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The analysis of the influence of the plane coils geometry configuration on the efficiency of WPT system

***Abstract**. The article presents a method and results for numerical and analytical analysis of Wireless Power Transfer (WPT) system consisting of transmitting and receiving plane coils. In the analysis took into account different variants of the WPT system geometry (number of turns, distance between the transmitting-receiving coils). The influence of variable system geometry and the frequency on system efficiency was analysed. The Finite Element Method (FEM) with the using antiperiodicity boundary conditions for the analysis was used. The results obtained by numerical and analytical method indicate at which system parameters wireless energy transfer is possible.*

***Streszczenie.** W artykule przedstawiono metody i wyniki analizy numerycznej oraz analitycznej układu Wireless Power Transfer (WPT) złożonego z cewek płaskich (nadawczych i odbiorczych). W analizie uwzględniono różne warianty geometrii układu WPT (liczba zwojów, odległość między cewkami). Analizowano wpływ geometrii układu oraz częstotliwości na sprawność układu. Do analizy wykorzystano metodę elementów skończonych (FEM) z zastosowaniem aperiodycznych warunków brzegowych. Otrzymane wyniki wskazują, przy jakich parametrach układu możliwy jest bezprzewodowy transfer energii. (**Analiza wpływu geometrii konfiguracji cewek płaskich na sprawność bezprzewodowego przesyłu mocy**).*

Keywords: wireless power transfer (WPT), magnetic field, numerical and analytical analysis, Finite Element Method (FEM).
Słowa kluczowe: bezprzewodowa transmisja energii (WPT), pole magnetyczne, analiza numeryczna i analityczna, FEM.

Introduction

Recently, there has been an increase in energy demand in wireless and mobile devices. Their computing power and the number of supported sensors are still growing (e.g. fingerprint sensor, iris scanner). These factors affect the growing demand for batteries with increased capacity, extending their charging time and determine the mobility of devices [1-8, 14-18, 20, 21].

One way to supply mobile devices with energy is charging using wireless power transfer (WPT). Technology of WPT became more accessible in extensive scattered grids of many interdependent sources and loads [19]. Thanks to the concept of inductive power transfer (IPT) it is possible, among others wireless charging of electric vehicles and modern technology (telephones, smartphones, laptops) [1, 6]. WPT is increasingly used, among others in the automotive industry in solutions for hybrid and electric cars [4-5]. The possibility of charging batteries at a distance of 10 cm without using wires has already been developed [7]. Wireless charging is also considered in lighting in hard-to-reach places [10] or intelligent buildings with sensors inside the walls and in the systems of beacons in hard-to-reach places [3, 14-18, 20]. Recently, intensive work is underway on wireless power supply of implanted medical devices such as pumps (LVAD) and pacemakers [11].

WPT is considered an alternative method of charging wireless devices, in which the most common pair of transceiver coils [1-3, 8] or coil system and in some cases power transfer is assisted using metamaterial structures [9, 12]. For low frequencies (f < 1 MHz), the system of coils as domino-resonators and the linear system of resonators are taken into account [3].

However, the topology of parallel flat coils, working as a group of transmitters and receivers, is still not fully developed. In this article will be presented one of these systems, which included checker structure composed of transceivers and receivers coils. Proposed WPT system could be used to charge electric devices as the wireless power transfer system. An analysis of the influence of system parameters will be carried out, including number of turns, distance between coils and frequency of the system operation on the efficiency of energy transmission.

Also the article presents the results of numerical analysis, which were compared with the analytic solution previously described in [14].

Analysed model of wireless power transfer

In modern WPT solutions, apart from systems with several coils, also those consisting of many induction elements are used. The transmitter-receiver pair, consisting of identical coils with a radius r = 10 mm and number of turns n_t, is a WPT cell with external dimensions $d \times d$, where $d \approx 2^*r$ (Figs. 1, 2). The transmitting and receiving coils are coaxial and placed at a distance h. The turns are placed on a plastic carcass, in which compensating capacitors connected in series with the coil are embedded. The considered system is a checker because adjacent coils have the opposite winding direction of the coils (Fig. 2). For this reason, the system can also be called non-periodic. Spatial distribution of WPT cells on the plane leads to the creation of a non-periodic network, which includes the transmitting and receiving surfaces, between which energy transmission occurs.

