Jacek Maciej STANKIEWICZ

Białystok University of Technology, Faculty of Electrical Engineering
ORCID.

doi:10.15199/48.2021.10.08

Comparison of the efficiency of the WPT system using circular or square planar coils

***Abstract**. The article presents results for numerical analysis of Wireless Power Transfer (WPT) system consisting of transmitting and receiving plane coils. Two types of coils (circular and square) were included in the analysis. The influence of the type of coils, the number of turns and the distance between the coils on the efficiency of the WPT system was compared. The analysis covered a wide range of frequencies from 100 kHz to 1000 kHz. The Finite Element Method (FEM) with the using antiperiodic boundary conditions for the analysis was used. In the low frequency range (within the analysed range) the higher efficiency is for the WPT system composed of square coils. On the other hand, at higher frequency values, higher efficiency values were obtained for the WPT model containing circular coils. Proposed WPT system could be used to charge electric devices as the wireless power transfer system. The results indicate at which system parameters wireless energy transfer is possible.*

***Streszczenie.** W artykule przedstawiono wyniki analizy numerycznej systemu Wireless Power Transfer (WPT) składającego się z cewek płaskich nadawczo-odbiorczych. W analizie uwzględniono dwa rodzaje cewek (okrągła i kwadratowa). Porównano wpływ rodzaju cewek, liczby zwojów oraz odległości między cewkami na sprawność układu WPT. Analiza obejmowała szeroki zakres częstotliwości od 100 kHz do 1000 kHz. Do analizy wykorzystano Metodę Elementów Skończonych (MES) z wykorzystaniem antyperiodycznych warunków brzegowych. W zakresie niskich częstotliwości (w analizowanym zakresie) wyższa sprawność występuje dla układu WPT złożonego z cewek kwadratowych. Natomiast przy wyższych wartościach częstotliwości wyższe wartości sprawności uzyskano dla modelu WPT zawierającego cewki okrągłe. Proponowany system WPT mógłby służyć do ładowania urządzeń elektrycznych jako bezprzewodowy system przesyłania energii. Wyniki wskazują, przy jakich parametrach układu możliwy jest bezprzewodowy transfer energii. (**Porównanie sprawności układu WPT z wykorzystaniem okrągłych lub kwadratowych cewek płaskich**).*

Keywords: wireless power transfer (WPT), magnetic field, numerical analysis, Finite Element Method (FEM).
Słowa kluczowe: bezprzewodowa transmisja energii (WPT), pole magnetyczne, analiza numeryczna, metoda elementów skończonych.

Introduction

Recently there has been a clear increase in energy demand in wireless and mobile devices [1-16]. Their computing power and the number of supported sensors (e.g. fingerprint sensor) grew [1-9, 11, 15]. These factors influence on the increasing demand for batteries with e.g. increased capacity and determine the mobility of devices. One way to supply mobile devices with energy is charging using wireless power transfer (WPT). Through the concept of inductive power transfer it is possible wireless charging of modern technology devices [1, 9]. WPT is used e.g. in the automotive industry in solutions for hybrid and electric cars [2, 3, 4].

Wireless charging is also considered in lighting in hard-to-reach places [5, 6, 8, 11, 14, 15] or intelligent buildings with sensors inside the walls and in the systems of beacons [14]. WPT is also used in LED-based lighting [16]. This approach does not use wired power such as a battery. Thanks to this, it is possible to use cabin lighting and many architectural possibilities are created (Fig. 1).

Fig.1. The use of WPT for LED lighting [16]

Recently, intensive work is underway on wireless power supply of implanted medical devices such as pumps (LVAD) and pacemakers [11].

The authors [1, 6, 16] presented a WPT charging solution for e.g. laptops or smartphones. They found that in the next 10 years, this solution would cover up to 80% of applications. The possibility of charging the battery from a distance of 10 cm without the use of cables is described in [16].

WPT also has medical applications. Resonant coupling has been recognized in medical devices. Today, an internal battery powers most implantable medical devices and sensors [12, 13]. WPT technology reduces the need for a built-in power source to ensure the autonomy of this type of device.

