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Selection of load impedance in order to maximize the receiver power in the periodic WPT system

***Abstract**. The article presents the analytical and numerical approach to solve the periodic Wireless Power Transfer (WPT) system. The model under consideration contained two planes (transmitting and receiving). Each of them was composed of square coils forming a transmitting-receiving WPT cells, in which energy was transmitted. Various geometry variants were included in the analysis, such as the distance between the transmitting and receiving coils, as well as the number of turns and a wide frequency range (0.1-1 MHz). The Finite Element Method (FEM) with the using periodic boundary conditions for the analysis was used. The analysis concerned comparison of the efficiency of the system by appropriate selection of resistance in order to determine the maximum load power. The compliance of the analytical and numerical results indicates the correct selection of the conditions and assumptions of the adopted methods and shows at which system parameters wireless energy transmission is possible. The proposed systems can be used for wireless charging of mobile devices, and can also be used to shape the distribution of the magnetic field.*

***Streszczenie.** W artykule przedstawiono analityczne i numeryczne podejście w celu rozwiązania periodycznego układu WPT. Rozpatrywany układ zawierał dwie płaszczyzny (nadawczą i odbiorczą). Każda z nich złożona była z cewek kwadratowych tworzących nadawczo-odbiorcze komórki WPT, w których dochodziło do przesyłu energii. W analizie uwzględniono różne warianty geometrii, takie jak odległość między cewką nadawczą i odbiorczą, a także liczbę zwojów i szeroki zakres częstotliwości (0.1-1 MHz). Do analizy wykorzystano metodę elementów skończonych (FEM) z zastosowaniem periodycznych warunków brzegowych. Analiza dotyczyła porównania sprawności układu poprzez odpowiedni dobór rezystancji w celu wyznaczenia maksymalnej mocy obciążenia. Zgodność wyników analitycznych i numerycznych wskazuje na poprawny dobór warunków i założeń przyjętych metod oraz pokazuje, przy jakich parametrach systemu możliwy jest bezprzewodowy przesył energii. Proponowane systemy mogą służyć do bezprzewodowego ładowania urządzeń mobilnych, a także mogą służyć do kształtowania rozkładu pola magnetycznego. (**Dobór impedancji obciążenia w celu maksymalizacji mocy odbiornika w periodycznym układzie WPT**).*

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

Introduction

Recently, there has been a noticeable increased interest in the improvement and efficiency of energy collection in order to charge wireless or mobile devices. Number of sensors (e.g. iris scanner) has contributed to the growing demand for batteries with a larger capacity, which include determine the practical mobility of devices. Recently, a common way of supplying mobile devices with energy is charging with the use of wireless power transfer (WPT) [1-6]. There are solutions that improve the efficiency of the WPT system, e.g. by introducing two additional coils into the transceiver system [7]. Also in the literature, approaches aimed at increasing energy transfer by reducing the winding resistance are considered [8]. This solution is possible through the use of a resonant system in which the coils do not have ferromagnetic cores. Another way to increase the efficiency of the system is to use a non-periodic coil system [9]. or appropriate selection of the type of coils, their geometry, or the number of turns [5]. WPT has become more popular through its use, among others in hybrid or electric cars [2, 10, 11]. It is also possible to charge vehicle batteries by transferring energy while driving. In this case, the transmitting coils are distributed along the path of the vehicle, which allows the use of such vehicles, e.g. in factories. The WPT system is also considered in medicine, eg for wireless charging of medical implants in the human body [12, 13] and a beacon [14]. Due to the increasingly growing requirements in architecture and interior design, WPT has also found application in intelligent buildings [15, 16]. Each solution requires a multi-variant analysis and verification of the results. In order to avoid early prototyping and performing a series of analyzes, it is possible to use analytical and numerical methods already at the design stage.

The article presents an analysis of the WPT system, in which a set of several coils participating in energy transfer was replaced with surfaces made of periodically distributed planar coils. Adjacent segments containing a pair of coils (transmit and receive) between which energy is exchanged, can be used to power multiple independent loads or replace conventional WPT systems. A proprietary analytical method for solving systems of this type was developed and presented, which let to quickly determine the parameters of the system (e.g. efficiency). The article also presents the numerical model, taking into account the periodic distribution of the square coils. The results obtained by both methods were compered which confirmed assumptions made.