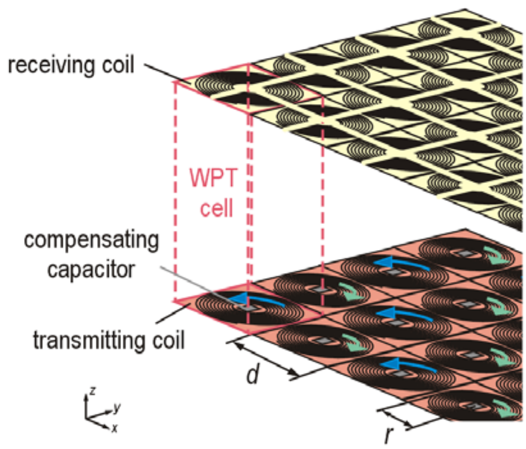

Fig.1. A view on an analysed WPT system

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 analysed configuration of the WPT system ensures an increase in the density of transmitted power in the area between the receiving and transmitting surfaces. It also allows the selection of power conditions depending on the imposed requirements. Each WPT cell is assigned a separate load, which is $\underline{Z}_l$.

The analysis of the WPT system can be reduced to a two-dimensional surface XY showing a set of transmitting/receiving coils (Fig. 1, 2). Elements marked in yellow contained turns wound in the same way. While, the cells adjacent to the edge of exemplary cell $A_{x,y}$ contained inversely wound turns (marked with a green line, e.g. $A_{x+1,y}$).

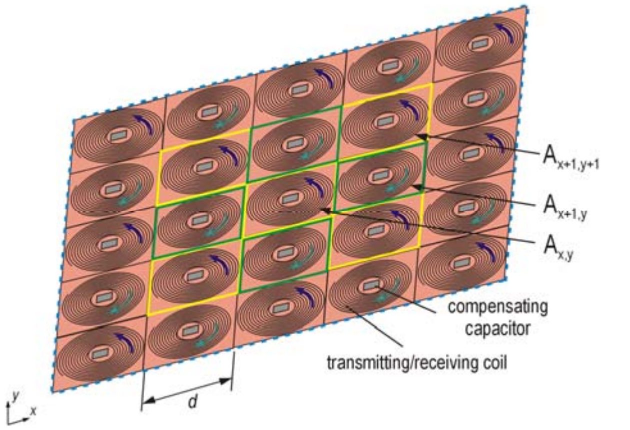

Fig.2. A two-dimensional network transmitting/receiving surface of the non-periodic WPT system ($A_{x,y}$ – the WPT cell)

Numerical and analytic analysis of WPT system

The analysis of the WPT system can be performed using the numerical methods (e.g. FEM, FDTD, FDFD) [9, 14], analytic analysis [14] or experimental research. When using numerical analysis, it is necessary to prepare a 3D model and set complex boundary conditions. The efficiency and accuracy of the solution depend on the size of the model - the number of degrees of freedom (NDOF). The greater NDOF, the more accurate the solution is, but the longer the calculation time. In contrast, experimental systems require the construction of a multi-segment prototype with specific geometry. This allows the system to be analysed due to different electrical parameters (e.g. frequency, load), but limits the potential identification of structure influence (e.g. coil radius, number of turns) on operating parameters. At the design and preliminary analysis of system properties (e.g. efficiency, power losses, load power), it is sufficient to use mathematical models.

In the analysis of WPT model the Finite Element Method (FEM) was used. In this case, the numerical analysis of the energy transfer in a system composed of many WPT cells requires taking into account: coil geometry, coil turns distribution, WPT cell number and elements of the electric circuit connected to each coil (Fig. 1, 3).

Used planar spiral coils were wound of several dozens of turns, made of very thin wires with diameter w. In order to reduce the number of degrees of freedom the current sheet approximation [14] was applied. This approach replaces the multi-turn coil with a homogeneous structure (Fig. 3). Numerical method of modelled coils – the current sheet is a model for a group of wires wound together around a carcass and insulated from each other by electrical insulator which thickness is marked as i. The current flows in the direction of wires. In this approximation of method is applied assumption:

(1) $$w < \delta$$

where δ is the penetration depth.

