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Chapter 9 Determining the maximum power of the WPT system by appropriate impedance selection

Jacek Maciej Stankiewicz
Bialystok University of Technology, Faculty of Electrical Engineering

Abstract: The article analyses the effect of the number of turns and the distance between the transmitter and the receiver surface, as well as the resulting power and efficiency of the Wireless Power Transfer (WPT) system. Each plane contained planar square coils of the same geometry. The article presents a numerical approach to the analysis of this type of systems. The aim of the presented solution is to quickly determine the output parameters (e.g. power, efficiency) without the need to perform experiments. The analysis takes into account the following variability: the number of turns, the distance between the transmitting and receiving coils, and the frequency of the energy source. The results concerned the appropriate selection of impedance to obtain the maximum power of the system. The obtained results allow for a detailed discussion of the dependence of the efficiency and power of the WPT system on the geometry of square coils.

Keywords: wireless power transfer (WPT), magnetic field, Finite Element Method (FEM).

Introduction

One of the commonly used methods of powering mobile devices with energy is charging by means of wireless power transfer (WPT) [1–10].

Increasing the efficiency of the WPT system is possible, among others, by using two additional intermediate coils [2, 11–13]. The advantage of this solution is an increase in system efficiency by 30%. Unfortunately, the disadvantage entails, among others, the need for a larger surface area in order to harmonize the system with four coils located on a square or cuboid-shaped surface.

In the case of loading small devices or cars, it is necessary to use planes containing transmitting and receiving coils [4–6]. The literature describes solutions used for charging batteries while driving a car, which is favorably perceived, for example, in factories or production halls. The WPT system is more and more often used in intelligent constructions, with the use of sensors [20].

The application of WPT applies to many industries and, for this reason, work is still being carried out on new and better solutions and their possible applications.

It is known that each solution requires a multivariate analysis as well as carrying out experiments. However, with the use of analytical and numerical methods, it is possible to initially determine the influence of geometry on parameters related to e.g. with the power of the transmitter and the receiver, and efficiency.

The article presents the WPT solution with the use of square coils constituting the transmitting and receiving surface. Each of the planes was composed of small planar coils of the same geometry, between which energy is exchanged. This solution can be used to power many independent receivers. For this purpose, the FEM numerical method was used to quickly determine the system parameters (e.g. power, efficiency) without the need to perform experiments.

Based on the analysis of the sample model, the possibilities of the developed numerical approach were shown, which takes into account the possibility of modifying the size of the coil, the number of turns and the distance between the planes.

The analysis concerned the influence of geometric parameters of the coil (number of turns, distance between the coils) and frequency on the efficiency of the WPT system and the power of the transmitter and the receiver. By appropriate selection of load resistance, it was possible to determine the maximum power of the WPT system.

The presented WPT system allows for simultaneous supply/charging of many low-power receivers, even on hard-to-reach surfaces (e.g. ceilings).

The analysed model of Wireless Power Transfer System

Using numerical methods (e.g. FEM, FDTD), it is possible to create a model of WPT system and determine the influence of specific parameters on the parameters of the system [10, 14, 15]. To perform such an analysis, it is necessary to create a model and set appropriate boundary conditions.

The analyzed WPT system consisted of many transmitter-receiver pairs that form a WPT cell with external dimensions $d \times d$ (Fig. 9.1). The coils on the transmitting and receiving surfaces have the same dimensions: radius (r) and number of turns (n_t). The transmitting surface consisting of the transmitting coils is connected in parallel with the sinusoidal voltage source (U).

The presented numerical model of the WPT system enables the selection of power conditions depending on the imposed requirements. This solution also allows for the simultaneous supply of many independent receivers, where the set or each of the WPT cells is assigned to a separate load.

The proposed periodic WPT system consists of two surfaces (transmitting and receiving). Each surface contains a set of coils with the same winding direction (Figs. 9.1, 9.2).

The analysed square planar coils are wound with several dozen turns, which are made of ultra-thin wires with a diameter (*w*) and insulated from each other by an electric insulator with a thickness (*i*).

