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Influence of the coil winding direction on the efficiency of Wireless Power Transfer Systems

***Abstract**. The article presents the results of numerical and analytical analysis of the Wireless Power Transfer System (WPT). The system consists of flat, square coils. Two WPT systems were considered: periodic and aperiodic. In the aperiodic arrangement, adjacent coils had their turns wound in the opposite direction. The influence of the winding direction, the number of turns and the distance between the coils on the efficiency of the WPT system was compared. The analysis covered a wide frequency range from 100 kHz to 1000 kHz. The results obtained with both proposed methods were consistent, which confirmed the correctness of the assumptions made. In periodic and aperiodic models, higher efficiency was achieved for a higher number of turns. The proposed aperiodic models of the WPT system show a higher system efficiency than periodic models by up to 40%. The proposed WPT system can be used for simultaneous charging of many sensors located e.g. in walls.*

***Streszczenie.** W artykule przedstawiono wyniki analizy numerycznej i analitycznej Systemu Bezprzewodowego Przesyłu Mocy (WPT). System składa się z płaskich cewek kwadratowych. Rozpatrzono dwa układy WPT: periodyczny i aperiodyczny. W układzie aperiodycznym sąsiednie cewki miały nawinięte zwoje w przeciwnym kierunku. Porównano wpływ kierunku uzwojenia, liczby zwojów oraz odległości między cewkami na sprawność układu WPT. Wyniki uzyskane obiema zaproponowanymi metodami były zgodne, co potwierdziło słuszność przyjętych założeń. Analiza została przeprowadzona w szerokim zakresie częstotliwości (100 - 1000 kHz). W modelach periodycznych i aperiodycznych wyższą sprawność uzyskano dla większej liczby zwojów. Zaproponowane aperiodyczne modele systemu WPT wykazują wyższą sprawność układu niż modele periodyczne nawet o 40%. Proponowany system WPT może służyć do jednoczesnego ładowania wielu czujników umieszczonych np. w ścianach. (**Wpływ kierunku nawinięcia zwojów cewki na sprawność systemów bezprzewodowej transmisji energii**).*

Keywords: wireless power transfer (WPT), planar coils, magnetic fields, FEM.
Słowa kluczowe: bezprzewodowa transmisja energii (WPT), cewki planarne, pole magnetyczne, FEM.

Introduction

Charging devices with cables is very lossy, difficult to assemble and often fails [1]. The number of portable devices is growing, but wired chargers make these devices not fully portable. Bearing in mind the above, alternative solutions related to charging devices, mainly home devices, were searched for.

The solution that eliminates the indicated problems is the Wireless Power Transfer (WPT) technology [1-10]. The WPT system can efficiently transfer power from the source to the device using the principle of electromagnetic induction. The advantage of this system is the mobility of devices and the lack of radiation.

There are many studies on electric vehicles described in the literature, including in order to reduce energy consumption [11, 12]. WPT technology is also used in medicine, e.g. while charging or powering medical devices, e.g. such as pacemakers [13, 14]. The WPT system is also used in beacon systems [15] and in intelligent buildings containing sensors placed in the structures of rooms [1, 16].

At higher frequencies, mainly one transmitter and many receivers are taken into account [17, 18, 19]. An ideal WPT system is expected to transmit power efficiently, regardless of the position of the transmitter in relation to the receiver. In practice, any deviation in the distance from the optimal transmission area causes the efficiency to be very low, which prevents transmission [20].

However, for low frequencies, which are intendent for low-power devices, a system of coils in the form of domino [21, 22] and linear resonators [23] is considered. In this approach, several resonators are used in the space between the transmitter and receiver to help transfer energy. Unfortunately, there is a problem with arranging a larger area. The analysis was carried out for the series configuration of resonators [23, 24], but the series-parallel topology of planar coils, acting as a group of transmitters and receivers of energy, is not fully developed yet [25].

When using WPT systems, the health aspect is a very important criterion. The operation of these systems uses inductive-capacitive couplings, which is associated with the generation of strong electromagnetic fields. Therefore, the adopted limits for these magnetic fields should be respected [26, 27]. An equally important element is the environment in which the WPT system operates. When installing sensors in intelligent buildings, not only the design of the room must be taken into account, where there may be reinforcement [28], but also the complexity of building materials that constitute non-ideal dielectrics and certainly affect the electromagnetic field [29].

The article presents multi-transmitter and multi-receiver systems using square planar coils. This solution allows for simultaneous charging of many receivers, which can be useful in LED lighting.