However, the topology of parallel flat coils, working as a group of transmitters and receivers, is still not fully developed [5, 18-22]. In this article will be presented one of these systems, which included two surfaces composed of transmitters and receivers coils. Presented system is checkerboard type (Fig. 4). The article compares two configurations: square and circular planar spiral coils, taking into account the same geometry of the system and the coil.

The aim of the research was to check the effect of the number of turns, the distance between the surfaces (transmitting and receiving), as well as the direction of wire winding on the efficiency of the system, the power of the transmitter and receiver. The analysis covers a wide range of frequencies from 100 kHz to 1000 kHz.

Proposed WPT system could be used to charge electric devices as the wireless power transfer system.

Models of wireless power transfer system

In this article was proposed a numerical method of wireless charging through the use of a system containing a plane made of transmitting coils and a plane of receiving coils (Fig. 2). The transmitting and receiving coils are placed at a distance (h). Each transmitter-receiver pair is consisting of identical coils and number of turns (n). This pair is a WPT cell with dimensions $d \times d$ (Figs. 2, 3). Spatial distribution of WPT cells on the plane leads to the creation of a checkerboard type network, which includes the transmitting and receiving surfaces, between which energy transmission occurs.

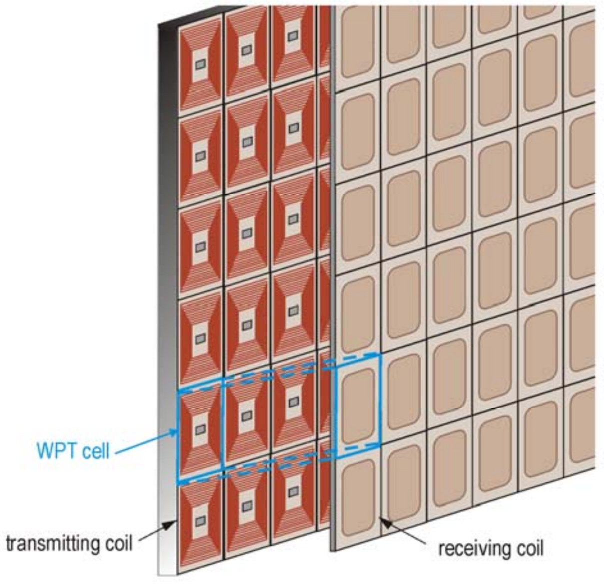

Fig.2. A view on an analysed WPT system

Two models of WPT system were analysed. The first one contained circular coils with a radius $r = 20$ mm, where $d \approx 2*r$ (Fig. 3a) and the second one had square ones (Fig. 3b). The turns are placed on a plastic carcass, in which compensating capacitors connected in series with the coils are embedded.

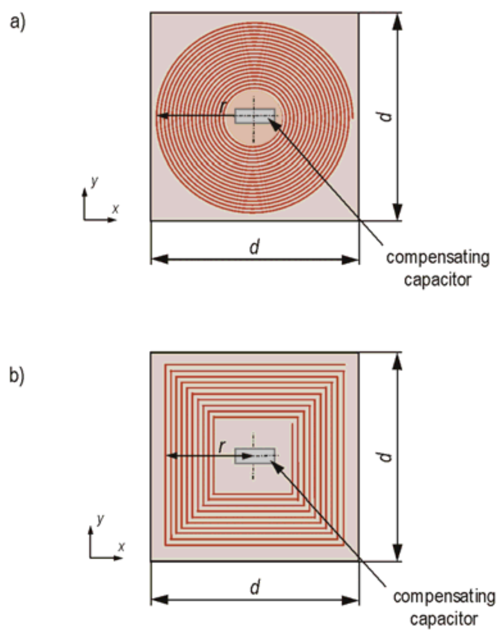

Fig.3. The types of coils considered in the models of WPT system: a) circular coil, b) square coil

The analysed system is a checkerboard type because adjacent coils (near the edge of cell) have the opposite winding direction of the coils, what is marked with arrows in the drawings (Fig. 4). Elements marked in blue frame contain turns wound in the same way. For cell $A_{x,y}$ adjacent cells: $A_{x+1,y}$, $A_{x,y+1}$, $A_{x-1,y}$, $A_{x,y-1}$ have the same winding direction opposite to $A_{x,y}$.

