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Estimate of the maximum range achievable by non-radiating wireless power transfer or near-field communication systems

Henri Bondar [a], Shailendra Oree [b,*], Zafrullah Jagoo [b], Keiichi Ichikawa [c]

[a] Technology and Marketing Management Solutions Research Center Limited, Flic en Flac, Mauritius
[b] Department of Physics, Faculty of Science, University of Mauritius, Réduit, Mauritius
[c] New Business Development Department, Technology & Business Unit, Murata Manufacturing Company Limited, Kyoto, Japan

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ABSTRACT

Models relating the coupling coefficient of coupled circuits to their physical layout and separation are essentially empirical in nature and have, until very recently, been available exclusively for inductive systems. In this work, we propose elementary models for representing the evolution, with distance, of the coupling coefficient between two dipoles arranged in different configurations. Both the electric and magnetic coupling cases are examined. We demonstrate that in the case of electrically coupled dipoles, with due consideration for specific practical constraints, the coupling coefficient is optimal when the dipoles are asymmetrical and arranged in an axial configuration. We show that the rate of fall of coupling coefficient increases with the relative separation between the dipoles. Finally, a simple formula for estimating the range of all non-radiating resonant power transport devices is proposed.

1. Introduction

Non-radiating Wireless Power Transfer (WPT) or Near-Field Communication (NFC) devices exchange power or data at a distance through resonant circuits coupled in their near-field regions. They are characterized by their small size compared to wavelength and consequent negligible radiative losses. Moreover, the field distribution between the devices is accurately described by the same equations that apply for static regimes. The coupling can be implemented through a magnetic field, as in a transformer, or through an electric field, as in a capacitor. In such systems, power is best transferred in a longitudinal manner [1], a result not consistent with the wave paradigm [2].

The history of electrically coupled devices has not been very eventful. Since the invention of the century-old electrostatic influence machines and the pioneering work of Nikola Tesla [3], the field stagnated even though sporadic attempts have been made to implement Capacitive Power Transfer (CPT) using two ideal capacitors, as described by Boie [4]. In the past seven years, thanks to sustained market interest for WPT, the field has witnessed a revival following the works of a small number of researchers who have qualified it by various non-consensual terms. In this work, we adopt the terms *electrical influence* or simply *influence*. The notion of total influence is applicable in the degenerate case of the ideal capacitor, whereas partial influence provides a generalized framework for studying capacitive coupling [5]. Similarly to magnetic induction systems, the technology of devices coupled by electrical influence involves interactions between coupled dipoles [6] (Fig. 1).

Analysis of these devices leads to matrix representations and to the notions of self-capacitance of an electrode and mutual capacitance between pairs of electrodes [7]. In practice, optimal implementation of this technology entails the use of highly asymmetrical electrical dipoles arranged along a common longitudinal axis [8]. One of the objectives of this article will be to justify these elements quantitatively.

Estimation of the power transfer capacity of a given arrangement, involves, in the simplest case, a two port system described by a 2×2 coupling matrix [9]. The determination of the amount of transferred energy per cycle relies essentially on the knowledge of a coupling coefficient which can be determined from a static analysis. Power transfer scales as frequency, while efficiency is related to the quality factor of the devices [10]. Knowing the evolution of the coupling coefficient with distance is then a key point for evaluating the maximum range achievable by near-field systems [11].

* Corresponding author. Tel.: +230 4037508; fax: +230 4549642.
E-mail addresses: henribondar@yahoo.fr (H. Bondar), oreesh@uom.ac.mu (S. Oree), zaf@physicist.net (Z. Jagoo), kichi@murata.co.jp (K. Ichikawa).

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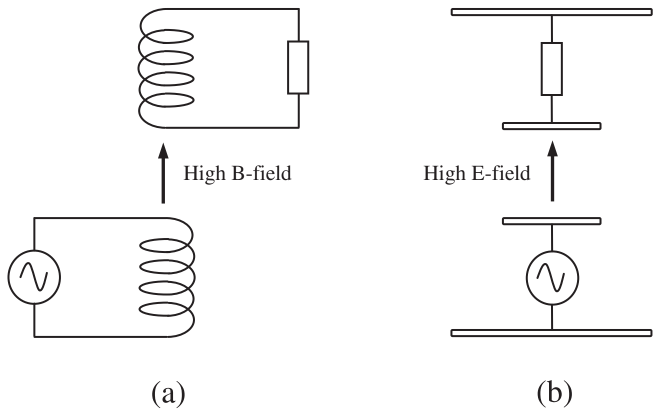

Fig. 1. Longitudinally coupled dipoles for WPT: (a) magnetic coupling and (b) electrical coupling.