The article presents a wireless power transer system with periodically arranged planar square coils. A numerical and analytical model was proposed that can be used to analyse the power transmission conditions in the discussed WPT systems. Both solutions reduce the size and complexity of numerical and analytical models and allow for quick analysis of WPT systems. The presented WPT models allow to assess the influence of the geometry of the coils and the distance between the transmitting and receiving coils on the power transmission. Regulation of geometric parameters makes it possible to achieve high efficiency. Two WPT systems consisting of square coils were analysed: periodic and aperiodic of the checkerboard type. The difference between these systems concerned the winding direction of the turns in the adjacent coils. Using both methods, an analysis of the influence of the winding direction and geometric parameters (number of turns and distance between the coils) on the transmitter power and receiver power, as well as on the power transfer efficiency was carried out.

The analysed model of a Wireless Power Transfer System

The proposed and analysed WPT system is composed of pairs of transmitting-receiving square coils. This pair is called a WPT cell (Fig. 1). The outside dimensions of each transmitter/receiver cell are $d \times d$, the same radius (r) and the number of turns wound around the dielectric carcass (n). The analysed WPT system contains many inductive elements, i.e. identical square coils. The distance between transmitter and receiver coils is marked by h.

The transmitting surface is powered so that each transmitter is connected in parallel to a sinusoidal voltage source with the effective value (U). The coils creating the receiving surface are connected directly to the load. Each WPT cell is assigned a separate load ($\underline{Z}$). The presented solution allows for simultaneous charging of many receivers. An example is the use of the WPT periodic structure in the case of very low voltage lighting. Periodically placed transmit coils can transfer energy to several LED chipsets through a dielectric barrier like a wall.

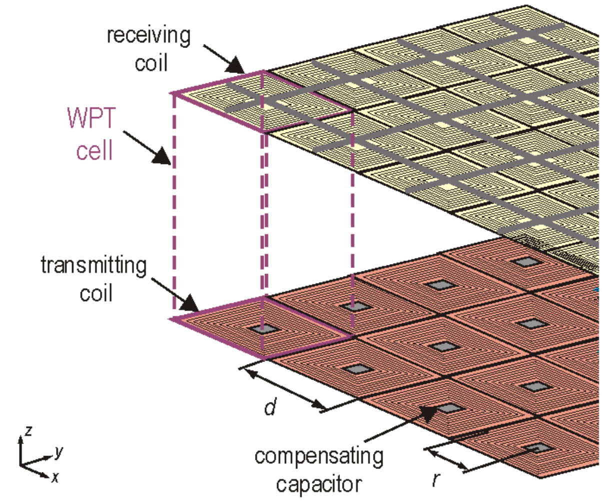
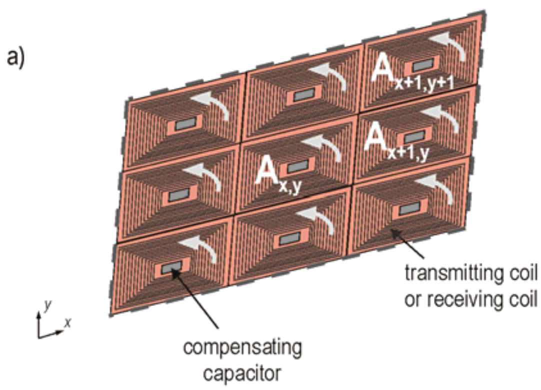


Fig.1. Proposed WPT system consisting of planar square coils

Two variants of the WPT system with square coils were analysed (Fig. 2):
- periodic model (Fig. 2a);
- aperiodic model (Fig. 2b).

The WPT system with a transmitting/receiving surface composed of coils wound in the same direction is called a periodic system (Fig. 2a). On the other hand, the WPT system with alternating wound turns was called aperiodic (Fig. 2b). For example, cells adjacent to the edge of an exemplary cell $A_{x,y}$ contained inversely wound coils marked with a blue arrow (e.g. $A_{x+1,y}$). Each adjacent coil is separated by the distance d taking into account that $d \approx 2r$.