The current densities in other directions are omitted. To correctly apply this method of approximation, one may make the following assumptions.

The compensating capacitor is modelled as an element with a concentrated capacity (C). The capacity of the compensating capacitor may be defined from the parametric analysis of the system for different C. On the basis of a series resonant it is possible to find the compensating capacity (C), at a specified frequency [14].

In the analysis 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 $\underline{I}_z$. In the receiving coil, the source is replaced by a linear load $\underline{Z}_l$ which conducts the induced current $\underline{I}_o$.

For the analysis of the WPT model, all cells forming the transmitting and receiving surfaces are taken into account. 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 coils (Fig. 2, 3). In model antiperiodicity boundary conditions both in x and y direction are applied, in order to project infinite array of WPT cells. In top and bottom of the model the perfectly matched layer (PML) was put.

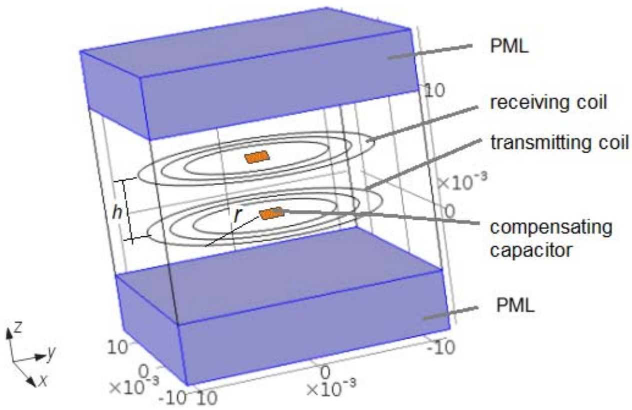

Fig.3. A three-dimensional view on one of WPT cell

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

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

Using the Helmholtz equation can solve description of magnetic phenomena in the frequency domain

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

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

The creation and solution of the numerical model of the WPT system is a multi-stage task that requires the use of numerical methods. Despite the possibility of performing simulations on typical computational units, a simpler model is desirable, providing a similar scope of analysis, but at the same time a less complex and much faster modelling and calculation process. The presented alternative is the analytic model described in [14]. It combines the use of passive four-terminal network and analytical formulas. As in the numerical model, the analysis of an infinitely extensive WPT network was reduced to the case of a single WPT cell. The solution of the model in the frequency domain is performed by any peripheral method. The difficulty is to determine the values of clustered parameters, taking into account the impact of adjacent segments on the replacement inductances of the transmitting coil L_z and receiving coil L_o and their mutual inductance M_{tr} [14].

The coil resistance can be determined by replacing the spiral structure of the windings with concentrically arranged circles of identical width ($w + i$). The average lengths of individual circles, respectively from the outer edge is [14]

$$l_n = \pi[2r - (2n-1)\cdot(w+i)] \tag{4}$$

Based on equation (3), the total length of all districts is

$$l_c = \sum_{n=1}^{n\_t} l_n = \pi\, n\_t[2r - n\_t(w+i)] \tag{5}$$

The self-inductance of a flat coil can be determined from [8]

$$L_{self} = 0.5C_1\mu_0 d_{avg}\, n\_t^2\left[\ln\left(C_2\rho^{-1}\right) + C_3\rho + C_4\rho^2\right] \tag{6}$$

where d_{avg} is the average diameter

$$d_{avg} = 2r - (w+i)n\_t \tag{7}$$

and ρ is the filling of the coil

$$\rho = \frac{(w+i)n\_t}{2r - (w+i)n\_t} \tag{8}$$

The coefficients: C_1, C_2, C_3, C_4 are depend on the geometry (shape) of the coil [8]. Because of passive load (Z_l) was considered, its active power is calculated by using the equation:

$$P_o = Z_l I_o^2 \tag{9}$$

Since of the resonant state obtained after an application of the compensating capacitor, the imaginary part of the transmitter current was negligible (Im[I_z] ≈ 0) therefore the voltage source produced only active power

$$P_z = U_t I_z \tag{10}$$

Taking into account obtained results for considered exemplary WTP system, was verified the validity of proposed electrical model by comparing absolute current of transmitter coils (I_z) and receiver coils (I_o), as also energy transfer efficiency (η). The power transfer efficiency is represented by

$$\eta = \frac{P_o}{P_z}\cdot 100\% \tag{11}$$

Results of the analysis

The calculation results of WPT system obtained by the numerical and analytical methods were compared. For this purpose, the norm of the current intensity of the transmitting coil (I_z) and receiving (I_o) and also the transfer efficiency (η) were compared, depending on the structure of the system. 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 antiperiodicity), and then solved using the FEM method. Analyzed model contained 597340 degrees of freedom.