The coupling coefficient is usually considered as a mere numerical variable that can either be measured experimentally or evaluated using lengthy numerical methods [12]. In this work, we establish some elementary formulas that quantify, in simple electric and magnetic coupling cases, the coupling coefficient in terms of relative dimensions and, in particular, the relative distance between the dipoles.

In dynamic electrical coupling situations, the material currents are replaced in the surrounding medium by Maxwell's displacement currents that cannot be easily followed or measured. We adopt here, following Ref. [8], a natural approach where only conservative material current paths are figured (open-ended representations). The problems are made amenable to a simplified analytical treatment by first considering dipoles consisting of closely spaced planar electrodes before focusing on dipoles made up of relatively distant electrodes of spherical shape. The first one concerns quasi-contact situations whereas the latter case involves intermediate and large separations. With reference to these configurations, we investigate the effects of electrode asymmetry and mutual orientation (longitudinal or transverse) of the dipoles.

For inductively coupled systems, we investigate the case of two distant coaxial flat coils by making use of Maxwell's method to evaluate the mutual and self inductances of the coupling matrix. The general behavior of the coupling coefficient of the magnetically coupled system is very similar to that of the electrically coupled systems.

Through the use of classical results on efficiency and power transfer, we provide a simple universal formula giving the maximum achievable range for both types of non-radiating near-field power transfer systems.

2. Electrical coupling models

2.1. Electrostatic theory

Classical electrostatic theory, applied to multiple interacting electrodes in quasistatic equilibrium provides the framework for expressing their potentials in terms of their charges [7]. In this frame, an elementary charge dQ generates, at distance r, within a medium of permittivity ε_0, a potential dV given by

$$\mathrm{d}V = \frac{\mathrm{d}Q}{4\pi\varepsilon_0 r}. \tag{1}$$

The theorem of superposition of potentials can be used to calculate, at any point, the net potential resulting from a charge distribution over a volume ν according to

$$V = \int_{\nu} \frac{\mathrm{d}Q}{4\pi\varepsilon_0 r}. \tag{2}$$

If the charges are distributed over the surface of several conductors, the above integral can be split as a sum of contributions of all the conductor surfaces. Applying Equation (2) to evaluate the potential V_j at a point on conductor j gives

$$V_j = \sum_i \oint_{S_i} \frac{\mathrm{d}Q_i}{4\pi\varepsilon_0 r}, \tag{3}$$

where dQ_i represents the infinitesimal charge carried by an element of the surface S_i of the ith conductor. Since perfectly conducting surfaces are equipotentials and Equation (3) is linear, the problem boils down to finding the matrix linking the potentials of the various conductors to the charges they carry, or its inverse capacitive matrix form

$$Q_i = \sum_j C_{ij} V_j. \tag{4}$$

In this document, we investigate the coupling between two pairs of electrodes. When an electrical dipole constituted by a pair of electrodes is asymmetric, we define the smaller electrode as the active and the larger one as the passive. Additionally, for studying energy transport, one electrode pair is virtually connected (without any field perturbations) to sinusoidal generator G while the other electrode pair is connected to a load L. We examine the behavior of such systems in different idealized configurations where simple analytical solutions for the coupling coefficient can be derived.

2.2. Longitudinal slim model

In this configuration we consider flat disc-shaped electrodes placed at distances that are small compared to the radii of electrodes according to Fig. 2.

The passive electrodes have larger radii than either of the active electrodes and the generator active is larger than the load active. We may regard, in first approximation, that the electric field at any point within the electrode structure is parallel to the longitudinal axis. In this situation, according to Gauss' theorem, the charges q_{ij} and $-q_{ij}$ borne by the overlapping area A_{ij} of electrodes i and j, separated by distance d_{ij}, are linked to their potentials V_i and V_j through

$$q_{ij} = \varepsilon_0 \frac{V_i - V_j}{d_{ij}} A_{ij}. \tag{5}$$

The total charge carried by electrode i is obtained by summing over all electrodes having a common facing area with it, giving

$$q_i = \sum_{j=1}^{4} \varepsilon_0 \frac{A_{ij}}{d_{ij}} V_{ij}. \tag{6}$$

In this expression, the coefficients of the potential differences V_{ij} represent the capacitances between facing areas of pairs of

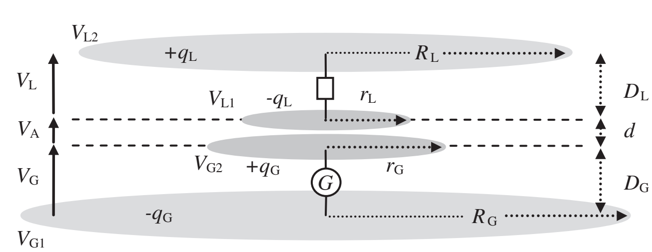

Fig. 2. Longitudinal slim model (longitudinal dimensions are exaggerated for clarity).