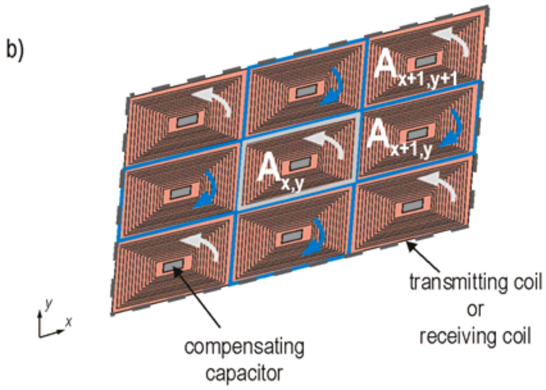


Fig.2. The analysed transmitting/receiving surface composed of: a) square coils with the same winding direction, b) square coils with the opposite winding direction.

The influence of the change in the number of turns and the distance between the transmitting and receiving surface (h) on the efficiency was analysed (Table 1). Additionally, the influence of the winding direction on the parameters of the system was considered.

Table 1. Variants of geometric parameters accepted for analysis.

r (mm)	n (-)	h (mm)	
		h = 0.5 r	h = r
5	10	2.5	5.0
	30	2.5	5.0

The presented models, which are a solution for the WPT system, were solved by the numerical and analytical methods. Of course, the results of both methods were compared.

Solution by numerical method

The proposed WPT systems can be calculated and analysed using numerical, analytical or experimental methods. Changes in parameter values such as number of turns, distance, wire thickness are easier in numerical and analytical models. On the other hand, the experimental analysis would require the preparation of a new model and its settings. For this reason, two methods have been proposed that will allow for a multi-variant and quick analysis of the efficiency of the system without the need to use measuring stations.

The numerical analysis can be performed using the numerical methods like FEM [30], FDTD [29, 31] or FDFD. The accuracy of the solution is depended on the size of the model - the number of degrees of freedom (N_{DOF}). The Finite Element Methods (FEM) used for the analysis allows for using various types of finite elements. This possibility lets to increase or decrease the dimensions of elements in certain zones of the considered volume (the so-called adaptation of the finite element mesh).

The numerical analysis requires taking into account e.g.: the geometry and distribution of the coil turns, the number of WPT cells and elements of the electric circuit connected to each coil. The turns of the coils were made of thin wire (w) with insulation layer (i). The compensating capacitor is modelled as an element with a concentrated capacity (C). The capacity of the capacitor is 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 the specific frequency [32]. The parameters for the WPT model, coil windings and the frequency domain are shown in Table 2.

Table 2. Parameters of the wire and model used to the analysis.

Parameter	Symbol	Value
Diameter of the wire	*w*	150 μm
Thickness of the wire insulation	*i*	1 μm
Conductivity of the wire	*σ*	$5.6 \cdot 10^7$ S/m
Voltage source	*U*	1 V
Load impedance	*Z*	50 Ω
Frequency domain	$f_{min} \div f_{max}$	100÷1000 kHz

In the proposed numerical approach, the whole WPT system is simplified to a single cell $A_{x,y}$ including a pair of transmitting and receiving square coils. An infinite array of resonators was modeled by using periodic or antiperiodic boundary conditions (PBC). They are placed on the four side surfaces of the cell. In periodic models, an infinite array of the coils was modelled using the periodic boundary conditions (PBC) [30]. In aperiodic models, antiperiodic boundary conditions are applied. To simulate an infinite dielectric background, on the top and bottom of the numerical model a perfectly matched layer (PML) was put.

Each transmitting coil is connected to a voltage source with an effective value (*U*) and frequency (*f*) that forces the transmitter current ($\underline{I}_{tr}$) to flow. In the receiving coil the source is replaced by a linear load ($\underline{Z}$), which conducts the induced current ($\underline{I}_{re}$).

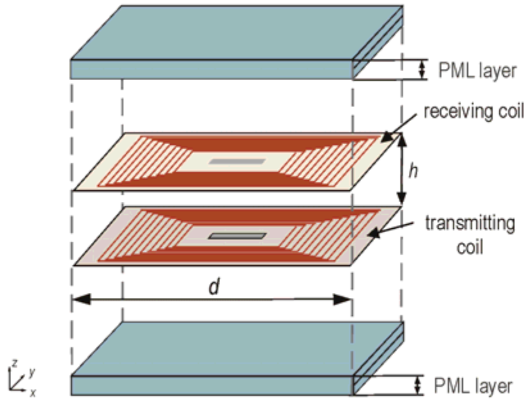


Fig.3. Numerical model of one WPT cell

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 description of magnetic phenomena in the frequency domain 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:
$\mathbf{J}_{ext}$ – external current density vector [A/m²];
ω – pulsation [rad/s];
σ – conductivity [S/m].