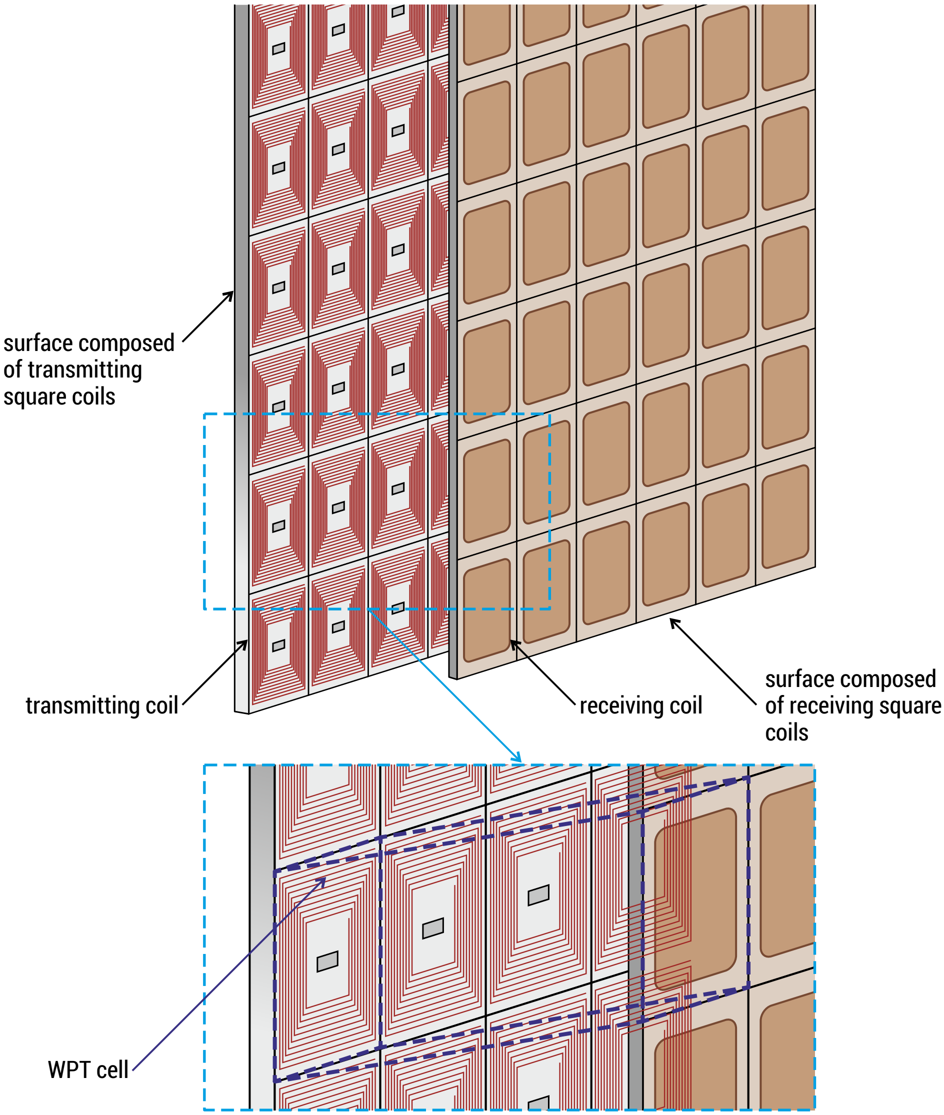

FIGURE 9.1. The analysed WPT system with a transmitting and receiving surface

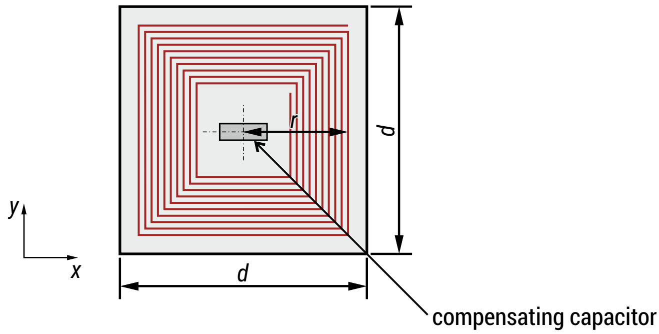

FIGURE 9.2. One of the many square coils that make up the transmitting and receiving plane

The compensation capacitor can be modeled as an element with concentrated capacitance (C). A voltage source (U) with a frequency (f) is connected to each coil and the current flows through the transmitter ($\underline{I}_{tr}$). A receiving coil connected to a linear load Z carries the induced current ($\underline{I}_{re}$).

Periodic boundary conditions (PBC) were used to reduce the model to one WPT cell. On the other hand, a perfectly matched layer (PML) was placed on the upper and lower surface of the WPT cell to imitate the dielectric background [10, 14] (Fig. 9.3).