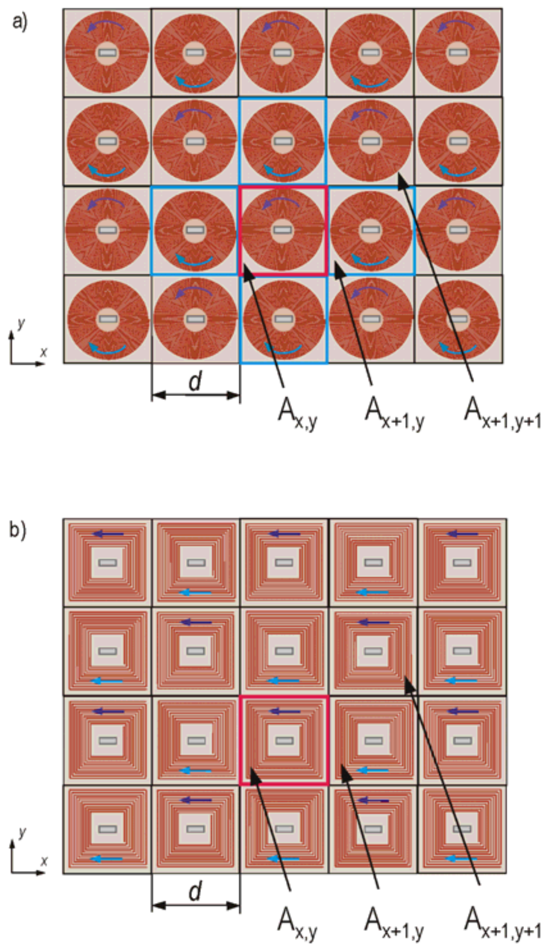

Fig.4. A two-dimensional set transmitting/receiving surface of the checkerboard type WPT system for: a) circular coils ($A_{x,y}$ – the WPT cell), b) square coils

The transmitting surface is powered so that each transmitter is connected in parallel with a sinusoidal voltage source with the effective value U. The coils forming the receiving surface are connected directly to the load.

The analysed structures of the WPT system ensure an increase in 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 $\underline{Z}_l$.

Numerical analysis of WPT system

The analysis of the WPT system can be performed using the numerical methods (e.g. FEM, FDTD, FDFD) [5, 17], analytic analysis [5] or experimental research [8, 19]. 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 causes the more accurate the solution, but the longer the calculation time. While 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, load power), it is sufficient to use numerical models.

In this analysis of WPT models 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: kind of coils, coil geometry, number of turns and elements of the electric circuit connected to each coil (Figs. 3-5).

Used square or circular planar spiral coils were wound of several dozens of turns, made of very thin wires with diameter (w) and with electrical insulator which thickness is marked as (i). The compensating capacitor is modelled as an element with a concentrated capacity (C).

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 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 (Figs. 2, 3, 4). In model antiperiodicity boundary conditions both in x and y direction were 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. 5).

