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The influence of coils system geometry on the efficiency of wireless power transfer

***Abstract**. The article presents an analysis of the effectiveness of the Wireless Power Transfer (WPT) periodic system consisting of transmitting and receiving coils. In the analysis taken into account various variants of the system geometry (radius of the coil, number of turns, distance between the transmitting-receiving coils). The influence of variable system geometry and frequency on system efficiency was analysed. The Finite Element Method (FEM) with the using periodic boundary conditions for the analysis was used. Based on the results obtained, it was checked at which system parameters wireless power transfer of the system is possible.*

***Streszczenie.** W artykule przedstawiono analizę efektywności układu periodycznego WPT (Wireless Power Transfer) złożonego z cewek nadawczych i odbiorczych. W analizie uwzględniono różne warianty geometrii układu (promień cewki, liczba zwojów, odległość między cewkami). Analizowano wpływ zmiennej geometrii układu oraz częstotliwości na sprawność układu. Do analizy wykorzystano metodę elementów skończonych (FEM) z zastosowaniem periodycznych warunków brzegowych. Na podstawie uzyskanych wyników sprawdzono, przy jakich parametrach układu możliwy jest bezprzewodowy transfer energii. (**Wpływ geometrii układu cewek na sprawność bezprzewodowego przesyłu energii**).*

Keywords: wireless power transfer (WPT), numerical analysis, magnetic fields, FEM.
Słowa kluczowe: bezprzewodowa transmisja energii (WPT), numeryczna analiza, pole magnetyczne, FEM.

Introduction

In recent years there has been a rapid increase the used mobile devices. For this reason, new solutions for wireless loading of devices have been sought. The computing power of mobile devices and the number of supported sensors increased (e.g. accelerometer, fingerprint sensor, iris scanner). This resulted in an increasing demand for increasing battery capacity and also the load time. These factors significantly determine the mobility of devices. One of the ways to load mobile devices is using wireless power transfer (WPT) [1-3, 6, 9-12].

The article will be presented a system of periodically arranged transceivers and receivers coils. This proposed system could be used to load mobile devices as the wireless power transfer system. An analysis of the influence of system parameters will be carried out, including radius of the coil, number of turns, distance between coils and frequency of the system operation on the efficiency of energy transmission.

Wireless power transfer – proposed periodic model

In the article, the WPT system containing many inductive elements was analysed. The WPT cell consists of a transmitter-receiver pair constituting an arrangement of identical coils with a radius *r* and the number of turns *n_t.*

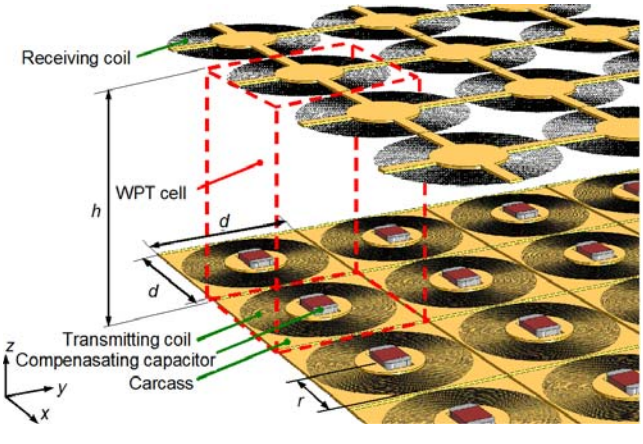

Fig.1. A three-dimensional view on periodic WPT system

The WPT cell has external dimensions $d \times d$. The transmitting and receiving coils are coaxial and placed at a distance of *h*. The turns are placed on a plastic carcass in which capacitors compensatory connected in series with the coil are mounted. The spatial distribution of WPT cells leads to the creation of a periodic network, which includes the transmitting and receiving surfaces, between which energy transmission occurs (Fig. 1). The transmitting surface is powered so that each transmitter is connected in parallel with a sinusoidal voltage source with the effective value U_t. The coils forming the receiving surface are connected directly to the load.

The presented and analysed system ensures an increase the density of transmitted power in the area between the receiving and transmitting surface. It also allows to the choice of feed conditions depending on the imposed requirements. The article presents one of several possible variants of analysis, in which it is possible to feed of multiple independent receivers, where the set or separately each WPT cell is assigned a separate load. Assuming that each of the receivers is connected to the load $\underline{Z}_l$.

