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doi:10.15199/48.2023.01.14

Evaluation of the influence of the skin effect on the maximum efficiency of the WPT system

***Abstract**. The article presents the influence of the skin effect on the maximum possible efficiency in the developed periodic Wireless Power Transfer (WPT) systems. The presented periodic WPT system allows for the simultaneous supply / charging of many low-power receivers. The analysis was performed based on the two proposed methods, i.e. analytical and numerical. The analytical solution of the transmitting-receiving system takes into account the parameters calculated based on analytical equations concerning the influence of magnetic couplings, structure geometry and loads. A numerical solution was also proposed, which allows the number of degrees of freedom to be reduced by applying periodic conditions. In order to verify the proposed methods and check the influence of the skin effect on the efficiency of the WPT system, calculations and analysis were performed for models that took into account the variability of the number of turns, the distance between the transmitting and receiving coils, and the frequency of the energy source. The results prove that taking into account the skin effect in the proposed low-power WPT systems reduces the efficiency of the system by up to 8%.*

***Streszczenie.** W artykule przedstawiono wpływ efektu naskórkowości na maksymalną możliwą do uzyskania sprawność w opracowanych periodycznych układach Wireless Power Transfer (WPT). Zaprezentowany periodyczny układ WPT pozwala na jednoczesne zasilanie/ładowanie wielu odbiorników małej mocy. Analiza przykładowych wariantów została wykonana na podstawie zaproponowanych dwóch metod, tj. analitycznej i numerycznej. Rozwiązanie analityczne układu nadawczo-odbiorczego, uwzględnia parametry obliczone na podstawie równań analitycznych dotyczących wpływu sprzężeń magnetycznych, geometrii konstrukcji i obciążeń. Zaproponowano również rozwiązanie numeryczne, które pozwala na redukcję liczby stopni swobody poprzez zastosowanie warunków periodycznych. W celu weryfikacji zaproponowanych metod i sprawdzenia wpływu efektu naskórkowości na sprawność układu WPT wykonano obliczenia i analizę dla modeli, w których uwzględniono zmienność liczby zwojów, odległość między cewką nadawczą i odbiorczą oraz częstotliwość źródła energii. Wyniki dowodzą, że uwzględnienie efektu naskórkowości w zaproponowanych układach WPT małej mocy powoduje zmniejszenie sprawności układu nawet o 8%. (**Ocena wpływu efektu naskórkowości na maksymalną sprawność systemu WPT**).*

Keywords: wireless power transfer (WPT), magnetic fields, numerical and analytical analyses, skin effect, Finite Element Method (FEM).
Słowa kluczowe: bezprzewodowa transmisja energii, pole magnetyczne, analiza numeryczna i analityczna, efekt naskórkowości, FEM.

Introduction

The power obtained from the power station in the form of electricity is very costly and the transmission efficiency is very low (about 30%), because high tension conductors due to the high energy loss in high resistive wire. Also the power station that is running on coal, gas spends a lot of these resources to make electricity and is not cost effective and has a trouble connected with environmental issues. The other problem is the wires for powering home appliances at e.g. house, workplace, because reduces the range of machines and are failure prone. Considering the above, the method of wireless charging system would be beneficial in both economic and social aspects. Many industries are trying to explore the use of electric vehicles in order to the reduce fuel consumption (Fig. 1) [1-4].

Fig.1. Dynamic charging of EV systems with a rail composed of coils [4]

The main focus of researchers connected with wireless power transmission (WPT) system is to develop a wireless powering mechanism useful for private sector (e.g. medical, consumer use, industrial) [5-7] and also for public sector (e.g. transfer power over large scale at low cost and without pollution) [8]. In most systems, to obtain the flow of active energy, it is necessary to properly compensate the reactive power and balance the load [9]. WPT has become one of the most important research points in this century. Portability is the main motivation for WPT as the number of portable devices is enormously increasing and wired chargers will limit their portability. Several review works [10, 11, 12] explained the WPT theory and applications in brief.

In the late 20th century, WPT became popularity because of charging of portable consumer devices gained like e.g. electric toothbrushes, charging pad for cell phone [11] (Fig. 2). For the WPT applications of a few kilowatts (KW) like charging of electric vehicles, almost 90% of transmission efficiency can be achieved by increasing its operating frequency, and over 70% of efficiency is also possible to achieve for low-power (maximum 5W) mobile phone charging (Fig. 2).