The spiral coils considered are made of several dozen turns, made with thin wires with a diameter of w = 250 μm, the conductivity $\sigma = 5.6\cdot10^7$ S/m and thickness of coil isolation i = 10 μm. A source with an effective value U_t = 5 V and a frequency from f_{min} = 100 kHz to f_{max} = 1000 kHz is connected to the transmitter. The load Z_l = 50 Ω is attached to the receiving coil. Coils of size (r = 10 mm) and different number of turns (n_t) and distance (h) were analysed (Tab. 1).

Table 1. Considered variants of the WPT system

r [mm]	n_t	h [mm]
10	15	5 and 10
	25	5 and 10
	35	5 and 10

Figures 4 and 5 show the variability of the source current (I_z) depending on the frequency and number of turns. With the increase in frequency, the I_z decrease regardless of the number of turns or the distance between the transmitting and receiving coils. In the whole frequency range the I_z is larger for h = 10 mm than for h = 5 mm. For example, n_t = 15 the source current is 8 A at frequency equal 400 kHz and h = 5 mm. However, the same current value at n_t = 15 and h = 10 mm was observed at f = 1000 kHz. In the model with a smaller distance between the coils (h = 5 mm) the difference in the values between the numerical and analytical analysis does not exceed 12%. At twice the distance (h = 10 mm) the difference does not exceed 3%.

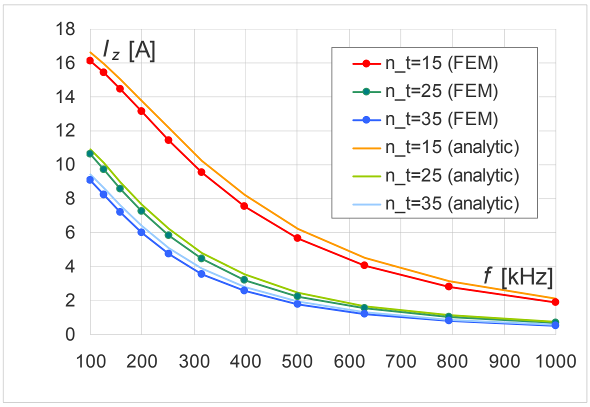

Fig.4. Results comparison of source current (I_z) dependent of number of turns (n_t) for the case h = 5 mm

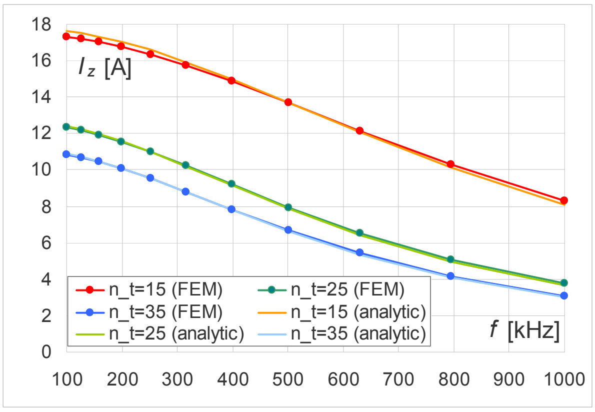

Fig.5. Results comparison of source current (I_z) dependent of number of turns (n_t) for the case h = 10 mm

Figures 6 and 7 show the variability of the receiver current (I_o) depending on the frequency and number of turns for different distances between the coils. The value of the receiver current increases until the efficiency for a given case reaches 50%. However, after achieving efficiency equal 50%, the I_o decreases.

With the increase in frequency, the efficiency of the WPT system increases regardless of the number of turns or the distance between the transmitting and receiving coils (Figs. 8, 9).