In order to analyse the WPT periodic system, it is possible to replace the system with a two-dimensional model on the XY surface, which shows a set of transmitting/receiving coils (Fig. 2).

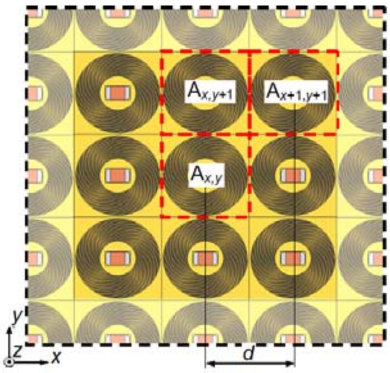

Fig.2. A two-dimensional model – transmitting/receiving surface of the periodic WPT system ($A_{x,y}$ - WPT cell, $A_{x,y+1}$ - adjacent WPT cell (by edge), $A_{x+1,y+1}$ - adjacent WPT cell)

The selected cell $A_{x+k,y+w}$ belongs to a network of identical coils, where k is the number of the column, and w is the number of the row in the network, k, $w \in \mathbf{C}$, where **C** is a set of integers. Adjacent coils (e.g. $A_{x,y+1}$ or $A_{x-1,y}$) of any $A_{x,y}$ element are separated from it by a distance d.

Analysing model by using Finite Element Method (FEM)

The analysis of the WPT periodic system can be performed using e.g. the numerical methods (for example FEM, FDTD, FDFD). In the analysis proposed model the FEM was used, thanks to which it is possible to create a model of the system and solve it due to the distribution of the magnetic field [4, 5, 6, 7]. It is then necessary to prepare a 3D model and set complex boundary conditions. The effectiveness and accuracy of the solution are depended on the size of the model (the number of degrees of freedom). The more number of degrees of freedom allow receiving the greater the accuracy of the solution, but the longer the calculation time.

Numerical analysis of the energy transfer in a system composed of many WPT cells requires consideration of:

- coil geometry, coil turns distribution, WPT cell number;
- elements of the electric circuit connected to each coil.

The spiral coils considered are made of several dozen turns, made with thin wires with a diameter of d_w and meeting the conditions:

(1) $$n\_t \geq 10$$

(2) $$d_w < \delta$$

where: n_t – number of coil turns, δ - penetration depth.

Assumptions (1) and (2) lead to the need to map each of the coil turns, which unfortunately significantly increases the size of the model (the number of degrees of freedom).

The compensating capacitor can be modelled as an element with a concentrated capacity C. Additionally, in the analysis, it is possible to omit the carcass in the model assuming that it is made of non-conductive and non-magnetic material ($\mu = \mu_0$). Each transmitting coil was connected to a voltage source with an effective value U_t and frequency f, which forcing the flow current transmitter's $\underline{I}_t$. In the receiving coil, the source is replaced by a linear load $\underline{Z}_l$ which conducts the induced current $\underline{I}_r$.

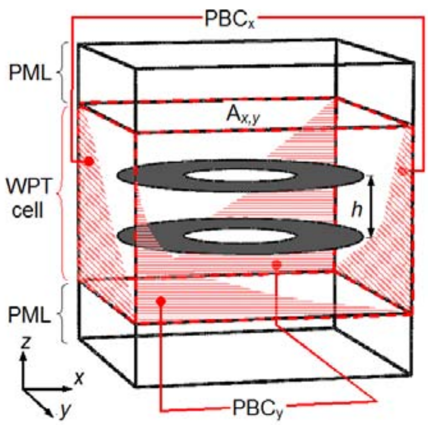

Fig.3. The numerical model of the periodic WPT system

In order to calculate periodic WPT system all cells forming transmitting and receiving surfaces have to be taken into account. However, for system with many WPT cells another simplification is possible. In model periodic boundary conditions (PBCs) both in x and y direction were be applied. In this case, the WPT system will be simplified to single cell $A_{x,y}$, which was filled with air and containing a pair of transmitting and receiving coil (Fig. 3). Periodic boundary conditions are applied on left and right (PBC_x) as well as front and back (PBC_y) boundaries, in order to project infinite array of WPT cells. To imitate dielectric background the perfectly matched layer (PML) was put in top and bottom of the model.