Fig.2. Wireless Power Pad chargers [12]

The application and growing market of portable mobile appliances, remote charging and powering of these portable devices, demand for contactless RFID (Radio-Frequency Identification) for security applications all are playing main role in push-forward of resonant coupled WPT system. In 2008, Intel explored the resonant coupled WPT by using flat coils, which are very easier to fit in to mobile devices than the helix coils used in [13]. In [14] an advanced contact less approach for simultaneous powering to multiple receiving devices (e.g. laptops, cellphones) was presented.

In oppose to the traditional 2-coil system [15], the 4-coil wireless powering approach is designed by placing two intermediate multi-turn coils between two loop coils (Fig. 3). Each loop coil is a form of impedance matching mechanism and acts as a nonresonator to exchange energy between the circuits and intermediate coils [13]. Advantage of this approach is that the two intermediate coils are physically set free from circuits but the main disadvantage is it requires bigger space than any other transmission structure.

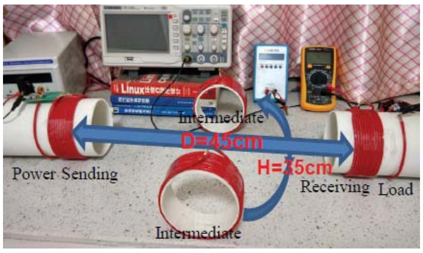

Fig.3. Experimental WPT circuit with additional intermediate two coils [16]

Wireless transmission of electricity to multiple receivers using a single coil has been described in [17]. Disadvantage this approach is fact that the resonant frequency of coils splits when two receivers are in close enough proximity and it lowers the efficiency. Array of coils [18] as domino form resonators [19] and linear resonator arrays [20] are considered, where in intermediate space between transmitter and receiver energy transfer is assisted using several resonators. However, detail analysis was performed for a series configuration of resonators, while proposed in this work parallel-series topology of planar coils, acting as group of energy transmitters and receivers are still not fully developed [21].

A wireless power transfer system bring comfort to human life, but a radiation of magnetic field around the WPT system can be harmful to humans and the environment [22]. Due to application limitations of aluminum and ferrite materials, it is pressing to find a new type of shielding material. One of these materials can be metamaterial [23, 24]. In [25] proposes a detailed model and analysis method of the matrix shielding metamaterial (MSM), which was applied to the low-frequency WPT system in an electric vehicle.

Energy supply or charging of many devices located in close range to each other may be simplified using WPT systems as a grid of periodically arranged coils, which forms surfaces for transmitting or receiving the energy. This solution increases the density of transferred power and also simultaneous energy supply (using single power source) for many devices is possible (e.g. for charging many electric cars in one parking or charging many LED). Proposed solutions can be used to power either one or multiple independent loads. The developed periodic WPT system allows for the simultaneous supply/charging of many low-power receivers, such as mobile devices or sensors repeatedly distributed over hard-to-reach areas.

The article presents a wireless charging system with periodically arranged planar coils. The proposed unit cell analysis with periodic boundary conditions does not require a full 3D model with many turns [26], which results in many degrees of freedom and the need to reduce the size of the model in order to perform the analysis [27]. The main purpose of this work is to anlyse the influence of the skin effect on the efficiency of the proposed WPT system.

The article proposes two approaches: analytical and numerical. For the solution of the periodic system with multiple transmitting and receiving coils, an analytical model was developed based on the equivalent circuit of coupled resonators (Fig. 4b). The numerical model of the proposed WPT periodic system is also presented. The analysis also takes into account the skin effect.

The proposed methods may show an alternative to the experimental prototypes currently used to analyse the electrical and magnetic properties of WPT systems. Both of the presented approaches allow obtaining good results of the efficiency of the system. By appropriate selection of the load resistance, it was possible to determine the maximum efficiency of the WPT system taking into account different frequency values (from 0.1 MHz to 1 MHz). The analysis was multivariate as the influence of the number of turns, the distance between the coils and the frequency on the power transfer efficiency and the power of the transmitter and receiver were analysed. The developed periodic WPT system allows for the simultaneous supply/charging of many low-power receivers, repeatedly distributed even on hard-to-reach surfaces (e.g. ceilings, internal walls).

Analysed Wireless Power Transfer System

In the article, periodic wireless power transfer system with many inductive elements is analysed.