By appropriate selection of the load resistance, it was possible to determine the maximum load power of the WPT system. Therefore, calculations of exemplary periodic WPT systems were performed over a frequency range from 0.1 MHz to 1 MHz. The analysis has taken into consideration the influence of geometric parameters of the coils on the efficiency of the system.

Wireless power transfer – proposed periodic model

The considered and analysed WPT system contains many inductive elements – square coils (Fig. 1). The one WPT cell consists of a transmitter-receiver pair (Fig. 2) constituting an arrangement of identical coils with a radius (r) and the number of turns (n).

In this configuration, it is possible to supply multiple receivers at the same time. An example of the use of the periodic structure of the WPT is very low voltage lighting. Arrays of light emitting diodes (LEDs) consist of many chipsets, such light sources can be powered by WPT, which provides the ability to independently control each light source. Periodically placed transmitting coils can transfer energy to several LED chipsets through a dielectric barrier (e.g. a wall or ceiling).

The each cell has outdoor dimensions $d \times d$ (Fig. 2). The transmitter-receiver pairs are coaxial. The distance between transmitter and receiver coils is represented by h. The turns are placed on a plastic carcass in which compensatory capacitors connected in series with the coils are mounted. The spatial distribution of the WPT cells leads to the creation of a periodic net that includes the transmitting and receiving surfaces. Between them the energy transmission occurs (Figs. 1, 3). The transmitting surface is powered so that each transmitter is connected in parallel with a sinusoidal voltage source with the RMS value ($\underline{U}$). The coils forming the receiving surface are connected directly to the load.

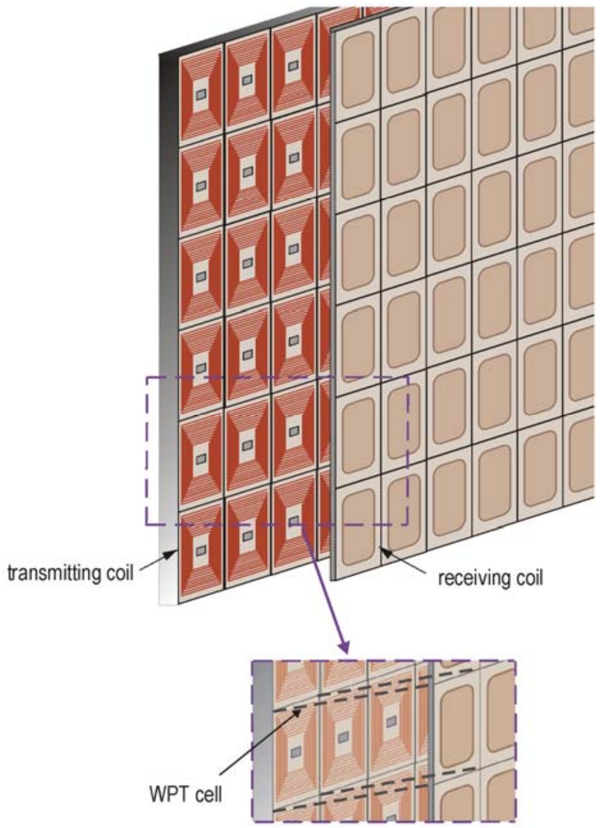

Fig.1. A three-dimensional view on the periodic WPT system composed of square coils

The presented WPT system with square coils ensures an increase density of transmitted power in the area between the receiving and transmitting surface. It also allows to the choice of conditions for the power supply depending on the dictate requirements. The article presents analysis, in which it is possible to power supply of multiple independent receivers. In this system the net or separately each WPT cell is assigned a separate load ($\underline{Z}$).

In order to analyse the periodic WPT 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).