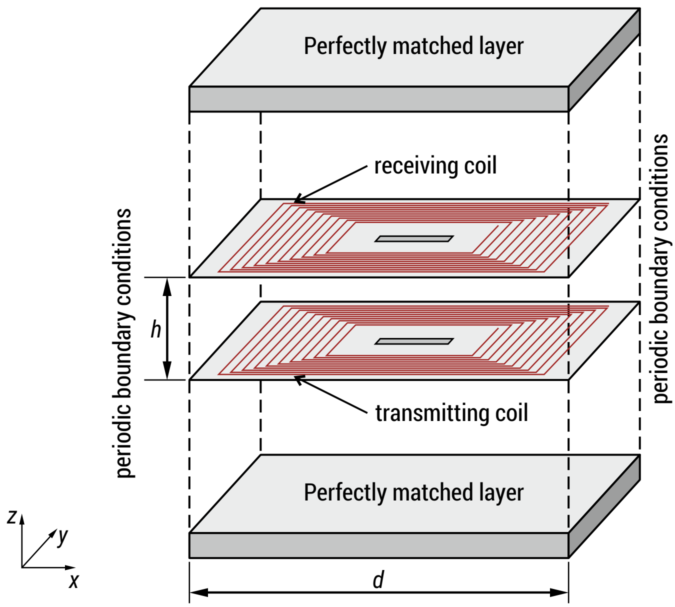

FIGURE 9.3. Three-dimensional view of one of the WPT cells

The issue of energy transport can be solved using magnetic vector potential:

$$\mathbf{A} = [\mathbf{A}_x \ \mathbf{A}_y \ \mathbf{A}_z], \tag{9.1}$$

and using the Helmholtz equation:

$$\nabla \times \left(\mu_0^{-1} \nabla \times \mathbf{A}\right) - j\omega\sigma\,\mathbf{A} = \mathbf{J}_{ext}, \tag{9.2}$$

where:
ω – pulsation [rad/s],
σ – conductivity [S/m],
μ_0 – permeability of an air [H/m],
$\mathbf{J}_{ext}$ – external current density vector [A/m^2].

In order to verify the adopted assumptions, an analysis of exemplary variants of the proposed solution of the WPT system was performed. For this purpose, the transmitter power was determined:

$$P_o = Z\left|\underline{I}_{re}\right|^2 . \tag{9.3}$$

Additionally, the transmitter power was determined:

$$P_z = U\underline{I}_{tr} . \tag{9.4}$$

Using equations (3) and (4) the power transfer efficiency was represented by equation:

$$\eta = \frac{P_o}{P_z} 100\% . \tag{9.5}$$

The analysis concerned a comparison of P_z and P_o and efficiency for proposed variants of the WPT system. The results concerned the appropriate selection of impedance Z_p to obtain the maximum receiver power of the WPT system [16–19]:

$$Z_p = R_c + \frac{\omega^2 M_{tr}^{\ 2}}{R_c}, \tag{9.6}$$

where:
R_c – resistance of the inductor [Ω],
M_{tr} – mutual inductance [H/m].

Parameters of the analysed models of the WPT system

The analysis concerned variants differing in the number of turns and the distance between the surfaces (transmitting and receiving) (Tab. 9.1).

TABLE 9.1. Geometrical parameters of models

radius (r [mm])	number of turns (n_t)	distance between coils (h [mm])
10	20	5 and 10
	30	5 and 10

The parameters were accepted for described calculations: wire thickness $w = 200$ µm, insulation thickness $i = 5$ µm, conductivity of the wire $\sigma = 5.6 \cdot 10^7$ S/m, voltage source $U = 1$ V. The analysis was performed for a wide frequency range: from 0.1 MHz to 1 MHz.

Calculation results

The source power (P_z), the receiver power (P_o), and power transfer efficiency (η) are presented in the below figures. Transmitter power, receiver power and power transfer efficiency were calculated within frequency range from <0.1–1> MHz. The numerical model was created in the Comsol Multiphysics program. Using the FEM method, a numerical analysis was performed. The analyzed model contained 231460 degrees of freedom.

The source power (Figs. 9.4, 9.7), the receiver power (Figs. 9.5, 9.8) and power transfer efficiency of the WPT system (Figs. 9.6, 9.9) are presented.

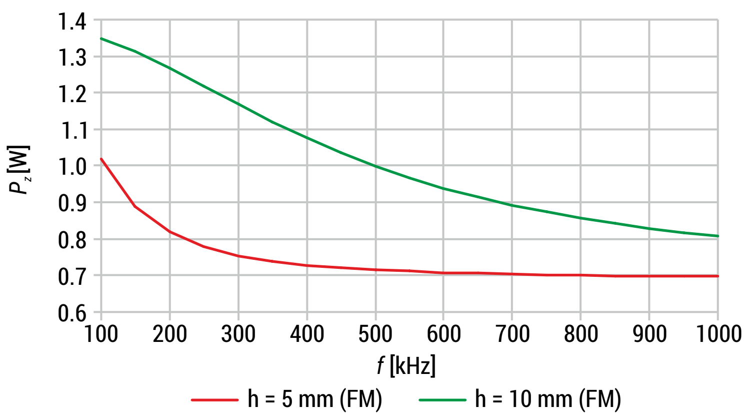

FIGURE 9.4. Results comparison of the source power (P_z) depending on the distance h (n_t = 20)