The issue of energy transport in the presented periodic model can be solved using magnetic vector potential

(3) $$\mathbf{A} = [\mathbf{A}_x \ \mathbf{A}_y \ \mathbf{A}_z]$$

and a description of magnetic phenomena in the frequency domain by using the Helmholtz equation

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

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

Periodicity conditions on four side surfaces are given in the form of magnetic isolation

(5) $$\mathbf{n} \times \mathbf{A} = 0$$

where $\mathbf{n} = [1_x \ \ 1_y \ \ 1_z]$ is a normal vector to surface.

The voltage force U_t with frequency f determines the value of $\mathbf{J}_{ext}$, and taking into account the equation (5) allows to solve the relationship (4) and determine to the spatial distribution of magnetic vector potential $\mathbf{A}(x,y,z)$. For this purpose, can be used method FEM. The compensating capacitor capacity can be determined, e.g. based on parametric analysis of the system at different capacitance values (C). For the case when $\mathrm{Im}[\underline{I}_t] \approx 0$ it is assumed that the system has a resonance state and the selected C is the capacity sought.

Calculation results

The field model, taking into account a range of phenomena and geometry system, is characterized by high accuracy in solving the problem of power transport.

It has been assumed that the system consists of an infinite number of WPT cells, and a single $A_{x,y}$. element is analysed.

The system was built of identical coils arranged coaxially at a distance of h and made of thin wire with a diameter of d_w = 150 μm and conductivity $\sigma = 5.6 \cdot 10^7$ S/m. A source with an effective value U_t = 5 V and a frequency from f_{min} = 0.1 MHz to f_{max} = 1 MHz. is connected to the transmitter. The active load Z_l = 50 Ω is attached to the receiving coil. Coils of small size (r = 5 mm) and larger size (r = 20 mm) and different number of turns n_t and distance $h / r \in \{0.5, 1.0\}$ were analysed (Tab. 1).

Table 1. Geometrical parameters for analyse cases

r [mm]	n_t	h [mm]
5	10	2.5 and 5
	20	2.5 and 5
	30	2.5 and 5
20	30	10 and 20
	50	10 and 20
	70	10 and 20

The numerical model (Fig. 3) was created in the *Comsol Multiphysics program*, using included coil approximation models with attached circular part and boundary conditions (PML and PBC), and then solved using the Finite Element Method.

Figures 4-7 present comparisons of WPT efficiency results for different values of the number of turns of the transmitting and receiving coils and different distances between these coils.

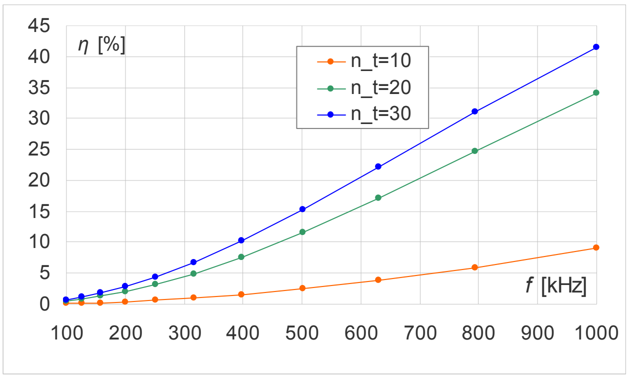

Fig.4. Results comparison of power transfer efficiency dependent of number of turns (n_t) for the case r = 5 mm, h = 2.5 mm

Figure 4 shows a comparison of results for the radius of the coils r = 5 mm and the distance between the coils h = 2.5 mm. It can be seen that as the frequency increases, the efficiency of the WPT system increases. A two-fold increase in the number of turns of the coils (from n_t = 10 to n_t = 20) results in an even fourfold increase in the efficiency of wireless energy transmission at higher frequencies. Further increasing the number of turns of the coils (from n_t = 20 to n_t = 30) results in an increase in efficiency of up to 30%.