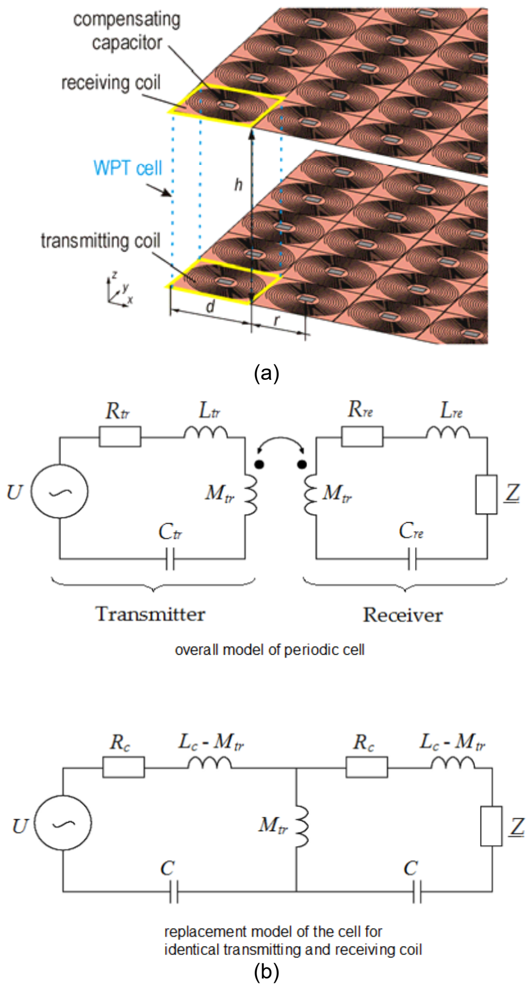

Fig.4. The proposed WPT system: (a) periodic wireless power transfer system composed of transmitting and receiving surfaces, (b) analytical model

The WPT system is composed of many pairs of transmitter and receiver. The WPT cell is with outer dimensions $d \times d$ (Fig. 4a). The coils are identical with paremeters: radius (r) and number of turns (n). Windings are wound around a dielectric carcass with additional compensating capacitors.

The analysed periodic distribution of WPT cells have transmitting and receiving surfaces where between them the energy transmission occurs. Transmitting surface consist of transmitting coils is connected parallel to sinusoidal voltage source (*U*). The proposed periodic WPT system includes two surfaces (transmitting and receiving). Each surface includes a set of many coils with the same winding direction (Fig. 4a).

The analysed model of the WPT system ensures an increase in the power transmitted density in the area between the receiving and transmitting surfaces. It enables the selection of power conditions depending on the imposed requirements. It is also possible to supply multiple independent receivers simultaneously, where the set or each of the WPT cells is assigned to a separate load.

Numerical and analytical approaches to the analysis of WPT system

In the article were compared the results obtained with the proposed analytical method with the results determined using the Finite Element Method (FEM) [28]. The aim was to assess the correctness of the adopted assumptions of the developed mathematical solution and evaluation of WPT system efficiency.

Using specialized programs for numerical analysis and the numerical methods (e.g. FEM, FDTD) [28-31], it is possible to create a model and determine the distribution of the magnetic field. In numerical analysis, it is necessary to prepare a 3D model and set suitable boundary conditions. The accuracy of the solution depend on the size of the model. The more number of degrees of freedom cause the greater the accuracy of the solution but results the longer the computation time.

Planar spiral coils were wound of several dozen of turns, which are made of ultra-thin wires with diameter (*w*) and insulated from each other by an electrical insulator of a thickness (*s*). On each coils compensating capacitor was modelled as an element with lumped capacity (*C*). A voltage source value (*U*) and frequency (*f*) is connected to each coil and current, which flows through transmitter (I_{tr}). Receiving coil, connected with a linear load *Z*, carry induced current I_{tr}. In numerical approach, periodic boundary conditions were applied. In this case, the wireless charging system was simplified to a single cell filled with air and containing a pair of transmitting and receiving coils (Fig. 4a). Perfectly matched layer (PML) is put in top and bottom of the model to imitate dielectric background [21, 28].

The problem of energy transport in the presented model was solved using the vector magnetic potential

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

while the formulation of the magnetic field phenomena in the frequency domain was presented by the Helmholtz equation

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

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

The implementation of the numerical model is more difficult than the analytical one due to, inter alia, complexity of the model, model reflection, appropriate selection of boundary conditions and related constraints, as well as the possibility of analysis if there is a large number of degrees of freedom.

Bearing in mind the above, a simpler model is often needed, which will allow to determine the initial results of the analysis, but at the same time, it is less complex and does not require numerical modelling. The proposed analytical solution is a combination of a two-port network with analytical equations for determining lumped parameters (Fig. 4b). The analysis of the infinitely wide periodic solution was reduced to the single WPT cell case (Fig. 4a). The solution of the analytical model in the frequency domain was performed using circuit analysis methods. The problem in this type of analysis is the determination of the values of the lumped parameters taking into account the influence of adjacent sections on the equivalent inductances of the transmitting coil L_{tr} and receiving coil L_{re} and their mutual inductance M_{tr}.