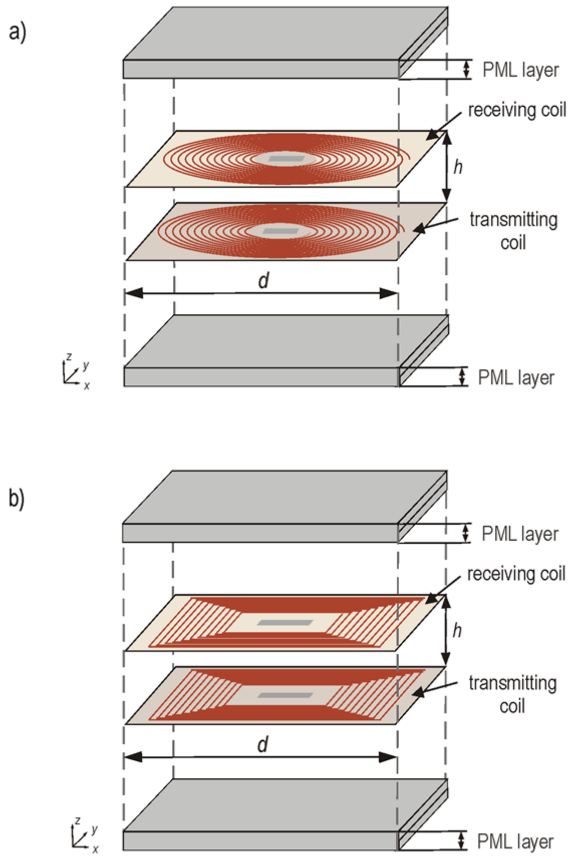

Fig.5. A numerical three-dimensional model of WPT cell for: a) circular coils, b) square coils

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

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

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

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

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

The analysis concerned selected variants of the model in order to confirm the correctness of the assumptions for numerical model. A model with a coil of $r = 20$ mm was considered. The variation in the number of turns $n \in \{30; 70\}$ and the distance between the transmitting and receiving surfaces $h \in \{10;\ 20\}$ mm are taken into account. 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	150 μm
conductivity of wire	σ	$5.6 \cdot 10^7$ S/m
source with an effective value	U	1 V
thickness of wire insulation	i	1 μm

The analysis connected with frequency domain from f_{min} = 100 kHz to f_{max} = 1000 kHz.

Results of the analysis of WPT system

The results of analysis WPT system were obtained by the numerical method (FEM) using boundary conditions (PML and antiperiodicity). Analysed model with circular coils contained 210878 degrees of freedom but NDOF=221764 for WPT system with square coils.

Figures 6-17 present the results of the analysis. The comparisons of WPT efficiency (Figs. 8, 11, 14, 17), the transmitter power (Figs. 6, 9, 12, 15), the receiver power (Figs. 7, 10, 13, 16) for different values of the number of turns of coils and different distance between the transmitting-receiving planes were presented. The graphs show the comparative characteristics for both types of coils: circular (marked with a dashed line) and square (marked with a solid line).

The characteristics for the model, where the distance between the coils was half the radius (h = 10 mm), are shown in Figs. 6-8, 12-14. On the other hand, Figs. 9-11, 15-17 show the characteristics for the model, where the distance between the coils was equal to the radius (h = 20 mm).

As can be seen, as the frequency increases, the value of the transmitter power P_z decreases, regardless of the configuration of the system (Figs. 6, 9, 12, 15). The highest transmitter power (for circular coils P_z = 0.27 W and for square coils P_z = 0.21 W) was observed for f = 100 kHz, n = 30 and h = 20 mm (Fig. 9). Increasing the number of turns to n = 70 reduces the power P_z in both cases (Figs. 12, 15). The lowest transmitter power was obtained for n = 70 and h = 10 mm (Fig. 12). Transmitter power was always higher for circular coils than for square coils.

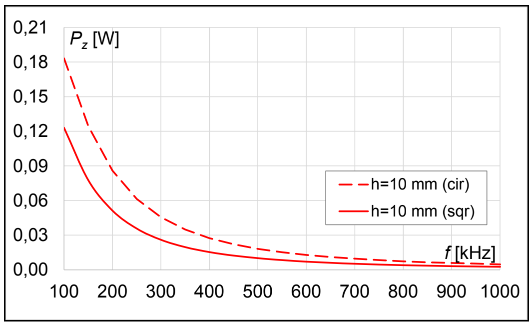

Fig.6. Results of transmitter power (P_z) dependent of kind of coils, number of turns (n=30) at distance (h=10 mm)