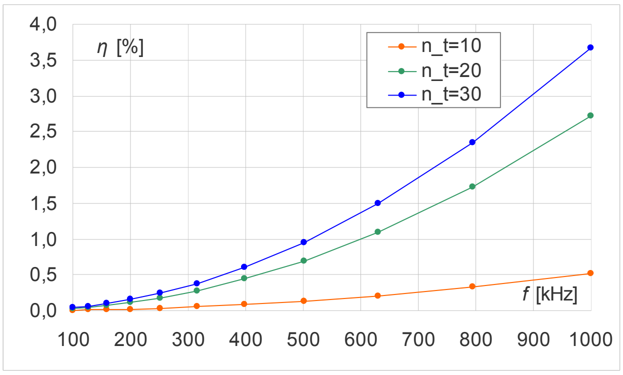

Fig.5. Results comparison of power transfer efficiency dependent of number of turns (n_t) for the case r = 5 mm, h = 5 mm

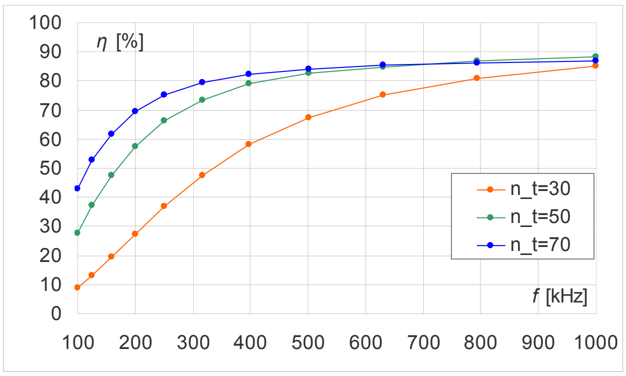

Fig.6. Results comparison of power transfer efficiency dependent of number of turns (n_t) for the case r = 20 mm, h = 10 mm

Figure 5 shows a comparison of results for the radius of the coils r = 5 mm and the distance between the coils h = 5 mm. A two-fold increase in the number of turns of the coils (from n_t = 10 to n_t = 20) causes even an almost six-fold increase in the efficiency of wireless energy transmission at higher frequencies. Further increasing the number of turns of the coils (from n_t = 20 to n_t = 30) results in an increase in efficiency of up to 35%. However, it can be seen that the efficiency of wireless power transmission is very low and does not exceed 4%. This is due to too much distance between the transmitting and receiving coil.

Comparison of results for the radius of the coils r = 20 mm and the distance between the coils h = 10 mm was presented in Fig. 6. There is a similar relationship here as with previous characteristics, i.e. that as the frequency increases, the efficiency of the WPT system increases. Increasing the number of turns of coils (from n_t = 30 to n_t = 50), at frequencies up to 200 kHz, causes a double increase in the efficiency of wireless energy transmission. At 800 - 1000 kHz, the efficiency increase reaches 10%. Further increasing the number of turns of the coils (from n_t = 50 to n_t = 70), at frequencies up to 200 kHz, results in an increase in efficiency of up to 50%. At higher frequencies, the increase in efficiency is small and does not exceed several percent.

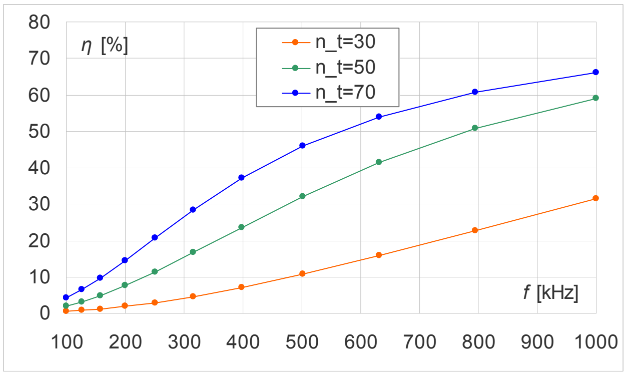

Fig.7. Results comparison of power transfer efficiency dependent of number of turns (n_t) for the case r = 20 mm, h = 20 mm

Analysing the system for the radius of the coils r = 20 mm and the distance between the coils h = 20 mm, it can be seen that increasing the number of turns of the coils (from n_t = 30 to n_t = 50) causes even a threefold increase in the efficiency of the WPT system (Fig. 7). Further increasing the number of turns of the coils (from n_t = 50 to n_t = 70), at frequencies up to 200 kHz, causes a double increase in the efficiency of the WPT system. At higher frequencies, the increase in efficiency is much smaller (Fig. 7).

In addition, Figures 8-9 show the characteristics for the source (I_z) and receiver (I_o) current for the case where the highest efficiency was obtained (almost 90%), i.e. for r = 20 mm, h = 10 mm.