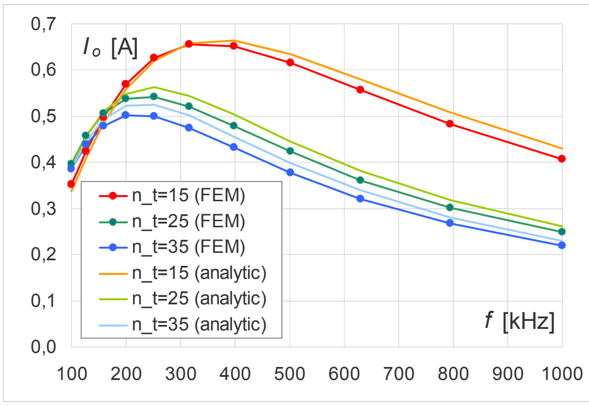

Fig.6. Results comparison of receiver current (I_o) dependent of number of turns (*n_t*) for the case *h* = 5 mm

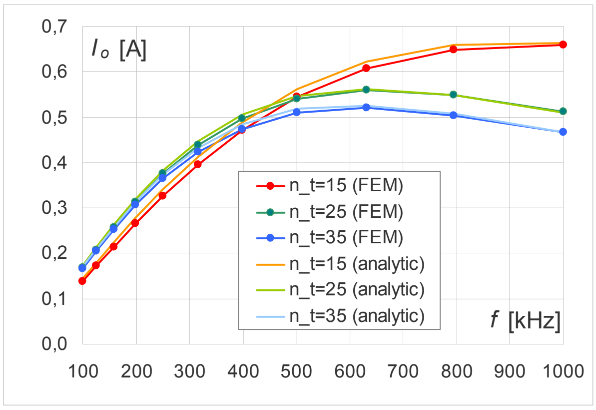

Fig.7. Results comparison of receiver current (I_o) dependent of number of turns (*n_t*) for the case *h* = 10 mm

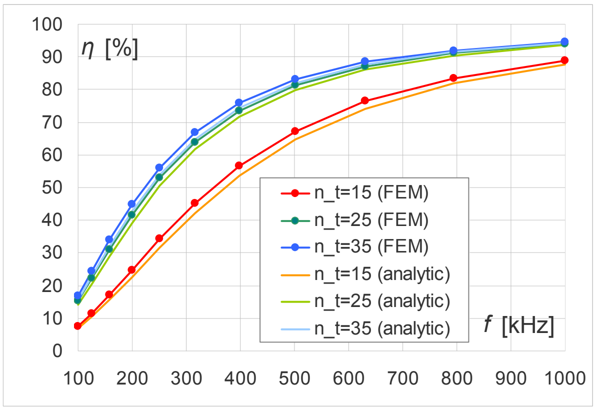

Fig.8. Results comparison of power transfer efficiency dependent of number of turns (*n_t*) for the case *h* = 5 mm

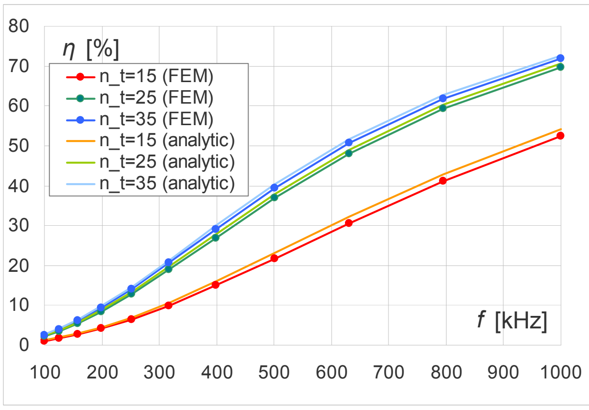

Fig.9. Results comparison of power transfer efficiency dependent of number of turns (*n_t*) for the case *h* = 10 mm

The highest efficiency of WPT system (94%) was observed for *f* = 1000 kHz, *n_t* = 35 and *h* = 5 mm. However, for *n_t* = 25 the efficiency of the system was slightly lower (92%). For model with *n_t* = 15 the maximum efficiency was 88%. The efficiency exceeds 90% already at 800 kHz for *n_t* = 25 and *n_t* = 35 (Fig. 6). Twice increasing the distance between the coils (*h* = 10 mm) reduced the efficiency of the system. The maximum efficiency value equal 72% was observed for *n_t* = 35 (Fig. 9).