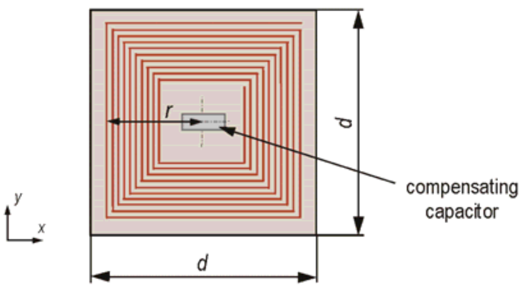

Fig.2. A transmitting/receiving coil of the periodic WPT system ($A_{x,y}$ is one of many WPT cells)

In the figure 2, the selected coil ($A_{x,y}$) is presented. It represents one of the coils in the net. Each coil is marked by $A_{x+i,y+j}$ and belongs to the net of identical coils, where i is the number of the column and j is the number of the row in the net (i, $j \in \mathbf{C}$, where **C** is a set of integers). Presented coil has 8 neighbours, where 4 are in the corners ($A_{x+1,y+1}$, $A_{x+1,y-1}$ and $A_{x-1,y+1}$, $A_{x-1,y-1}$). In this case, the others 4 coils of any $A_{x,y}$ element – the adjacent coils ($A_{x+1,y}$, $A_{x-1,y}$, $A_{x,y+1}$, $A_{x,y-1}$) are spaced from it by a distance d.

Numerical approach – Finite Element Method (FEM)

These types of WPT issues can be calculated using numerical, analytical and experimental methods. In the case of the numerical and analytical methods, a multivariate analysis is possible, because it is easier to modify the reference model than in the case of the experiment. The analysis of the WPT system can be performed using e.g. the numerical methods like FEM [5, 17], FDTD [18] or FDFD. The article proposes an analysis of the WPT system with the use of FEM. The accuracy of the solution is depended on the size of the model, which is represented by the number of degrees of freedom (N_{DOF}). The more N_{DOF} allows receiving the greater the accuracy of the solution, but results the longer the calculation time. In the case of numerical methods, it is necessary to accurately reproduce the model, adopt appropriate assumptions and boundary conditions. In this case, the model had N_{DOF} = 226470.

Numerical analysis of the WPT system requires consideration e.g.: coil geometry, number of turns and their distribution and also elements of the electric circuit connected to each coil [5, 19, 20]. The proposed solution of the WPT system composed of many WPT cells allows for the analysis of a single WPT cell with periodic boundary conditions both in x (PBC_x) and y (PBC_y) directions (Fig. 3). PBC are applied on left and right as well as front and back boundaries, in order to project infinite array of WPT cells. In top and bottom of the model the perfectly matched layer (PML) was put. The compensating capacitor (Fig. 3) is modelled as an element with a concentrated capacity (C). In the proposed analysis, it is possible to omit the carcass in the WPT 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 the RMS value ($\underline{U}$) and frequency (f), which forcing the flow current transmitter's ($\underline{I}_{tr}$). In the receiving coil the source is replaced by a linear load ($\underline{Z}$), which conducts the induced current ($\underline{I}_{re}$).

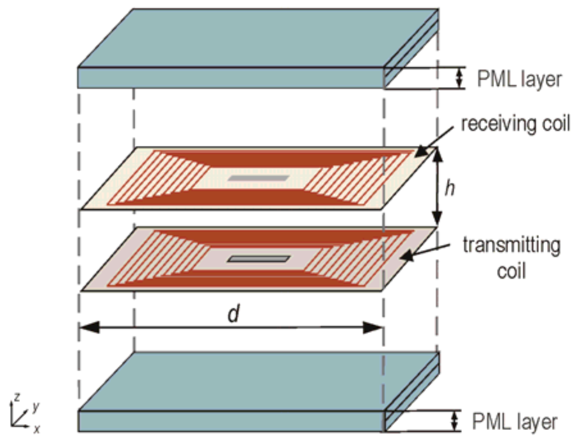

Fig.3. The numerical model of the periodic WPT system represented by one WPT cell

The problem of energy transport in the analysed model is solved using magnetic vector potential

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

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

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

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 where **n** is a normal vector to surface

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

(4) $$\mathbf{n} = [\mathbf{1}_x \ \mathbf{1}_y \ \mathbf{1}_z]$$

Analytical approach

The realization of the numerical model is more difficult than the analytical one. The numerical model has to take into account the appropriate choice of boundary conditions and many necessary simplifications dictate by the accepted numerical method. Therefore, in many cases an analytical model is advisable, because gives a faster preliminary solution.