In infinite periodic grid, where each coil has identical electrical parameters and magnetic couplings with its neighbours, it is possible to reduce an analysis to the single WPT cell (Figure 4b). Then mutual inductances between adjacent coils appear and affect inductance of coil in $A_{x,y}$, which is expressed as:

$$L_c = L_{self} - \sum_i \sum_j \left(M_{x+i,y+j}\right) \tag{3}$$

where: L_c – effective self-inductance [H], $M_{x+i,\ y+j}$ – mutual inductance between coils adjacent in horizontal plane [H], L_{self} – self-inductance of spiral coil [H], which is presented by [7, 18]:

$$L_{self} = \frac{\mu_0 c_1 d_m n^2}{2}\left[\ln\left(\frac{c_2}{v}\right) + c_3 v + c_4 v^2\right] \tag{4}$$

where a mean diameter is expressed by:

$$d_m = 2r - n\left(w + s\right) \tag{5}$$

where: *w* – wire thickness, *s* – insulation thickness.

A fill factor is presented by:

$$v = \frac{n\left(w+s\right)}{2r - n\left(w+s\right)} \tag{6}$$

c_1, c_2, c_3, c_4 are coefficients which are depending on shape of the coil [23]. In these cases, where are circular coils: c_1=1, c_2=2.5, c_3=0, c_4=0.2 [10]. Equation (3) can be presented as

$$L_c = L_{self} - M_{pe} \tag{7}$$

M_{pe} is a sum of mutual inductances in a periodic grid and since they reduce the inductance of coil, M_{pe} is with a minus. For the case when loads Z=∞ and there is no capacitor in series with transmitter coils at arbitrary frequency one may find M_{pe} as:

$$M_{pe} = \frac{U/\underline{I}_{t,\infty} - R_c}{\mathrm{j}2\pi f} - L_{self} \tag{8}$$

where: R_c – coil resistance [Ω], $\underline{I}_{t,\ \infty} = |\underline{I}_{t,\ \infty}|e^{\ \mathrm{j}\psi}$ – source current [A], $|\underline{I}_{t,\ \infty}|$ – RMS value of the source current [A], ψ – phase angle between the source voltage and current. Instead of calculating each inductances $M_{tr,x+i,y+j}$, an effective mutual inductance (M_{tr}) can be found using the equation:

$$M_{tr} = \frac{\underline{U}_{r,\infty}/\underline{I}_{t,\infty}}{\mathrm{j}2\pi f} \tag{9}$$

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

After calculations of self-inductance (L_{self}) and mutual inductance (M_{pe}) it is possible to find series resonant capacity (*C*):

$$C = \frac{1}{4\pi^2 f^2 L_c} = \frac{1}{4\pi^2 f^2\left(L_{self} - M_{pe}\right)} \tag{10}$$

Resistance of coil (R_c) can be determined using formula of the straight wire resistance. For a wire with width ($w + s$), a total length of a resulting spiral is expressed by:

$$l_{sum} = 2\pi n\left[r - \frac{(n-1)(w+s)}{2}\right] \tag{11}$$

The equations for the resistance of coil are presented by:

$$R_c = \frac{l_{sum}}{\sigma_c \pi \frac{(w^2)}{4}} \tag{12}$$

for the case without taking into account the skin effect and

$$R_{c\_ac} = \frac{l_{sum}}{\sigma_c a_w} = \frac{2\pi n\left[r - \frac{(n-1)(w+s)}{2}\right]}{\sigma_c a_w} \tag{13}$$

for the case with taking into account the skin effect.

where: σ_c – electrical conductivity of a wire [S/m], a_w – effective cross-section of a wire [m^2].

Taking into account that the current flows through the "skin" of the conductor at high frequencies of magnetic field, an effective cross-section of wire (a_w) is taken into account in formulas (12) and (13), where a_w is presented by Equation (14), where δ_e is an effective skin depth [34]:

$$a_w = \pi\left(w\delta_e - \delta_e^2\right) \tag{14}$$

Effective skin depth is measured in [m] and is expressed by:

$$\delta_e = \delta\left(1 - \exp\left(\frac{-w}{2\delta}\right)\right) \tag{15}$$

Whereas δ is a skin depth, which is presented by:

$$\delta = \sqrt{1/\left(\pi f \sigma_c \mu_0\right)} \tag{16}$$

Analysed models

In order to verify the correctness of the assumptions made in the proposed analytical solution, calculations were also made using the numerical method for the exemplary variants of the WPT system (Table 1). The change in the number of turns and the distance between the transmitting and receiving coils were taken into account.