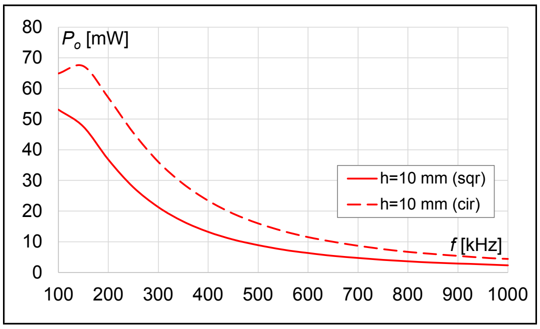

Fig.7. Results of receiver power (P_o) dependent of kind of coils, number of turns (n=30) at distance (h=10 mm)

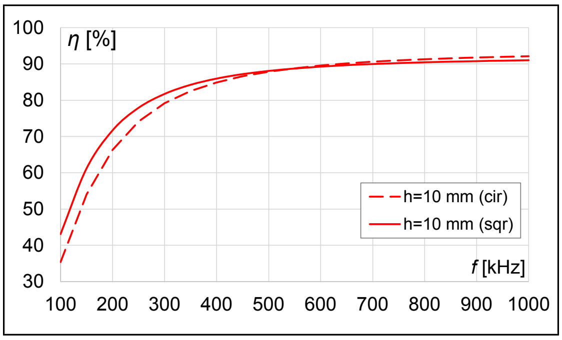

Fig.8. Results of transfer efficiency (η) dependent of kind of coils, number of turns (n=30) at distance (h=10 mm)

Figures 7, 10, 13, 16 present comparisons of the receiver power for different values of the number of turns and different distances between coils. As can be seen on Figs. 7, 10, 16, the value of the receiver power P_o increases until the efficiency for a given case reaches 50%. However, after achieving efficiency equal to 50%, P_o decreases. For the number of turns equal to 30 the maximum values of the receiver power P_o are almost the same for h = 10 mm and h = 20 mm and achieves approx. 68 mW for circular coils and 52 mW for square coils (Figs. 7 and 10). For the case where n = 70 and h = 10 mm, as the frequency increases, the value of the receiver power P_o decreases, regardless of the configuration of the system (Fig. 13). For the number of turns n = 70, the maximum value of the receiver power P_o decreases three times for h = 10 mm, and for h = 20 mm it decreases twice (Figs. 13, 16). Receiver power was always higher for circular coils than for square coils.

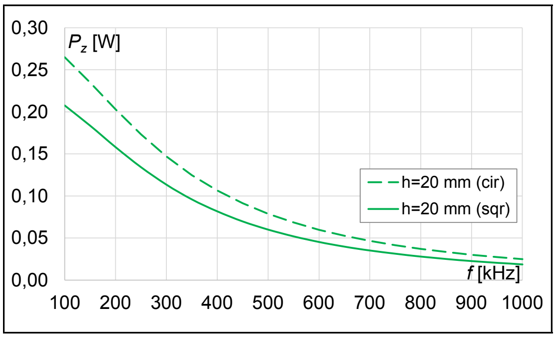

Fig.9. Results of transmitter power (P_z) dependent of kind of coils, number of turns (n=30) at distance (h=20 mm)

Figures 8, 11, 14, 17 present comparisons of the efficiency for different values of the number of turns and different distances between coils. 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. The highest efficiency (approx. 91% at f = 1000 kHz for circular and square coils) was observed for the case where n = 30 and h = 10 mm (Fig. 8). For this case, the efficiency equal to 80% was achieved at the frequency of 300 kHz, while for twice the distance between the coils (h = 20 mm), the same efficiency was achieved only above f = 750 kHz (Figs. 8, 11). Increasing the number of turns to n = 70 resulted in the system efficiency of 80% being achieved at lower frequencies, i.e. 150 kHz for h = 10 mm and 450 kHz for h = 20 mm (Figs. 14, 17). As can be seen in Figs. 8, 14, 17, at lower frequencies the efficiency of the WPT system is higher for square coils (the difference does not exceed 8%), and at higher frequencies the efficiency is higher for circular coils (the difference does not exceed 4%). Only for the case where n = 30 and h = 20 mm (Fig. 11), the system efficiency for circular and square coils is almost the same (the difference does not exceed 1%). For all considered cases, the efficiency of the WPT system increases with increasing frequency.