In the article, the developed analytical solution for model of periodic WPT system composed of many square coils (transmitting and receiving) is presented. The analysis of the infinitely wide periodic net was reduced to the case of a single WPT cell. The solution of analytical model in frequency domain can be performed using methods of circuit analysis (Fig. 4). The primary problem in this type of analysis is to determine the values of the lumped parameters, taking into account the influence of adjacent segments on the equivalent inductances of the transmitting coil (L_{tr}), receiving coil (L_{re}) and their mutual inductance (M_{tr}).

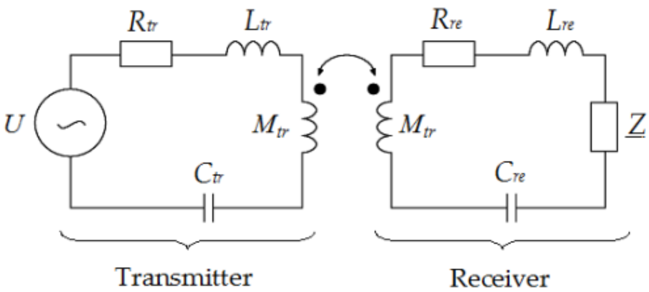

Fig.4. The analytical model of the periodic WPT system represented by one WPT cell

The system was built of identical coils arranged coaxially at a distance of *h* and made of thin wire with a diameter of (*w*) with thickness of wire insulation (*i*) and conductivity (σ). Length of windings in one coil is described by equation

(5) $$l_{sum} = 4n\left[2r - n\left(w + i\right)\right]$$

For identical transmitting and receiving coils calculated resistances are equal $R_c = R_{tr} = R_{re}$ [20].
Taking into account equation (5) the formula for the resistance of coil is

(6) $$R_c = \frac{l_{sum}}{\sigma\pi \frac{w^2}{4}} = \frac{4n\left[2r - n\left(w+i\right)\right]}{\sigma\pi \frac{w^2}{4}}$$

In infinite periodic grid, where each coil has identical electrical parameters and magnetic couplings with its neighbors, it is possible to reduce an analysis to the single WPT cell (Fig. 4). Mutual inductances between coil in the cell $A_{x,y}$ and coils in cells $A_{x+i,y+j}$ appear and affect inductance of coil in $A_{x,y}$, which can be expressed as

(7) $$L_c = L_{self} - \sum_i \sum_j \left(M_{x+i,y+j}\right)$$

where: L_c – effective self-inductance; $M_{x+i,y+j}$ – mutual inductance between coils adjacent in horizontal plane, for $i\neq0$ and $j\neq0$; L_{self} – self-inductance of a square planar coil.

Self-inductance is calculated using equation [5, 20, 21]

(8) $$L_{self} = \frac{\mu_0 c_1 d_m n^2}{2}\left[\ln\left(\frac{c_2}{wsp}\right) + c_3 wsp + c_4 wsp^2\right]$$

where d_m is mean diameter and *wsp* is a fill factor

(9) $$d_m = \frac{2r + 2\left[r - n\left(w+i\right)\right]}{2}$$

(10) $$wsp = \frac{2r - 2\left[r - n\left(w+i\right)\right]}{2r + 2\left[r - n\left(w+i\right)\right]}$$

In the equation (8), used coefficients c_1, c_2, c_3, c_4 are depending on shape of the coil [21]. For square coil coefficients are: c_1=1.46, c_2=1.9, c_3=0.18, c_4=0.13. For identical transmitting and receiving coils calculated inductances are equal $L_c = L_{tr} = L_{re}$ (Fig. 4).

From equation (7), the inductance of the considered coil in the segment $A_{x,y}$ take a form

(11) $$L_c = L_{self} - M_{pe}$$

where: M_{pe} – sum of mutual inductances in a periodic grid and since they reduce the inductance of coil.

The mutual inductance M_{pe} is written with a minus. For the case when loads $Z=\infty$ and there is no capacitor in series with transmitter coils at arbitrary frequency *f* one may find M_{pe} as

(12) $$M_{pe} = \frac{U/\underline{I}_{t,\infty} - R_c}{\mathrm{j}2\pi f} - L_{self}$$

where: $\underline{I}_{t,\infty}=|\underline{I}_{t,\infty}|e^{\mathrm{j}\psi}$ – source current; $|\underline{I}_{t,\infty}|$ – RMS value of the source current, ψ – phase angle between the source voltage and current.

