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Estimating the possibility of maximizing efficiency in the periodic WTP system

***Abstract**. The article presents an analysis of the maximum efficiency available to obtain in periodic Wireless Power Transfer (WPT) systems. The article also proposes analitycal solution of the transmitter-receiver system, taking into account the parameters calculated on the basis of analytical equations concerning the influence of magnetic couplings, structure geometry and the type of loads. The purpose was to quickly determine the output parameters (e.g. power, efficiency) both with analytical model and by using equivalent numerical model. Also a numerical model with simplified structure and boundary conditions as well as equivalent circuit model is proposed to solve WPT system with many magnetically coupled planar coils. A multivarint analysis is performed, which took into account the variability of the number of turns, distance between a transmitting and receiving coil, and a frequency of an energy source. The formulas for the load impedance to maximize efficiency, which are taking into account electrical parameters of the system resulting from its geometry, are presented. The results obtained from proposed models were consistent, which confirmed the correctness of the adopted circuit model. The results allow for a detailed discussion of the dependence of the efficiency and power of the WPT system with respect to geometry of spiral coils.*

***Streszczenie.** W artykule przedstawiono analizę maksymalnej możliwej do uzyskania sprawności w układach periodycznych Wireless Power Transfer (WPT). W artykule zaproponowano również rozwiązanie analityczne układu nadawczo-odbiorczego, uwzględniające parametry obliczone na podstawie równań analitycznych dotyczących wpływu sprzężeń magnetycznych, geometrii konstrukcji i rodzaju obciążeń. Celem było szybkie określenie parametrów wyjściowych (np. Moc, sprawność) zarówno za pomocą modelu analitycznego, jak i za pomocą równoważnego modelu numerycznego. Zaproponowano również model numeryczny z uproszczoną strukturą i warunkami brzegowymi, a także model obwodu zastępczego do rozwiązania układu WPT z wieloma cewkami planarnymi sprzężonymi magnetycznie. Przeprowadzono analizę wielowarstwową, w której uwzględniono zmienność liczby zwojów, odległość między cewką nadawczą i odbiorczą oraz częstotliwość źródła energii. Przedstawiono wzory na impedancję obciążenia w celu maksymalizacji sprawności uwzględniające parametry elektryczne układu wynikające z jego geometrii. Wyniki uzyskane z zaproponowanych modeli były zgodne, co potwierdziło poprawność przyjętego modelu obwodu. Uzyskane wyniki pozwalają na szczegółowe omówienie zależności sprawności i mocy układu WPT od geometrii cewek spiralnych. (**Oszacowanie możliwości maksymalizacji sprawności w periodycznym systemie WPT**).*

Keywords: wireless power transfer (WPT), magnetic fields, 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 devices. Their computing power and the number of supported sensors still grew. These factors contribute to the growing demand for batteries with increased capacity and determine the mobility of devices. One way to supply mobile devices with energy is charging using wireless power transfer (WPT) [1-4].

In the literature, solutions improving the efficiency of the WPT system by, for example, introducing two additional coils (apart from the transmitting and receiving) are presented [2]. This solution increased the efficiency of the system by 30%. WPT system is increasingly used, among others in the automotive industry in solutions for hybrid and electric cars [4, 5, 6]. In order to charge the batteries while driving, distributed coils along the path of the car were used. Through to such use of WPT, it is possible to use electric vehicles, e.g. in factories. WPT system is considered an alternative method of charging wireless devices, in which the most common pair of coils [7-10] or pair with additional coils [11-15] and in some cases power transfer is assisted using metamaterial structures [16]. WPT system is also considered in the medical implants in body [17, 18] and buildings with sensors inside construction due to e.g. architectural appearance [19, 20].

Despite the wide application of WPT is still analyzed various solutions and configurations of this type of systems. Each solution requires a multi-variant analysis and verification of the results. In order to avoid early prototyping and performing a number of analyzes, it is possible to apply analytical and numerical methods already at the design stage.