Table 1. Parameters of the WPT system adopted for analysis

Radius (r [mm])	Number of turns (n)	Distance between coils (h [mm])
25	40	12.5 and 25
	80	12.5 and 25

The analytical model is characterized by high accuracy of solving the problem of power transport. The proposed analytical model enables simplification and acceleration of calculations of the periodic systems of the WPT.

On the basis of obtained results was verified the validity of proposed analytical model by comparing active power of receiver (P_o) and power on the transmitting coil (P_z)

$$P_o = R_o I_{re}^2 \tag{17}$$

$$P_z = U I_{tr} \tag{18}$$

The power transfer efficiency was presented by:

$$\eta = \frac{P_o}{P_z} 100\% \tag{19}$$

The results concerned the appropriate selection of impedance Z_e to obtain the maximum efficiency of the system by equations:

$$Z_e = \sqrt{R_c^{\ 2} + \left(2\pi f M_{tr}\right)^2} \tag{20}$$

for the case without taking into account the skin effect and

$$Z_{e\_ac} = \sqrt{R_{c\_ac}^{\ \ 2} + \left(2\pi f M_{tr}\right)^2} \tag{21}$$

for the case with taking into account the skin effect.

The comparison concerned the determination of P_z and P_o and efficiency. The following parameters were adopted for multivariate calculations: w = 200 µm (wire thickness), s = 5 µm (insulation thickness), $\sigma_c = 5.6 \cdot 10^7$ S/m (conductivity of wire) and U = 1 V (voltage). Transmitter (P_z) and receiver power (P_o) and power transfer efficiency were calculated for analytical and numerical models within frequency range f_{min} = 0.1 MHz to f_{max} = 1 MHz. Lumped parameters of analytical model were found using previously presented equations and were presented in Tables 2-4.

Table 2. Calculated parameters

n	L_{self} (µH)	M_{tr} (µH)	
		$h = 0.5\,r$	$h = r$
40	107	14.79	3.37
80	227	39.56	9.16

Table 3. Calculated parameters for analysed WPT system (without skin effect)

n	R_c (Ω)	Z_e (Ω) at $f_{\max}$	
		$h = 0.5\,r$	$h = r$
40	3.00	93	21.37
80	4.83	249	57.78

Table 4. Calculated parameters for analysed WPT system (with skin effect)

n	R_{c_ac} at $f_{\max}$ (Ω)	Z_{e_ac} (Ω) at $f_{\max}$	
		$h = 0.5\,r$	$h = r$
40	3.90	93	21.51
80	6.27	249	57.91

In order to determine the maximum efficiency, the impedance Z_e and Z_{e_ac} values were calculated taking into account the variable number of turns and the distance between the coils. As the number of turns increases, the impedance increases. Doubling the distance between the coils, causes more than four times decrease in the impedance value.

In Table 2 are presented values of mutual inductance M_{tr} between transmitter and receiver at two distances: h = 12.5 mm, h = 25 mm and different number of turns. When the number of turns increases then the mutual inductance increases too. Doubling the distance between the coils causes more than four times decrease the values of mutual inductance.

In Table 3 are presented the values of the resistance of coil R_c and impedance Z_e for the case without taking into account the skin effect. In Table 4 are presented the values of the resistance of coil R_{c_ac} and impedance Z_{e_ac} taking into account the skin effect at the frequency $f_{\max}$ = 1 MHz. The skin effect increases the resistance of coil by approx. 30%, regardless of the number of turns of the coil. In the case of impedance at the distance between the coils

h = 25 mm, the skin effect causes an increase in this impedance by about 0.7%, while at h = 12.5 mm, the skin effect does not affect this impedance.

Results of the analysis

The analysis concerned the verification of the correctness of the proposed analytical solution, which allows determining the efficiency of the WPT system containing pairs of transmitting-receiving coils distributed periodically. The analysis also took into account the skin effect. A numerical solution was also proposed, which allows for the reduction of the number of degrees of freedom. The results obtained with both methods were compared. In the analysis, the influence of skin effect on the efficiency of the WPT system was checked. For this purpose, source power, receiver power, and transmission efficiency were compared. The structure of the WPT system (number of turns, distance between coils) was taken into account. The power of the transmitter and receiver as well as the efficiency of power transmission were calculated in the frequency range from 0.1 MHz to 1 MHz.