Figures 10-11 show the distribution of the magnetic flux density norm. These values are always higher for twice the distance between the transmitting and receiving coils. For example, for *n_t* = 15, values of the magnetic flux density norm are higher more than four times for *h* = 10 mm.

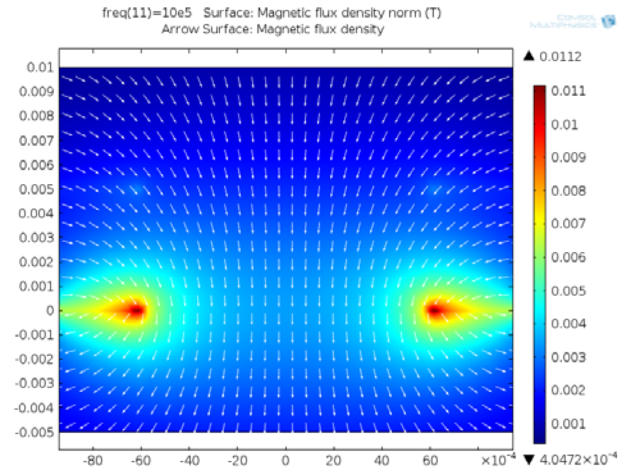

Fig.10. Distribution of the magnetic flux density norm [T] for the case where the number of turn is 15, *h* = 5 mm (XZ plane)

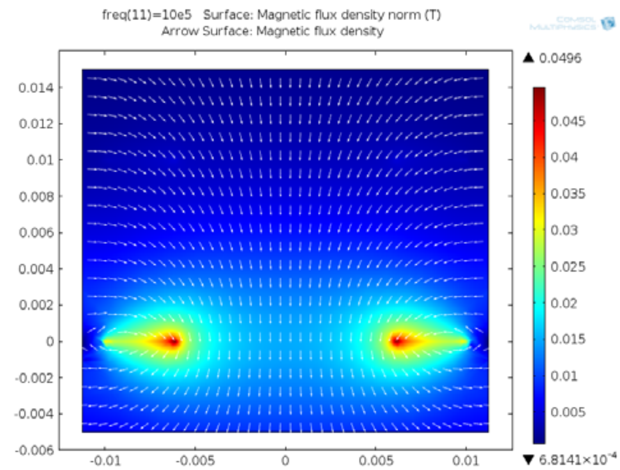

Fig.11. Distribution of the magnetic flux density norm [T] for the case *n_t* = 15, *h* = 10 mm (XZ plane)

Conclusions

The proposed non-periodic wireless power transfer system was investigated using numerical and analytical methods. The article presents the author's numerical model containing two planes of transmitting and receiving coils forming the WPT system. The influence of e.g. the distance between transmitter-receiver and the number of turns on the efficiency of the WPT system was checked. The analysis covered a wide frequency range. Numerical results were compared with the analytical solution presented in [14] where the equivalent electrical circuit model of the WPT cell was proposed. This model is an alternative for complex numerical analysis or experimental research of physical prototypes.

The numerical and analytical results indicated acceptable agreement of both models. The average difference for computed variants of WPT system was only 7%. In the model with a smaller distance between the coils ($h = 5$ mm) the difference in the values between the numerical and analytical analysis does not exceed 10%. At twice the distance ($h = 10$ mm) the difference does not exceed 8% (Figs. 8, 9).

This confirms the possibility of using both methods to analyse various WPT variants. Thanks to these methods, you can analyse, among others influence of the number of turns, radius of the coil, materials of which the WPT cell was made, distance between coils, size of the WPT cell on the value of wireless power transmission.

The presented results numerical analysis can be helpful with the use of optimisation algorithms in order to obtain maximum efficiency system [4, 6, 8].

Numerical modelling through the appropriate selection of geometry and electrical parameters of the model provides construction WPT systems with the desired parameters. A further analysis of wireless power transfer will focus on plane coils with different shapes, geometry and configuration.

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