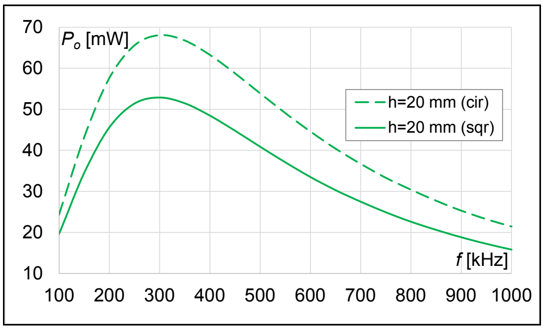

Fig.10. Results of receiver power (P_o) dependent of kind of coils, number of turns (n=30) at distance (h=20 mm)

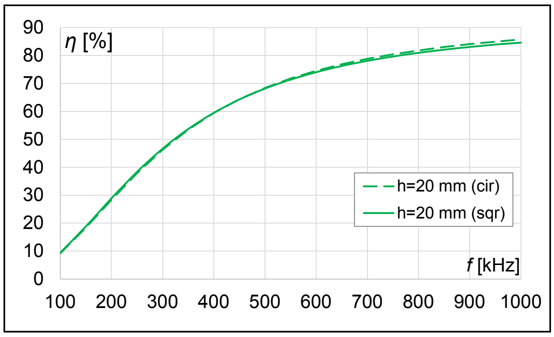

Fig.11. Results of transfer efficiency (η) dependent of kind of coils, number of turns (n=30) at distance (h=20 mm)

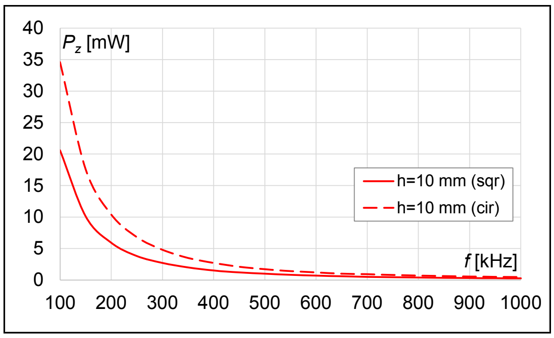

Fig.12. Results of transmitter power (P_z) dependent of kind of coils, number of turns (n=70) at distance (h=10 mm)

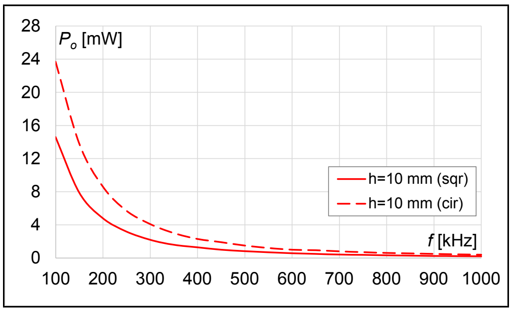

Fig.13. Results of receiver power (P_o) dependent of kind of coils, number of turns (n=70) at distance (h=10 mm)

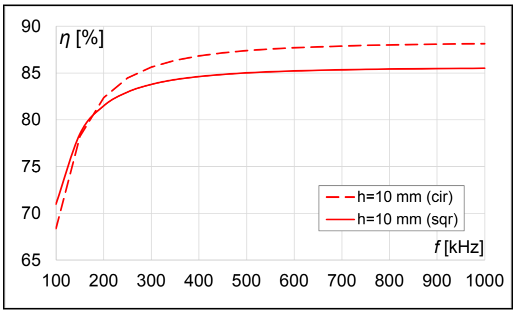

Fig.14. Results of transfer efficiency (η) dependent of kind of coils, number of turns (n=70) at distance (h=10 mm)