The numerical model was created in Comsol Multiphysics using boundary conditions (PML and periodicity). The numerical analysis was performed using the FEM method.

Figures 5-10 present the results of the analysis. The comparisons of WPT system efficiency (Figs. 9, 10), the transmitter power (Figs. 5, 6), the receiver power (Figs. 7, 8) for different values of the number of turns of coils and frequency were presented. The graphs show the comparative characteristics for models: with skin effect (marked with a dashed line) and without skin effect (marked with a solid line) for different distance between the transmitting-receiving planes.

The transmitter power P_z decreases over the entire frequency range, regardless of the distance between the coils h and the number of turns n (Figs. 5, 6). The smallest P_z values are for n = 80 and at the distance h = 12.5 mm. The skin effect has basiclly no effect on the P_z power.

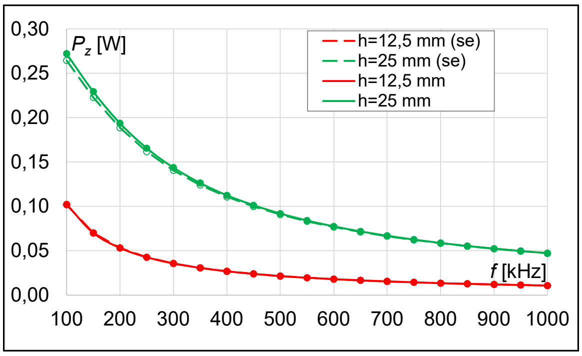

Fig.5. Results of transmitter power (P_z) for WPT systems with the number of turns n=40 at two distances (h=12.5 mm and h=25 mm)

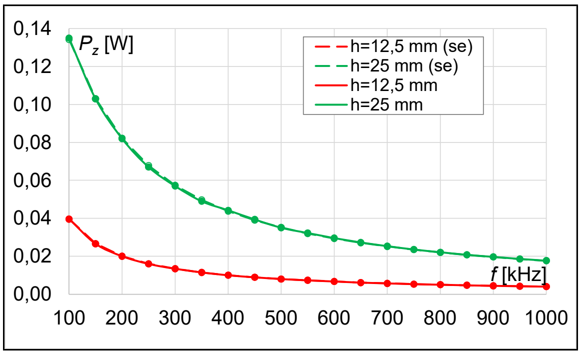

Fig.6. Results of transmitter power (P_z) for WPT systems with the number of turns n=80 at two distances (h=12.5 mm and h=25 mm)

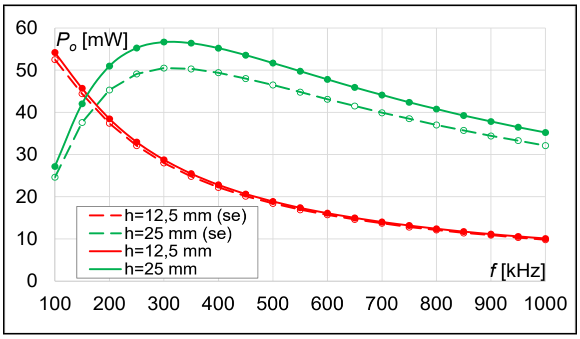

Fig.7. Results of receiver power (P_o) for WPT systems with the number of turns n=40 at two distances (h=12.5 mm and h=25 mm)

The receiver power P_o decreases over the entire frequency range at the distance h = 12.5 mm and regardless of the number of turns n (Figs. 7, 8). However, at the distance h = 25 mm the P_o power increases, and when the efficiency reaches approximately 50% the receiver power P_o reaches its maximum value. Then the receiver power decreases as the frequency increases. Maximum receiver power is achieved at h = 25 mm, n = 40 and reaches almost 60 mW. The lowest P_o values are achieved at h = 12.5 mm and n = 80 (Fig. 8). The influence of the skin effect on the power P_o at h = 12.5 mm is negligible (the P_o power decreases by less than 1 mW). On the other hand, at h = 25 mm, the influence of the skin effect is greater for n = 40 (Fig. 7). The biggest difference occurs when the power P_o reaches its maximum value and equals about 6 mW.