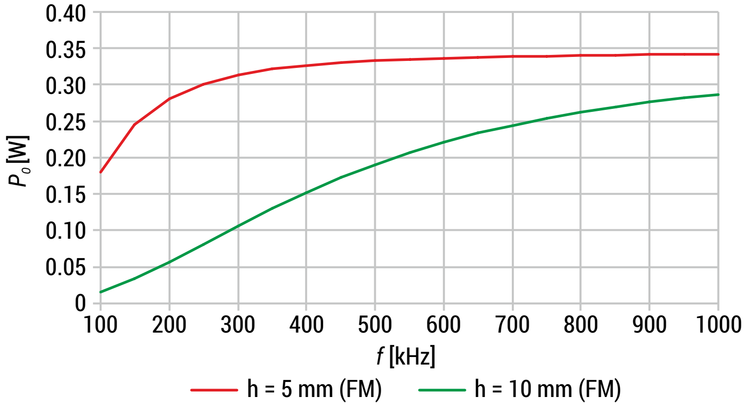

FIGURE 9.5. Results comparison of the receiver power (P_o) dependent of the distance *h* (*n_t* = 20)

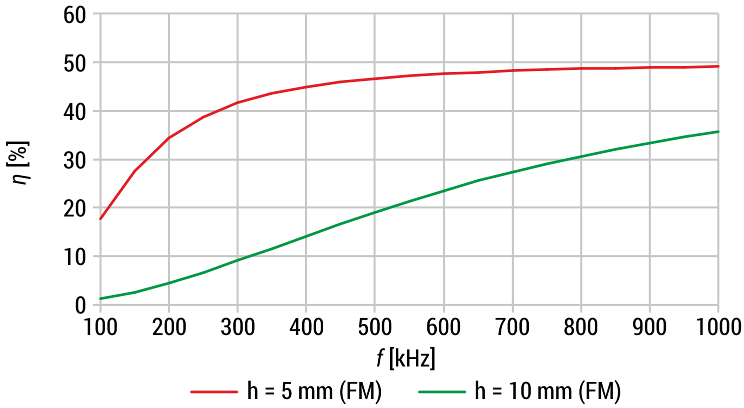

FIGURE 9.6. Results comparison of power transfer efficiency depending on the distance *h* (*n_t* = 20)

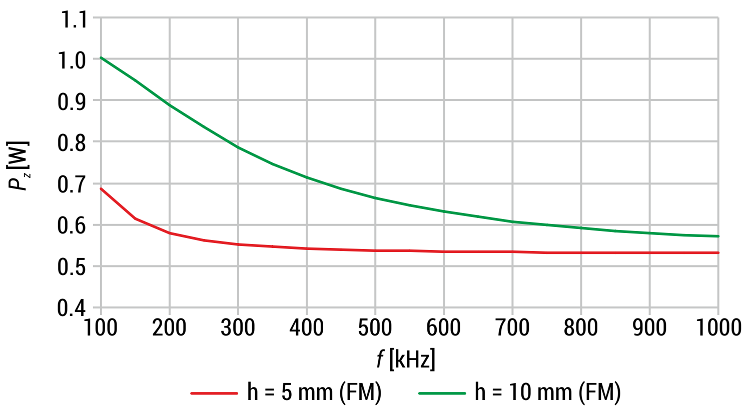

FIGURE 9.7. Results comparison of the source power (P_z) depending on the distance *h* (*n_t* = 30)

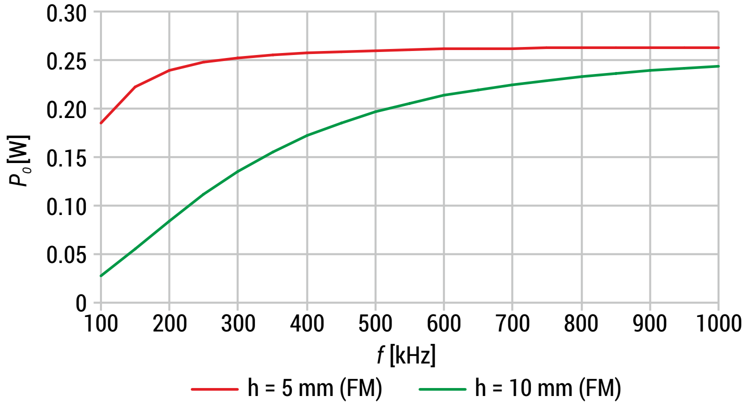

FIGURE 9.8. Results comparison of the receiver power (P_o) depending on the distance *h* (*n_t* = 30)