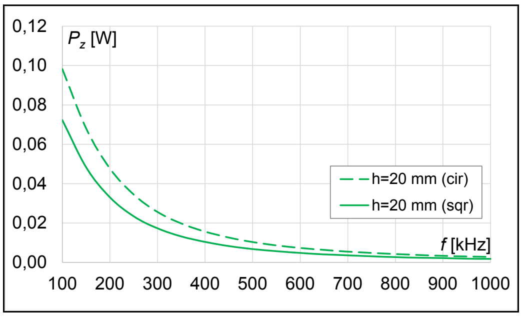

Fig.15. Results of transmitter power (P_z) dependent of kind of coils, number of turns (n=70) at distance (h=20 mm)

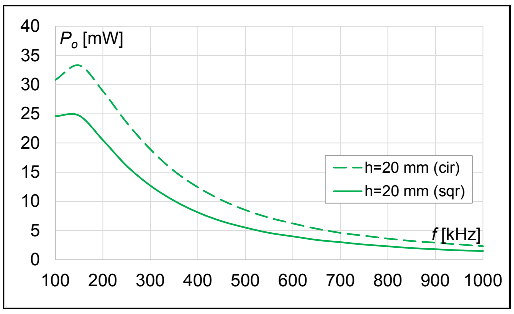

Fig.16. Results of receiver power (P_o) dependent of kind of coils, number of turns (n=70) at distance (h=20 mm)

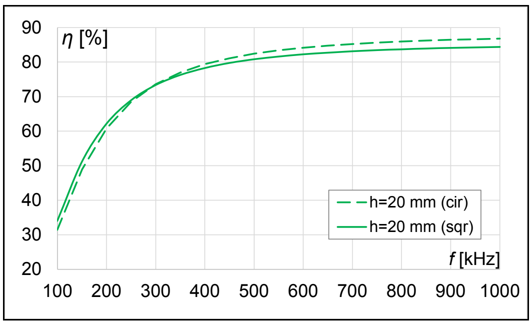

Fig.17. Results of transfer efficiency (η) dependent of kind of coils, number of turns (n=70) at distance (h=20 mm)

Conclusions

The presented checkerboard type wireless power transfer system was investigated using numerical method. 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. kind of coils, the distance between transmitter-receiver and the number of turns on the efficiency of the WPT system was analysed. The analysis covered a wide frequency range.

In the initial frequency range, efficiency is much lower for the model where the distance between the coils is the same as the radius, i.e. 20 mm, than for the model where the distance between the coils is half the radius, i.e. 10 mm. However, for higher frequencies, the efficiency values for both distances are similar. In the low frequency range (within the analysed range) the higher efficiency is for the WPT system composed of square coils. On the other hand, at higher frequency values, higher efficiency values were obtained for the WPT model containing circular coils.

Numerical analysis of WPT system consisting of many WPT cells requires consideration of the details of the model structure, such as: geometry of the coils, winding distribution, as well as elements of the electric circuit connected to each of the coils and the adopted boundary conditions. The increase in the accuracy of the mapping of the model results in an increase in the number of degrees of freedom and computation time.

The proposed configuration of the system ensures an increase in the power transmitted density in the area between the receiving and transmitting surfaces. It also enables the selection of power conditions depending on the imposed requirements. The proposed solution can be used for wireless charging of mobile devices, and can also be used to shape the distribution of the magnetic field. Proposed WPT system could be used to charge electric devices as the wireless power transfer system. The results indicate at which system parameters wireless energy transfer is possible.

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.

***Author**: mgr inż. Jacek Maciej Stankiewicz, Białystok University of Technology, Faculty of Electrical Engineering, Wiejska 45D, 15-351 Białystok, E-mail: j.stankiewicz@doktoranci.pb.edu.pl*

REFERENCES

[1] Barman S.D., Reza A.W., Kumar N., Karim Md. E., Munir A.B., Wireless powering by magnetic resonant coupling: Recent trends in wireless power transfer system and its applications, *Renewable and Sustainable Energy Reviews*, 51 (2015), 1525-1552

[2] Sun L., Ma D., Tang H., A review of recent trends in wireless power transfer technology and its applications in electric vehicle wireless charging, *Renewable and Sustainable Energy Reviews*, 91 (2018), 490-503

[3] Rim C.T., Mi C., Wireless Power Transfer for Electric Vehicles and Mobile Devices; John Wiley & Sons, Ltd.: Hoboken, United States, 2017, 473-490