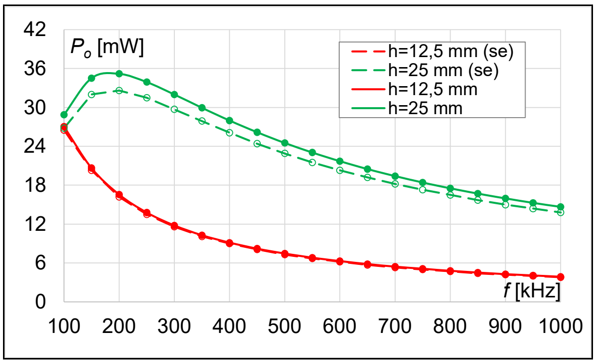

Fig.8. Results of receiver power (P_o) for WPT systems with the number of turns n=80 at two distances (h=12.5 mm and h=25 mm)

The highest efficiency of the system η is for the number of turns n = 80 at h = 12.5 mm and f = 1 MHz and reaches approx. 96%, (Fig. 10). In addition, for n = 80 there is the highest difference in efficiency between models at h = 12.5 mm and h = 25 mm reaching almost 50% at f = 100 kHz. The lowest efficiency is always for models at h = 25 mm.

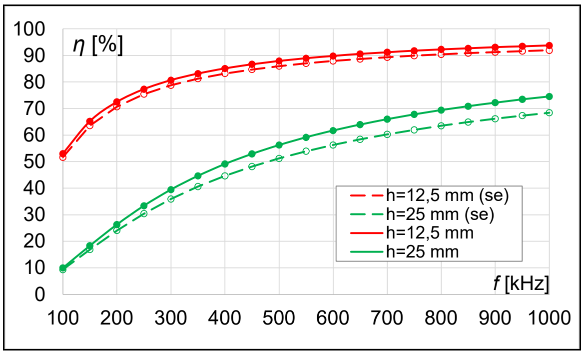

Fig.9. Results of power transfer efficiency for WPT systems with the number of turns n=40 at two distances (h=12.5 mm and h=25 mm)

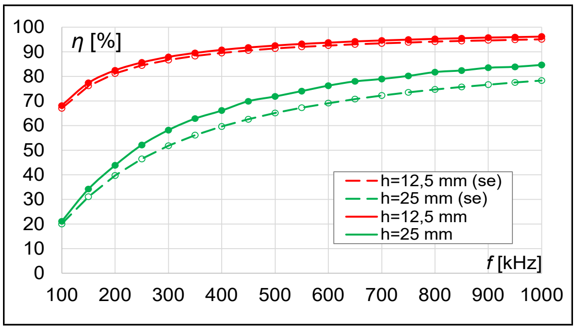

Fig.10. Results of power transfer efficiency for WPT systems with the number of turns *n*=80 at two distances (*h*=12.5 mm and *h*=25 mm)

The skin effect causes a decrease in the efficiency of the WPT system, it is especially visible the higher the frequency. Regardless of the number of turns at *h* = 12.5 mm, the influence of the skin effect on the efficiency of the WPT system does not exceed 1.5%. On the other hand, at *h* = 25 mm and *f* = 1 MHz, the skin effect causes a decrease in efficiency of the system even by approx. 6% for *n*=40 and approx. 8% for *n*=80 (Figs. 9, 10).

It can be noted that, on all characteristics, comparing the values from numerical model (FEM) and analytical model almost perfect agreement have appeared.

Figures 11-14 show the distribution of the magnetic flux density norm.

Values of magnetic flux density norm are always higher for twice the distance between the transmitting and receiving coils. For the considered cases, i.e. *n* = 40 and *h* = 25 mm values of the magnetic flux density norm are higher more than four times, whereas for *n* = 80 and *h* = 25 mm values of the magnetic flux density norm are higher almost five times.

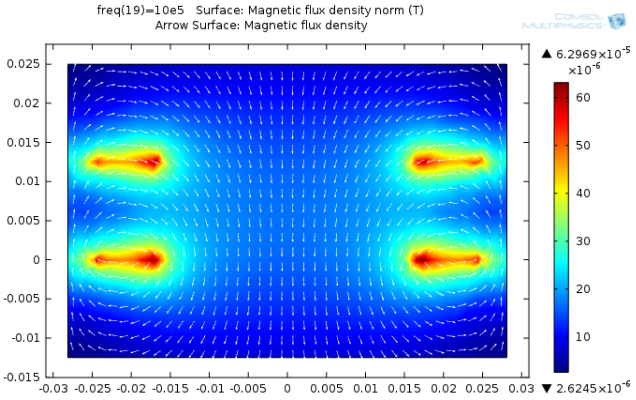

Fig.11. Distribution of the magnetic flux density norm for the case where the number of turns is 40, *h* = 12.5 mm (XZ plane)