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

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

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

Solution by the analytical method

As it was presented in the previous chapter, the execution of the numerical model is difficult, because appropriate boundary conditions or simplifications imposed by the adopted numerical method must be selected. For these reasons, it is easier to create an analytical model that allows you to obtain preliminary solutions. However, the disadvantage of the analytical method is that it is not possible to obtain a quick solution if the parameters of the system are changed. In this case, the numerical analysis works well.

As optional for the numerical solution, an analytical model connecting a two-port set with analytical equations for calculating lumped parameters was proposed (Fig. 4). In this method, the WPT wide area set analysis was reduced to the single WPT cell. The greater problem is to determine the values of the lumped parameters taking into account the influence of the adjacent cells on the equivalent inductances of the transmitting coil (L_{tr}), receiving coil (L_{re}) and their mutual inductance (M_{tr}) [9, 32].

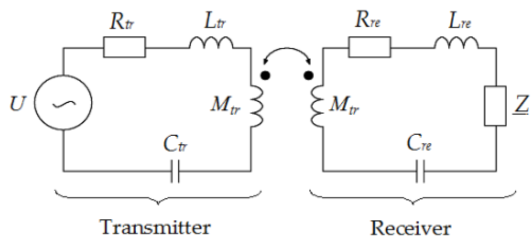


Fig.4. Circuit model of the cell in the WPT system

The length of the windings in one square coil is presented in the equation

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

Taking into account that the transmitter and receiver coils are identical, the resistance of the inductor is $R_t = R_r = R_c$. The formula for square coil resistance is:

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

The self-inductance of a square planar coil is calculated using equation [25, 33]

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

where d_m is a mean diameter:

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

and *wsp* is a fill factor presented by:

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

The coefficients (c_1, c_2, c_3, c_4) presented in equation (6) are depending on the geometry of the coil [33] and for square coil 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). Mutual inductance M_{pe}, which is directly from periodic distribution of coils arranged on the surface, is the sum of all mutual inductances [25]:

(9) $$M_{pe} = \sum_i \sum_j \left(M_{x+i,y+j}\right) - M_{x,y}$$

where:
$M_{x+i,y+j}$ – mutual inductance between coil and coil in the *i*-th column and *j*-th row,
$M_{x,y} = L_{self}$ – self-inductance.

Taking into account assumptions that the system is periodic and symmetrical ($M_{x+i,y+j} = M_{x-i,y-j}$) equation (9) is simplified to the dependence:

(10) $$M_{pe} = 8M_{x,y+1}$$

where: $M_{x,y+1}$ – mutual inductance between coil and an edge adjacent coil is calculated from [25]. Whereas, for the aperiodic system (Fig. 2b), $M_{pe} = 0$.

The inductance of the considered coil in the segment $A_{x,y}$ is described by:

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

Taking into account the equivalent circuit (Fig. 4), the mutual inductance (M_{tr}) [5] between the transmitter and the receiver is presented by:

(12) $$M_{tr} = \left| \frac{\underline{U}_{r,\infty}}{2\pi f \underline{I}_{t,\infty}} \right|$$

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

The compensating capacity at a specific frequency is determined by the formula:

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

The analysed variants of the WPT system

In order to confirm the correctness of the assumptions for the analytical and numerical model, an analysis was carried out for models with a coil with a radius of $r = 5$ mm. Variability of the number of turns $n \in \{10;\ 30\}$ and the distance between the transmitting and receiving surfaces $h \in \{2.5;\ 5\}$ mm are taken into account.

In order to determine the power transfer efficiency (η) of the system, the transmitter power (P_z) and the receiver power (P_o) were previously calculated. Since the passive load (Z) was considered, its active power is calculated by the equation:

(14) $$P_o = Z\left|\underline{I}_{re}\right|^2,$$

The power of the transmitter is calculated by

(15) $$P_z = U\underline{I}_{tr}$$

and also power transfer efficiency

(16) $$\eta = \frac{P_o}{P_z} 100\%$$

Lumped parameters of electrical circuit for square coils were presented in Tables 3-4. Values were calculated from the equations presented previously.

Table 3. Calculated parameters for periodic WPT system

n	L_{self} (μH)	*C* at f_{max} (nF)	M_{tr} (μH)	
			h = 0.5 *r*	*h* = *r*
10	1.87	21.08	0.15	0.03
30	4.83	7.20	0.69	0.16

Table 4. Calculated parameters for aperiodic WPT system

n	L_{self} (μH)	*C* at f_{max} (nF)	M_{tr} (μH)	
			h = 0.5 *r*	*h* = *r*
10	1.87	13.53	0.57	0.21
30	4.83	5.25	1.65	0.61

The L_{self} values are the same for periodic and aperiodic WPT system. The M_{tr} values are higher for the aperiodic system. Whereas, the compensating capacity values are higher for periodic WPT system (almost 50%). This capacity decreases as the number of turns increases.