In Figure 9 the receiver current values depending on the number of turns and the frequency were presented. It can be seen that if the WPT system efficiency is 50% and more, then the highest receiver current will be at an efficiency value of 50%. Regardless of the number of turns, this relationship is true and results from the properties of the energy transmission system.

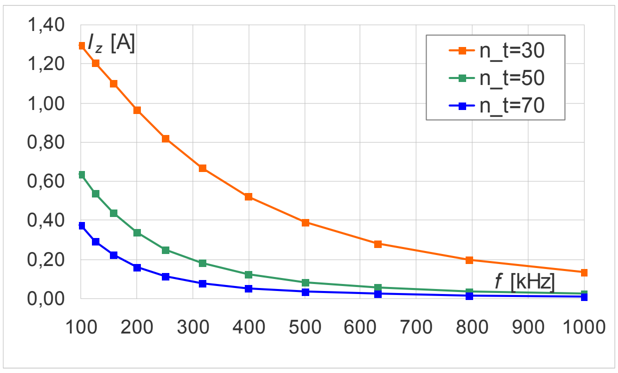

Fig.8. The influence the number of turns on the source current for the case r = 20 mm, h = 10 mm

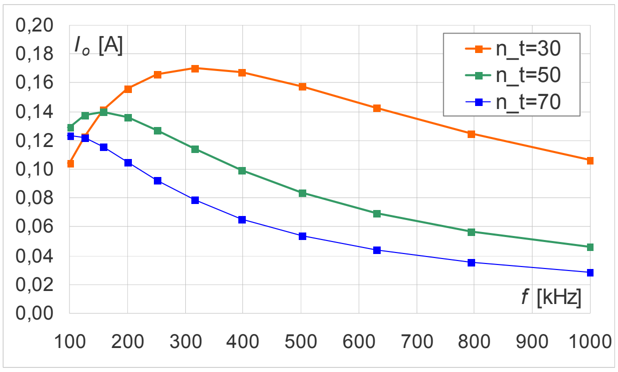

Fig.9. Receiver current characteristics dependent of number of turns for the case r = 20 mm, h = 10 mm

With wireless power transfer, the efficiency of the system increases as the frequency increases. Increasing the number of turns also causes a significant increase in the efficiency of the analysed system. The maximum efficiency of the WPT system for the radius of the coils r = 5 mm and the distance between the coils h = 2.5 mm does not exceed 45% at 1 MHz. For a system with a radius of coils r = 5 mm and twice greater distance between the coils, i.e. h = 5 mm, the efficiency of the WPT system is very low and does not exceed 4% at the same frequency. This is due to too much distance between the coils. The maximum efficiency of the wireless energy transmission system for twice larger radius of the coils i.e. r = 20 mm and the distance between the coils h = 10 mm reaches 90% at 1 MHz. For a system with a coil radius r = 20 mm and twice greater distance between the coils, i.e. h = 20 mm, the efficiency of the WPT system does not exceed 70% at the same frequency. The highest efficiency values are achieved for the largest number of turns, i.e. n_t = 30 and n_t = 70, respectively, and the smallest distance between coils, i.e. h = 5 mm and h = 10 mm, respectively. For a WPT system with a radius of coils r = 5 mm, the efficiency of energy transmission at the lowest analysed frequency, i.e. 100 kHz, is practically zero. For a WPT system with a radius of coils r = 20 mm, the efficiency of energy transmission at the lowest analysed frequency, i.e. 100 kHz, reaches up to 40% at h = 10 mm and does not exceed a few percent for twice the distance between the coils, i.e. h = 20 mm.

Conclusions

Nowadays, wireless power transfer is becoming more and more important. The analysis of the WPT periodic system can be carried out using numerical computational methods or through experimental testing of prototypes, which are time consuming and often difficult to perform. The presented results can be helpful with the use of optimisation algorithms when selecting appropriate operating conditions for the system in order to obtain maximum efficiency system [4, 6, 8].

Quick and easy modelling through the appropriate selection of geometry and electrical parameters of the system enables building WPT systems with the desired parameters. The proposed solution allows analysing the efficiency of the system. Appropriate selection of the radius, number of turns, distance between them and electrical parameters of the system allows to find a solution at which it is possible to load mobile devices.

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