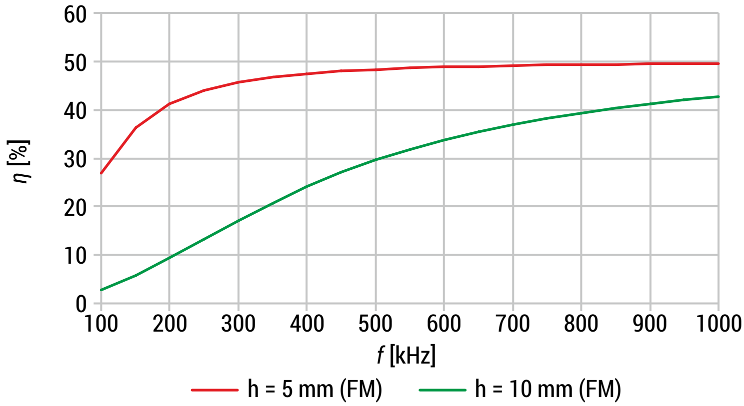

FIGURE 9.9. Results comparison of power transfer efficiency depending on the distance *h* (*n_t* = 30)

The transmitter power P_z decreases over the entire frequency range, regardless of the number of turns *n_t* and distance *h* (Figs. 9.4, 9.7). The power P_z is higher at the distance $h = r = 10$ mm than at $h = r/2 = 5$ mm.

At the distance $h = 5$ mm, the characteristics of receiver power P_o began to stabilize after exceeding a certain frequency (Figs. 9.5, 9.8). At the distance $h = 10$ mm, it was noticed that the maximum receiver power P_o began to stabilize at frequency at least equal to 1 MHz. On the other hand, the values of power P_o were smaller than at the distance $h = 5$ mm.

At the considered operation mode (maximum load power), the efficiency of the system tended to max. 50%. The exception was higher distance ($h = 10$ mm), where maximum efficiency was reached above 1 MHz (Figs. 9.6, 9.9).

Conclusions

The article presents the solution of the WPT system through the use of square planar coils forming both the transmitting and the receiving plane. The proposed solution can be used for charging and powering low-power systems. It can also be used as a charging device for multiple receivers.

The presented numerical approach allows to reduce the number of degrees of freedom by using the WPT cell and periodic conditions.

The numerical solution presented in the article allows to study the influence of the number of turns and the distance between the transmitter and the receiver in a wide frequency range on power transmission.

Thanks to the simple adjustment of the number of turns and increasing the frequency of the current, without the use of intermediate coils, it was possible to obtain the maximum power and the corresponding efficiency of the WPT system.

By means of an appropriate selection of load impedance, it was possible to determine the maximum power transmitted to the receiver and the appropriate efficiency. The results showed that the analysis of an extensive grid of periodic resonators can be numerically simplified to a single WPT cell.

Streszczenie: Artykuł zawiera analizę wpływy liczby zwojów i odległości między płaszczyzną nadawczą i odbiorczą, jak również wynikającej z tego mocy i sprawności dla systemu z bezprzewodowym przesyłem mocy (WPT). Każda z płaszczyzn zawierała planarne cewki kwadratowe o takiej samej geometrii. W artykule zaprezentowano numeryczne podejście do analizy tego typu układów. Celem przedstawionego rozwiązania jest szybkie określenie parametrów wyjściowych (np. moc, sprawność) bez konieczności wykonywania eksperymentów. W analizie uwzględniono zmienność: liczby zwojów, odległość między cewką nadawczą i odbiorczą oraz częstotliwość źródła energii. Wyniki dotyczyły odpowiedniego doboru impedancji w celu uzyskania maksymalnej mocy układu. Uzyskane wyniki pozwalają na szczegółowe omówienie zależności sprawności i mocy układu WPT od geometrii cewek kwadratowych. (Wyznaczenie maksymalnej mocy systemu WPT poprzez odpowiedni dobór impedancji).

Słowa kluczowe: bezprzewodowa transmisja energii (WPT), pole magnetyczne, metoda elementów skończonych (FEM).

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Author: mgr inż. Jacek Maciej Stankiewicz, Bialystok University of Technology, Faculty of Electrical Engineering, Wiejska 45D, 15-351 Białystok, E-mail: j.stankiewicz@doktoranci.pb.edu.pl, ORCID: 0000-0002-1757-2203

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