According to an equivalent circuit shown in Fig. 4, instead of calculating inductances $M_{tr,x+i,y+j}$, an effective mutual inductance (M_{tr}) can be found using equation

(13) $$M_{tr} = \frac{\underline{U}_{r,\infty}/\underline{I}_{t,\infty}}{\mathrm{j}2\pi f}$$

where: $\underline{U}_{r,\infty}=|\underline{U}_{r,\infty}|e^{\mathrm{j}\theta}$ – voltage induced in a receiving coil, $|\underline{U}_{r,\infty}|$ – RMS value of the induced voltage, θ – phase angle between the source voltage and induced voltage.

After calculations of self-inductance L_{self} and mutual inductance M_{pe}, it is possible to find the compensating capacity (C), at a specified frequency. Compensating capacity at definite frequency is represented by

$$C(f)=\frac{1}{4\pi^2 f^2 L_c}=\frac{1}{4\pi^2 f^2\left(L_{self}-M_{pe}\right)} \tag{14}$$

Accepted conditions for analysis

The analysis concerned selected variants of the model in order to confirm the correctness of the assumptions for the analytical and numerical model. A model with a coil of r = 25 mm was considered. The variation in the number of turns $n \in \{80;\ 90;\ 100\}$ and the distance between the transmitting and receiving surfaces $h \in \{12.5;\ 25\}$ mm are taken into account. Analysis connected with frequency domain from f_{min} = 100 kHz to f_{max} = 1000 kHz. The values, which were used in analysis, are presented in Table 1.

Table 1. Accepted values in the analysis of WPT system

parameter	symbol	value
wire with a diameter	w	200 µm
conductivity of wire	σ	$5.6\cdot10^7$ S/m
source with an effective value	U	1 V
thickness of wire insulation	i	5 µm

The aim of the study was to check both methods through estimate the highest possible load power of the WPT system. On the basis of obtained results for periodic WPT system, the correctness of the proposed circuit model was verified by comparing active power of the passive load (Z) (e.g. receiver power):

$$P_o = Z\left|\underline{I}_r\right|^2 \tag{15}$$

transmitter power represented by

$$P_z = U\underline{I}_t \tag{16}$$

and also transfer efficiency

$$\eta = \frac{P_o}{P_z}100\% \tag{17}$$

To make the maximum power transfer, the results were based on the correct selection of the optimal load impedance (Z) represented by:

$$Z = R_c + \frac{\omega^2 M_{tr}^{\ 2}}{R_c} \tag{18}$$

Calculated optimum load impedances and compensating capacities at f_{max} were presented in Table 2. The values were calculated using equations, which were previous presented.

Table 2. Calculated parameters

n	C (pF)	Z (Ω)		M_{tr} (µH)	
		h = 0.5 r	h = r	h = 0.5 r	h = r
80	124	9716	491	38.77	8.66
90	114	11355	578	43.08	9.66
100	109	12305	628	45.71	10.27

Calculation results

The results of the analysed WPT system were obtained by the numerical and analytical method. The numerical model (Fig. 3) was created in the *Comsol Multiphysics program*.

Figures 5-10 present comparisons of the source power (Figs. 5, 8), the receiver power (Figs. 6, 9) and WPT efficiency (Figs. 7, 10), for different values of the number of turns of the transmitting and receiving coils and different distances between these coils.