The results of the WPT systems analysis

The results of the presented WPT systems were obtained by the numerical and analytical method. The results presented in the Figures 5-10 refer to both proposed methods. In these figures, the results obtained by the analytical method are marked with dots. Whereas, the results obtained with the numerical method are marked with the line.

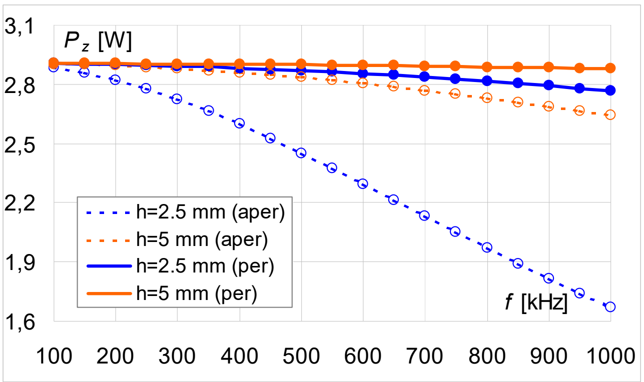


Fig.5. Results of transmitter power (P_z) for WPT systems with the number of turns $n = 10$ at two distances $h = 2.5$ mm and $h = 5$ mm

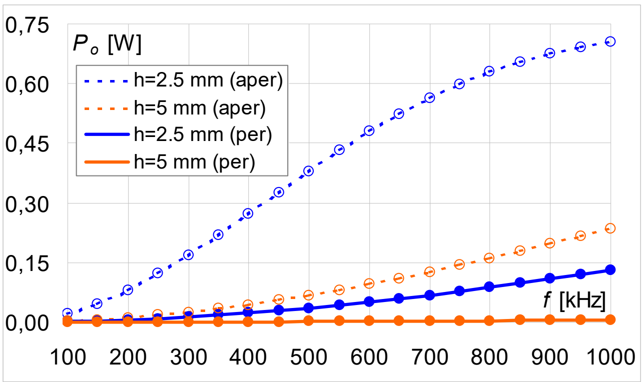


Fig.6. Results of receiver power (P_o) for WPT systems with the number of turns $n = 10$ at two distances $h = 2.5$ mm and $h = 5$ mm

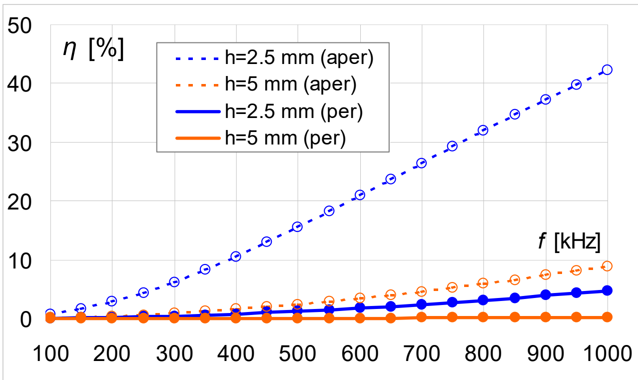


Fig.7. Results of power transfer efficiency (η) for WPT systems with the number of turns n = 10 at two distances h = 2.5 mm and h = 5 mm

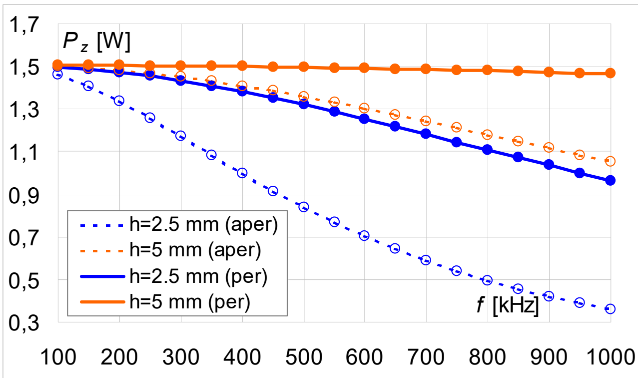


Fig.8. Results of transmitter power (P_z) for WPT systems with the number of turns n = 30 at two distances h = 2.5 mm and h = 5 mm