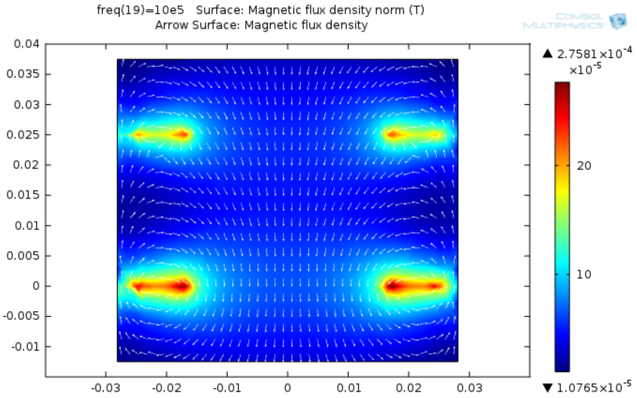

Fig.12. Distribution of the magnetic flux density norm for the case where the number of turns is 40, *h* = 25 mm (XZ plane)

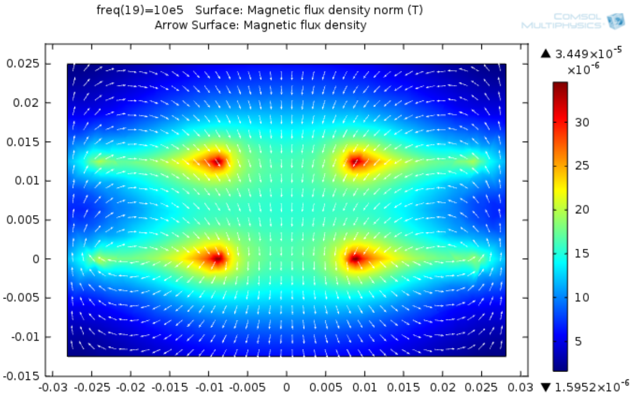

Fig.13. Distribution of the magnetic flux density norm for the case where the number of turns is 80, *h* = 12.5 mm (XZ plane)

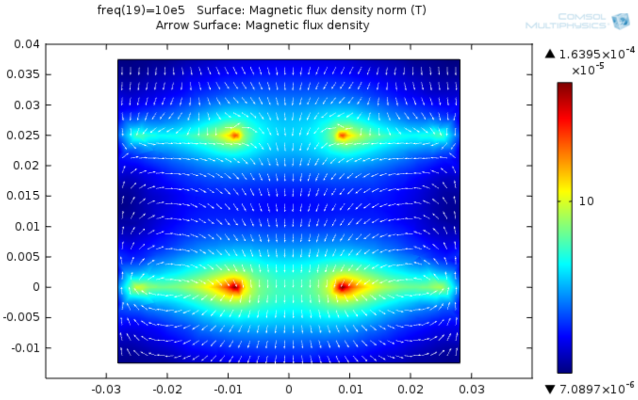

Fig.14. Distribution of the magnetic flux density norm for the case where the number of turns is 80, *h* = 25 mm (XZ plane)

Conclusions

The article presents the WPT system consisting of periodically distributed coils, which can be used to charge a receiver or multiple receivers. Among others, an analytical solution that allows determining, among others load efficiency and power already at the stage of preliminary system properties analysis. The aim was to quickly determine the output parameters like power or efficiency.

The article also presents the structure of an equivalent numerical model and the conditions that allow the number of degrees of freedom and the complexity of the model to be reduced.

The solutions presented in the article take into account the skin effect and allow studying the influence of the coil geometry and the distance between the transmitter and receiver on power transmission. The analysis concerned the influence of geometric parameters of the coils and the influence of skin effect on the efficiency of the system and the power of the transmitter and receiver in a wide frequency range. By adjusting the number of turns or increasing the frequency of the current, without the need to use intermediate coils, it is possible to achieve high efficiency of the system up to ≈96%. The skin effect causes a decrease in the efficiency of the WPT system, it is especially visible the higher the frequency. The analysis showed that taking into account the skin effect reduces the efficiency of the WPT system even by 8%.

Thanks to the appropriate selection of the load impedance, it was possible to achieve maximum efficiency of the WPT system. The analytical results were consistent with the numerical results, which confirmed the correctness of the assumptions made and the possibility of reducing the extensive network of periodic resonators to a single WPT cell.

This work was supported by the Ministry of Science and Higher Education in Poland at the Białystok University of Technology under research subsidy No. WI/WE-IA/11/2020.

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