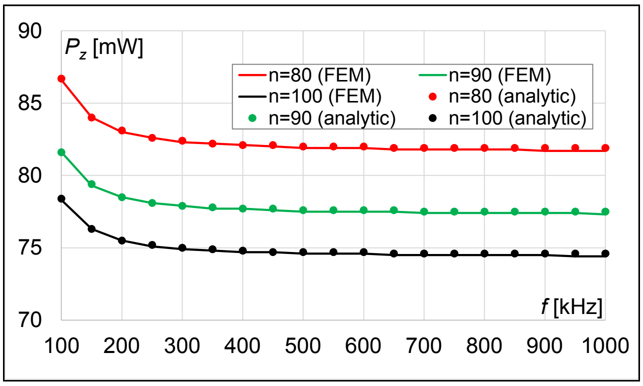

Fig.5. Results of transmitter power (P_z) dependent on the number of turns (n=80÷100) at distance h=12.5 mm

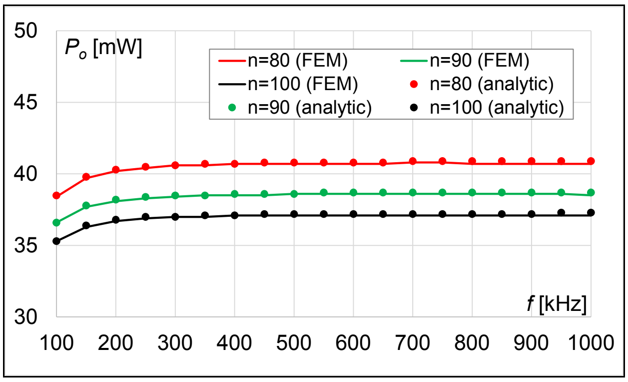

Fig.6. Results of receiver power (P_o) dependent on the number of turns (n=80÷100) at distance h=12.5 mm

Figures 5 and 8 show the variability of the source power (P_z) depending on the frequency and number of turns. When number of turns increases the P_z decrease. In the whole frequency range the P_z is larger for h = 25 mm (P_z = 128 mW at 100 kHz and n = 80) than for h = 12.5 mm (P_z = 87 mW at 100 kHz and n = 80) even by 45%. With the increase in frequency, the P_z decrease regardless of the number of turns or the distance between the transmitting and receiving coils.

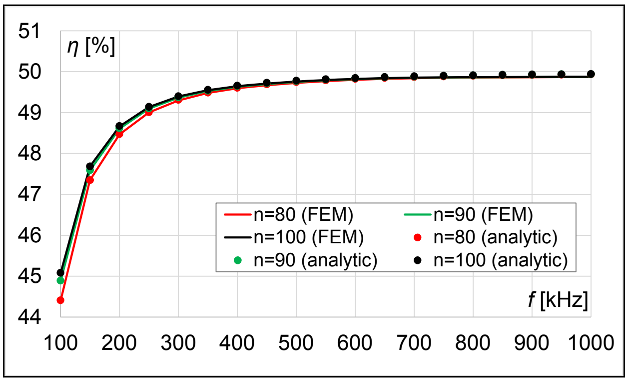

Fig.7. Results of power transfer efficiency (η) dependent on the number of turns (n=80÷100) at distance h=12.5 mm

Figures 6 and 9 show the variability of the receiver power (P_o) depending on the frequency and number of turns for different distances between the coils. In both cases (h = 12.5 mm and h = 25 mm), with the increase in frequency, the P_o increases regardless of the number of turns. For h = 25 mm, the receiver power reaches its maximum value when the efficiency reaches approximately 50%. For h = 12.5 mm, it was possible to broad the frequency range of maximum load power. Doubling the distance causes the receiver power to have lower values than at h = 12.5 mm.

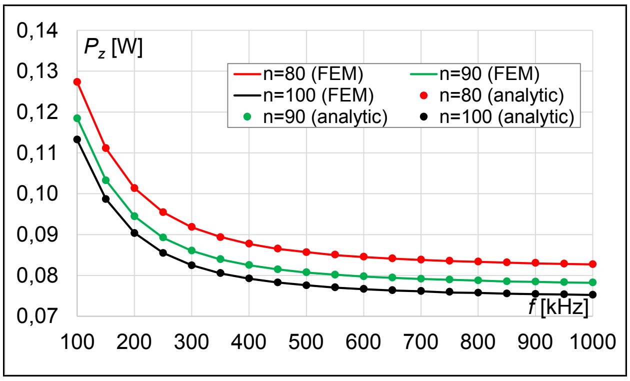

Fig.8. Results of transmitter power (P_z) dependent on the number of turns (n=80÷100) at distance h=25 mm