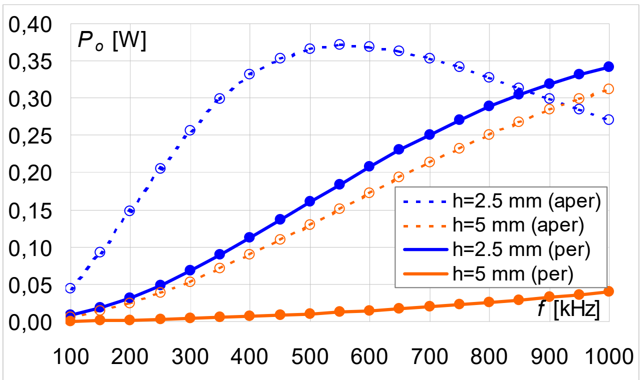


Fig.9. Results of receiver power (P_o) for WPT systems with the number of turns n = 30 at two distances h = 2.5 mm and h = 5 mm

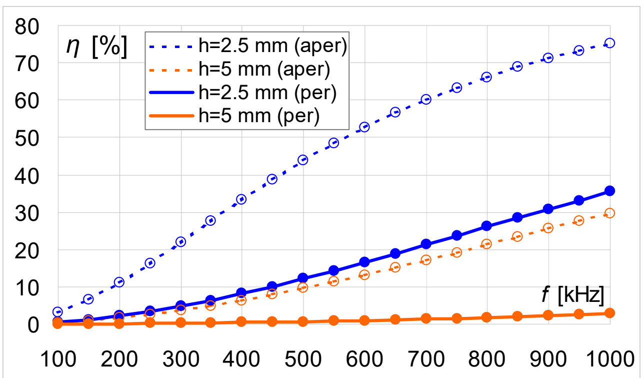


Fig.10. Results of power transfer efficiency (η) for WPT systems with the number of turns n = 30 at two distances h = 2.5 mm and h = 5 mm

Figures 5-10 show the characteristics of: the transmitter power, the receiver power and the efficiency at the distance $h = r/2$ and $h = r$ for periodic and aperiodic models with square coils. The characteristics depend on the number of turns and frequency.

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, 8). The smallest P_z values are for the aperiodic model and the small distance between the coils, h = 2.5 mm.

The receiver power P_o increases over the entire frequency range, regardless of the distance h and the number of turns (Figs. 6, 9), except for one case, where for the aperiodic model and n = 30 and h = 2.5 mm (Fig. 9), when the efficiency reaches approximately 50%, the receiver power P_o reaches its maximum value. Then, the receiver power decreases as efficiency exceeded 50%. Maximum receiver power is achieved for aperiodic model at the distance h = 2.5 mm regardless of the number of turns. The lowest P_o values are achieved for the periodic model for h = 5 mm, regardless of the number of turns (Figs. 6, 9).

The highest efficiency of the system η is for the aperiodic model and reaches approx. 75%, for the number of turns n = 30 at h = 2.5 mm and f = 1 MHz (Fig. 10). In addition, in this case there is the highest difference in efficiency between aperiodic and periodic models, reaching almost 40%. The lowest efficiency is always for the periodic model at h = 5 mm. Regardless of the number of turns the efficiency of the system is comparable for two models: periodic at h = 2.5 mm and aperiodic at h = 5 mm (Figs. 7, 10).

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

Conclusions

The article presents the methodology of creating and solving models of the WPT system using the analytical and numerical methods. Periodic and aperiodic distribution of square coils is taken into account. Both solutions allow for a quick analysis of the efficiency of WPT systems.

The analytical model of the WPT system is an alternative to complex numerical analysis or experimental research. It allows for quick preliminary calculations of WPT cells with different geometry of coils. The proposed numerical and analytical models make it possible to assess the influence of the design of the coil system and the coil itself on the efficiency of power transmission.

The article compares the results obtained with both methods. The difference was only 0.6%. Based on the comparison of the results obtained with both methods, it can be concluded that the adopted methodology and formulas are correct. Through detailed analysis of many variants of WPT systems, it is possible to economically select the geometry of the coils, the number of turns, the thickness of the wire, etc. in order to obtain a high efficiency of the system. The proposed aperiodic models of the WPT system show a higher system efficiency than periodic models by up to 40%. Further research on the WPT system is planned, which will focus on other coil shapes and capacitive loads.

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