URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Analysis of Capacitive Wireless Power Transfer SIMO Systems based on the Duality Principle

Ben Minnaert*(1), Giuseppina Monti(2), Alessandra Costanzo(3), and Mauro Mongiardo(4)
(1) Dep. of Industrial Science and Technology, Odisee University College of Applied Sciences, Ghent, Belgium.
(2) Dep. of Engineering for Innovation, University of Salento, Lecce, Italy.
(3) Dep. of Electrical, Electronic and Information Engineering Guglielmo Marconi, University of Bologna, Bologna, Italy.
(4) Dep. of Engineering, University of Perugia, Perugia, Italy.

Abstract

Inductive wireless power transfer is a more mature technology than capacitive wireless transfer. The aim of this work is to illustrate the duality principle as tool to transfer results from the inductive into the capacitive wireless power research. The efficiency maximization by varying the loads for a Single-Input Multiple-Output system is considered to exemplify this principle, and to highlight some limitations.

1 Introduction

Power can be transferred wirelessly through quasi-static fields, either by the magnetic field or by the electric field as medium:

- Inductive wireless power transfer (IPT) is based on the generation of a time-varying *magnetic field* by an alternating current in a transmitting coil. Another (receiving) coil captures the energy within this magnetic field for the generation of current.
- Capacitive wireless power transfer (CPT) utilizes one transmitter plate of a capacitor to generate an *electric field* by an alternating voltage. The other (receiving) plate of the capacitor, at a certain distance of the first plate, captures the energy of this electric field for the generation of current.

CPT has several disadvantages compared to IPT, such as higher switching frequencies, larger dimensions, higher voltages, and electric fields which can cause safety concerns for the environment [1, 2]. As a result, focus within the research community went to IPT first. This lead to a situation where IPT has entered the market in a broad range of applications from consumer electronics to electric vehicles [3], whereas CPT is still more in the research phase and development. However, for certain applications (e.g., electric vehicles), CPT has advantages compared to IPT, such as a large tolerance to misalignment, the absence of eddy-current losses and lower cost, weight and heat dissipation [4, 5, 6].

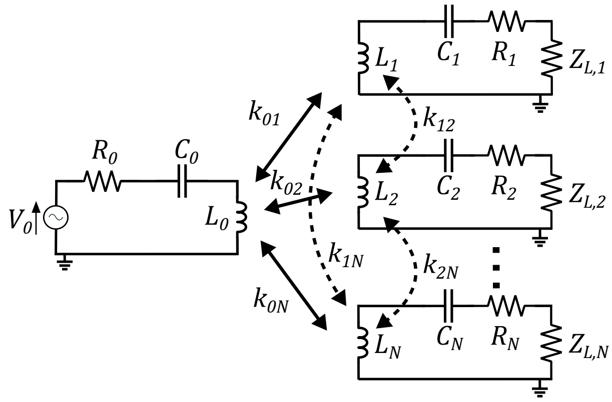

Figure 1. The equivalent circuit of an IPT system with a single transmitter (left) and N receivers (right).

The goal of this work is to emphasize to the research community that a lot of the research done for IPT can be easily translated to CPT by applying the duality principle, as well as highlighting some limitations of the duality principle for wireless power transfer. As an example, this manuscript focuses on a Single-Input Multiple-output (SIMO) system: a single transmitter powers multiple receivers. More specifically, by applying the duality principle, the load values that maximize the system efficiency for a SIMO *CPT*-system are determined from the known SIMO *IPT* values.

2 Inductive SIMO system

Figure 1 depicts the equivalent circuit of an IPT system with a single transmitter (subscript 0) and N receivers (subscripts 1 to N). A time-harmonic voltage source V_0 at angular frequency ω_0 powers the transmitter. The loads of the N receivers are given by the impedances $Z_{L,n}$ $(n = 1,\ldots,N)$. The losses within the system are given by the resistances R_i $(i = 0,\ldots,N)$. Resonance is created in each circuit by the capacitors C_i and inductors L_i, related by:

$$C_i = \frac{1}{\omega_0^2 L_i}. \tag{1}$$

The inductors L_i and L_j are coupled by their mutual inductance M_{ij} $(i, j = 0,\ldots,N,\ i \neq j)$, corresponding with a coupling factor k_{ij} given by:

$$k_{ij} = \frac{M_{ij}}{\sqrt{L_i L_j}}. \tag{2}$$

Notice that also cross-coupling between the receivers is taken into account.

The power gain or efficiency η of the IPT system is given by the ratio of the output power to the input power, with the output power defined as the power dissipated in the N loads.