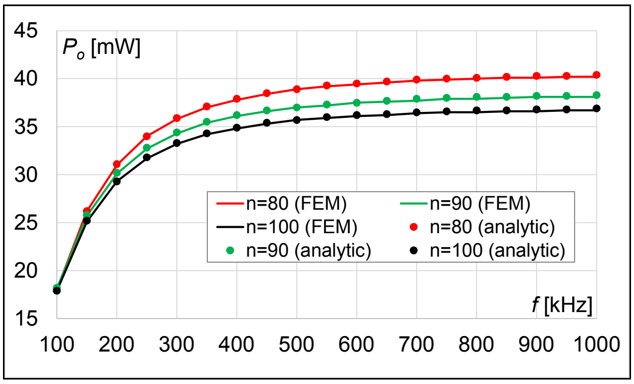

Fig.9. Results of receiver power (P_o) dependent on the number of turns (n=80÷100) at distance h=25 mm

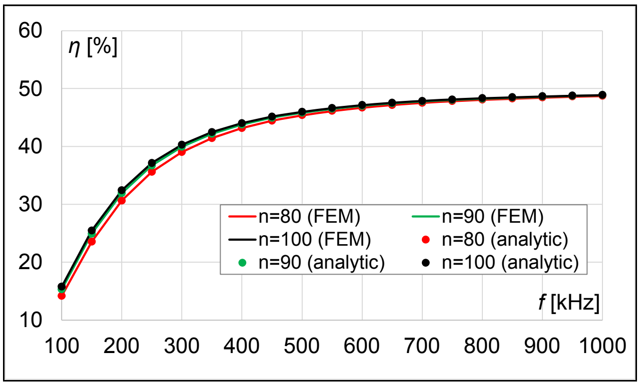

Fig.10. Results of power transfer efficiency (η) dependent on the number of turns (n=80÷100) at distance h=25 mm

Figures 7 and 10 show the variability of the transfer efficiency (η) depending on the frequency and number of turns for different distances between the coils. With the increase in frequency, the efficiency of the WPT system increases and then stabilizes. In both cases (h = 12.5 mm and h = 25 mm), in lower frequency range (100 kHz – 300 kHz), the efficiency values vary little (less than 3%) with the number of turns, but at frequeny over 400 kHz – 500 kHz the efficiency values are the same regardless of the number of turns. Doubling the distance between the coils (h = 25 mm) results in lower efficiency values in the lower frequency range e.g. at 300 kHz efficiency exceeds 49% for h = 12.5 mm and reaches only 40% for h = 25 mm.

On all characteristics, it can be noted that comparing the values from numerical model and analytical model (analytic) almost perfect agreement have appeared.

Conclusions

In the article a wireless power transfer system with periodically arranged planar square coils was presented. A proprietary analytical method for solving systems of this type was developed and presented. Its purpose is to quickly determine the parameters of the system (e.g. power, efficiency) without the need to make complex models and solve them using numerical methods. The article also presents the conditions that help to reduce the size and complexity of the model in commonly used numerical solutions. Adjusting the geometrical parameters makes it possible to obtain high efficiency of power transmission for many loads. The given solutions, adopted in the numerical and analytical methods, allow studying the influence of the coil geometry on the power transmission.

Additionally, the article presented the approach and results of both the analytical and numerical methods. By appropriate selection of the load resistance, it was possible to determine the maximum load power of the WPT system. The results obtained with the proposed analytical method were consistent with the results obtained with the numerical method, which confirmed the correctness of the assumptions of the proposed analytical method.

The analytical and numerical solutions presented in the article allow studying the influence of the coil geometry and the distance between the transmitter and receiver on power transmission. The calculations were made in a wide range of frequencies. The analysis concerned the influence of geometric parameters of the coils in the WPT cell on the efficiency of the system and the power of the transmitter and receiver. By adjusting the number of turns or increasing the frequency of the current, it was possible to obtain high efficiency of power transmission for the loads supplied by the proposed system, without the use of intermediate coils. Even at distances equal to the radius of the coil, the efficiency of the system was in the order of 50%.

These methods may constitute as an alternative to the experimental prototypes and simplified analytical-empirical models, currently used to analyse the electrical and magnetic properties of the WPT systems.

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