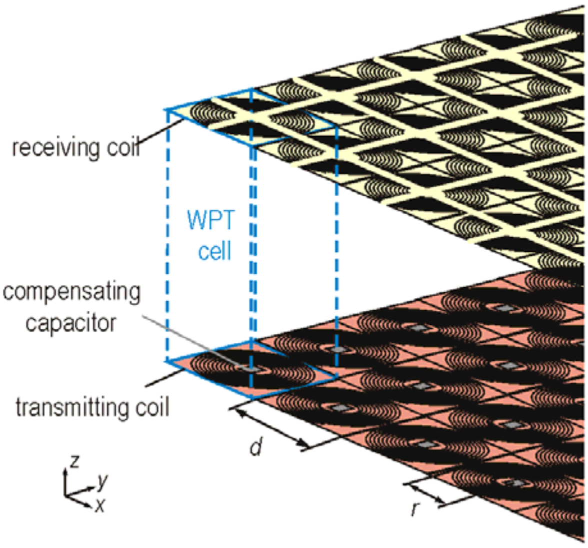
The article proposes an analysis of the WPT system, in which a set of several coils participating in energy transfer was replaced with surfaces made of periodically distributed planar coils. Adjacent segments containing a pair of coils (transmit and receive) between which energy is exchanged, can be used to power multiple independent loads or replace conventional WPT systems. A proprietary analytical method for solving systems of this type was developed and presented. Its purpose is to quickly determine the parameters of the system (e.g. power, efficiency) without the need to make complex models and solve them using numerical methods. The article also presents the developed numerical model of the proposed WPT systems, taking into account the periodic distribution of the coils and their diversified structure, intended for the analysis of magnetic phenomena in the frequency domain. Sample calculations were performed to determine selected electrical parameters of WPT systems, i.e. equivalent properties, source power, receiver power, and system efficiency. The analysis was multi-variant because, the geometry of the coils, their parameters and the distance between them were changed. The proposed systems can be used for wireless charging of mobile devices, and can also be used to shape the distribution of the magnetic field.

The analysis concerned the influence of the geometric parameters of the coil (number of turns, distance between the coils) and frequency on the efficiency of WPT system and the power of the transmitter and receiver. By appropriate selection of the load resistance, it was possible to either determine the maximum efficiency of the WPT system. The results obtained with the proposed analytical method were consistent with the results obtained with the numerical method, which confirmed the correctness of the assumptions of the proposed analytical method.

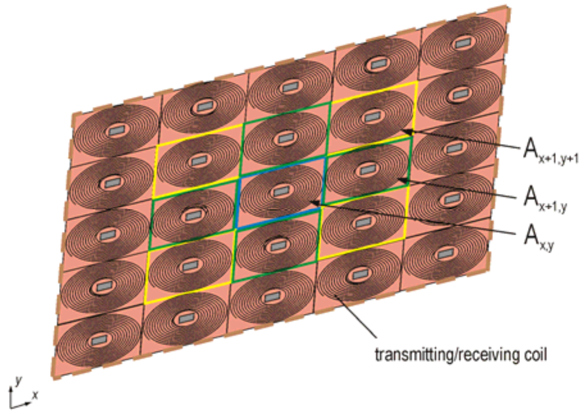
The developed periodic WPT system allows for the simultaneous supply/charging of many low-power receivers, repeatedly distributed over even hard-to-reach surfaces (e.g. ceilings, interior walls, housings of other devices).

Analysed Wireless Power Transfer System

In the article, periodic wireless power transfer system with many inductive elements is presented. The considered system is composed of many pairs of transmitter and receiver, which constitute the WPT cell with outer dimensions $d \times d$ (Fig. 1). 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 give 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).