[4] Fujimoto K., Itoh K., Antennas for Small Mobile Terminals, 2nd ed., Artech House: Norwood, USA, 2018, 30-70

[5] Stankiewicz J.M., Choroszucho A., Steckiewicz A., Estimation of the Maximum Efficiency and the Load Power in the Periodic WPT Systems Using Numerical and Circuit Models, *Energies*, 14 (2021), no. 4, 1-20

[6] Zhang Z., Pang H., Georgiadis A., Cecati C., Wireless Power Transfer – An Overview, *IEEE Trans. Ind. Electron.*, 66 (2019), 1044-1058

[7] Liu X., Wang G., A Novel Wireless Power Transfer System With Double Intermediate Resonant Coils, *IEEE Transactions on Industrial Electronics*, 63 (2016), 2174-2180

[8] Wenxing Z, Chi Kwan L, Hui S.Y.R., General analysis on the use of Tesla's resonators in domino forms for wireless power transfer, *IEEE Transactions on Industrial Electronics,* 60 (2013), no. 1, 261-70

[9] Liu S., Su J., Lai J., Accurate Expressions of Mutual Inductance and Their Calculation of Archimedean Spiral Coils, *Energies*, 12 (2017), no. 10, 1-14

[10] Luo Z., Wei X., Analysis of Square and Circular Planar Spiral Coils in Wireless Power Transfer System for Electric Vehicles, *IEEE Transactions on Industrial Electronics,* 65 (2018), 331-341

[11] Batra T., Schaltz E., Ahn S., Effect of ferrite addition above the base ferrite on the coupling factor of wireless power transfer for vehicle applications, *Journal of Applied Physics*, 117 (2015), 17D517

[12] Li X., Zhang H., Peng F., Li Y., Yang T., Wang B., Fang D., A wireless magnetic resonance energy transfer system for micro implantable medical sensors, *Sensors*, 12 (2012), 10292-10308

[13] Fitzpatrick D., Implantable Electronic Medical Devices; Academic Press: San Diego, United States, 2014, 7-35

[14] Martin P., Ho B.J., Grupen N., Muñoz S., Srivastasa M., An iBeacon Primer for Indoor Localization, *In Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings (BuildSys'14)*, Memphis, USA, 3-6 November 2014, 190-191

[15] Kim D., Abu-Siada A., Sutinjo A., State-of-the-art literature review of WPT: Current limitations and solutions on IPT, *Electr. Pow. Syst. Res.*, 154 (2018), 493-502

[16] Kesler M., Highly Resonant wireless power transfer: safe, efficient and over distance, WiTricity Corporation, 2013

[17] Choroszucho A., Butryło B., The numerical analysis of the influence conductivity of clinker bricks and the size of their hollows on the distribution of the electromagnetic field, *Przegląd Elektrotechniczny*, 88 (11A), (2012), 351-354

[18] Manivannan P., Bharathiraja S., Qi Open Wireless Charging Standard – A Wireless Technology for the Future, International Journal of Engineering and Computer Science, 2 (2013), no. 3, 573-579

[19] Rozman M., Fernando M., Adebisi B., Rabie K.M., Collins T., Kharel R., Ikpehai A., A New Technique for Reducing Size of a WPT System Using Two-Loop Strongly-Resonant Inductors, *Energies*, 10 (2017), 1614

[20] Mohan S., Hershenson M., Boyd S., Lee T., Simple Accurate Expressions for Planar Spiral Inductances, *IEEE Journal of solid-state circuits*, 34 (1999), no. 10, 1419-1424

[21] Raju, S., Wu, R., Chan, M., Yue, C.P., Modeling of Mutual Coupling Between Planar Inductors in Wireless Power Applications. *IEEE Trans. Power Electron*. 29, (2014), 481-490

[22] Tal N., Morag Y., Levron Y., Magnetic Induction Antenna Arrays for MIMO and Multiple-Frequency Communication Systems, *PIER C*, 75 (2017), 155-167