisting of aluminum plates (10 cm by 10 cm) and a transfer distance of 2.5 mm [6], [7]. We choose the values of the resistive loads G_1 and G_2 such that they correspond to the maximum efficiency configuration [8], which is distinct from the maximum power transfer optimization.

TABLE I
SIMULATION PARAMETERS FOR THE CPT SYSTEM WITH ONE TRANSMITTER AND TWO RECEIVERS.

Quantity	Value	Quantity	Value
g_0	1.00 mS	C_0	300 pF
g_1	1.50 mS	C_1	250 pF
g_2	2.00 mS	C_2	200 pF
C_{01}	200 pF	G_1	16.8 mS
C_{02}	100 pF	G_2	22.5 mS
f	10 MHz	I_S	1.00 A

From (1) and (2), the resonance inductances and coupling factors are calculated (Table II).

TABLE II
CALCULATED SIMULATION PARAMETERS OF THE CPT SYSTEM.

Quantity	Value	Quantity	Value
L_0	0.84 μH	k_{01}	73 %
L_1	1.01 μH	k_{02}	41 %
L_2	1.27 μH		

First, we simulate the setup without the insertion of an admittance inverter. It is found that the first load receives 31.4 W, whereas the second load receives 5.88 W. A non-regulated power distribution of 84.2% to 15.8% is achieved (Table III).

TABLE III
SIMULATION RESULTS FOR THE POWER DISTRIBUTION BEFORE AND AFTER THE APPLICATION OF THE ADMITTANCE INVERTER METHOD.

	$P_{out,1}$	$P_{out,2}$	$\%P_1$	$\%P_2$
Before method	31.4 W	5.88 W	84.2%	15.8%
After method 50%-50%	61.9 W	60.5 W	50.6%	49.4%
After method 30%-70%	37.3 W	83.8 W	30.8%	69.2%

Second, we insert admittance inverters into the receivers to realize a user-defined power distribution. We consider two different scenarios: a 50%-50% and a 30%-70% power distribution. From (7) and (14) we find the values of the inverter components (Table IV).

The simulations confirm the theoretical results: if we add the inverter that aims for an equal power distribution, we achieve a 50.6%-49.4% result, even though the loads and coupling factors of both receivers are very different. If we adjust the admittance inverter to target a 30%-70% distribution, 30.8%

TABLE IV

CALCULATED VALUES OF THE ADMITTANCE INVERTER COMPONENTS.

Distribution	C_{B1}(nF)	C_{B2}(nF)	L_{B1}(nH)	L_{B2}(nH)
50%-50%	1.16	0.662	219	383
30%-70%	1.49	0.556	169	455

of the power is sent to the first receiver, whereas the remaining 69.2% is delivered to the second receiver. The results are summarized in Table III.

The small difference between the targeted and simulated power distribution is caused by the fact that part of the power is dissipated in the resistive losses g_n instead of in the load G_n.

In both scenarios with admittance inverters, more power is delivered to the loads compared to the configuration without admittance inverters, at the cost of a decrease in efficiency. The power conversion efficiency from transmitter to both receivers drops from 84% without inverter to 49% for both configurations with admittance inverters B_n.

IV. CONCLUSION

In this work, a methodology was presented to realize a predefined power distribution towards different receivers in a CPT system. By inserting admittance inverters into each receiver, and adjusting its characteristic admittance accordingly, we demonstrated that we can regulate the power dissipated in each receiver. We analytically determined the values of the components of the inverter, given the system's characteristics, coupling factors and the desired power distribution. Our theoretical results were validated on an illustrative example in the simulation software LT Spice. As future work, we foresee adjustable admittance inverters, for example by a control algorithm, regulating the power distribution to different receivers in an experimental set-up. In this way, it will be possible to prioritize the charging of devices with lower battery status compared to almost fully charged devices.

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