It was found [7] that, for a given SIMO IPT-system the efficiency η is maximized when the load impedances $Z_{L,n} = R_{L,n} + jX_{L,n}$ are given by ($n = 1,\dots,N$):

$$R_{L,n} = R_n \alpha_{IPT} \tag{3}$$

$$X_{L,n} = \frac{\omega_0 R_n}{M_{0n}} \sum_{\substack{m=1 \\ m\neq n}}^{N} \frac{M_{0m} M_{mn}}{R_m} \tag{4}$$

with

$$\alpha_{IPT} = \sqrt{1 + \frac{\omega_0^2}{R_0} \sum_{m=1}^{N} \frac{M_{0m}^2}{R_m}}. \tag{5}$$

The maximum efficiency η_{max} attained with these optimized load values equals [7]:

$$\eta_{max} = \frac{\alpha_{IPT} - 1}{\alpha_{IPT} + 1}. \tag{6}$$

3 Solving the capacitive SIMO system by applying duality

The duality principle for electrical network theory results entirely from the fundamental symmetry of Maxwell's equations in the electric and magnetic fields. A quantity is said to be the dual of another if the two quantities can be interchanged in a statement or equation without invalidation. Table 1 lists some dual quantities. As example, the relation $Z = V/I$ remains true if the quantities are replaced by their duals, that is, $Y = I/V$.

Table 1. Electrical dual quantities.

Duality between		
Series topology	↔	Parallel topology
Voltage V	↔	Current I
Resistance R	↔	Conductance G
Inductance L	↔	Capacitance C
Reactance X	↔	Susceptance B
Impedance Z	↔	Admittance Y

Applying the duality principle to the equivalent circuit of Figure 1 for IPT results in the network of Figure 2. It represents a CPT system with a single transmitter, powered by current source I_0 at angular frequency ω_0 and N receivers with load admittances $Y_{L,n}$. The losses within the system are given by the conductances G_i ($i = 0,\dots,N$) connected in parallel. Resonance is created in each circuit by the parallel circuit of capacitors C_i and inductors L_i, related by (1).

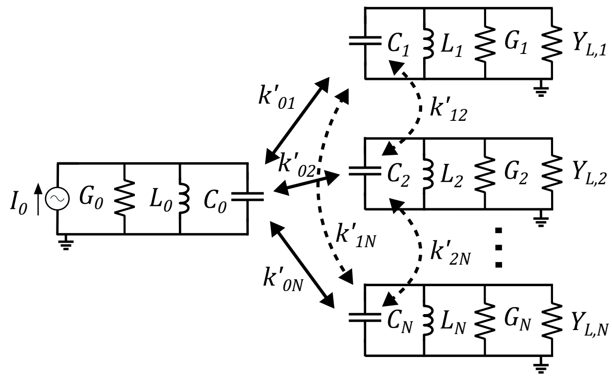

Figure 2. The equivalent circuit of a CPT system with a single transmitter (left) and N receivers (right).

The capacitors C_i and C_j are coupled by their mutual capacitance C_{ij} ($i, j = 0,\dots,N$, $i \neq j$), corresponding with a coupling factor k'_{ij} given by:

$$k'_{ij} = \frac{C_{ij}}{\sqrt{C_i C_j}}. \tag{7}$$

Figure 2 does not correspond to the physical structure of a CPT system, but represents an equivalent circuit representation [8]. The relation between this equivalent circuit and the physical structure can be easily determined by the procedure described in [9].

From the results from the IPT configuration, one can easily find the load values that maximize the efficiency of the CPT system. Replacing the quantities in (3), (4), (5) and (6) by their duals results in the load admittances $Y_{L,n} = G_{L,n} + jB_{L,n}$ that optimize the efficiency for the CPT configuration, and the expression for the maximum efficiency η'_{max}:

$$G_{L,n} = G_n \alpha_{CPT} \tag{8}$$

$$B_{L,n} = \frac{\omega_0 G_n}{C_{0n}} \sum_{\substack{m=1 \\ m\neq n}}^{N} \frac{C_{0m} C_{mn}}{G_m} \tag{9}$$

$$\eta'_{max} = \frac{\alpha_{CPT} - 1}{\alpha_{CPT} + 1}. \tag{10}$$

with

$$\alpha_{CPT} = \sqrt{1 + \frac{\omega_0^2}{G_0} \sum_{m=1}^{N} \frac{C_{0m}^2}{G_m}}. \tag{11}$$

These expressions, which were only derived by applying the duality principle, correspond to the values found in literature by rigorous elaboration [10]. This example illustrates how a result from IPT can be quite straightforward transferred to CPT.

However, some limitations of applying the duality principle should be highlighted. First of all, ideal inductors and capacitors are considered in the given example. This approximation is more accurate for IPT than for CPT, since the most non-ideal attribute, the series resistance of the inductors, is included in the series resistance of the IPT configuration, but not in the dual equivalent circuit of the CPT configuration.

Secondly, the SIMO example only focused on the wireless link itself and made abstraction of the remote electronics (e.g., power conditioner, rectifier, etc.). In particular, for CPT usually higher operating frequencies are preferred.

Nevertheless, applying the duality principle from IPT to CPT is a powerful tool for first approximations.

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