(a)



(b)

Fig.1. WPT system: (a) periodic wireless power transfer system composed of transmitting surface (bottom) and receiving surface (on top), (b) a fragment of the transmitting/receiving surface

The proposed model of the WPT 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. 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. 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. 1b). Considered cell $A_{x+i,y+j}$ is an element of an array with identical inductors, where i is a number of column and j is a number of row in a grid ($i, j \in \mathbf{N}$ and $\mathbf{N}$ is the set of integers numbers). Adjacent coils (e.g. $A_{x,y+1}$ or $A_{x-1,y}$) of element $A_{x,y}$ are separated by the distance d where there is relation $d \approx 2r$.

Numerical approach to the analysis of WPT system

Using the numerical methods (e.g. FEM, FDTD, FDFD) and also specialized programs for numerical analysis, it is possible to create a model and determine the distribution of the magnetic field [10, 21, 22]. In this approach, it is necessary to prepare a 3D model and set complex boundary conditions but the efficiency and accuracy of the solution depend on the size of the model (degrees of freedom, NDOF). The more number of degrees of freedom cause the greater the accuracy of the solution but result the longer the computation time.

In the article were compared the results obtained with the proposed analytical method with the results determined using the numerical method – Finite Element Method (FEM). The aim was to assess the correctness of the adopted assumptions of the developed mathematical solution, as well as the usefulness of this method.

In the numerical analysis of the energy transfer in a system composed of many WPT cells requires taking into account: coil geometry, coil turns distribution, number of the WPT cells and elements of the electric circuit connected to each coil. 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 (i). Compensating capacitor can be 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 ($\underline{I}_{tr}$). Receiving coil, connected with a linear load $\underline{Z}$, carry induced current $\underline{I}_{re}$.

In order to project infinite array of WPT periodic boundary conditions (PBC) were applied. In this case the wireless charging system will be simplified to single cell $A_{x,y}$ filled with air and containing a pair of transmitting and receiving coils (Fig. 2). Perfectly matched layer (PML) is put in top and bottom of the model to imitate dielectric background [22].

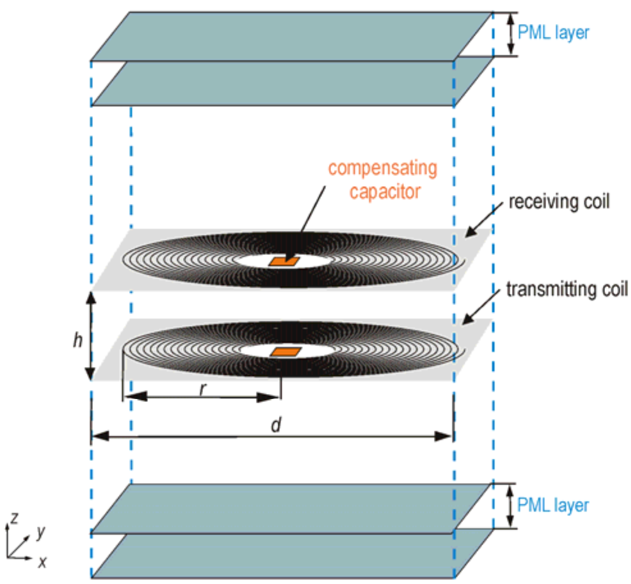


Fig.2. A three-dimensional view on one of WPT cell

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

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

and formulation of magnetic field phenomena in frequency domain using the Helmholtz equation

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

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].
Periodic boundary conditions on four external surfaces where defined as a magnetic insulation

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

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

Analytical approach to the analysis of WPT system

Despite the availability of computational units, it is more difficult to make a numerical model than an analytical one due to e.g. the appropriate selection of boundary values and many necessary simplifications imposed by the adopted numerical method. Therefore, in many cases, a simpler model is desirable, providing a similar scope of analysis, but less complex and much faster modelling and calculation processes.

The proposed analytical solution is combining two-port network with analytical equations for calculating lumped parameters (Figure 3). The analysis of the infinitely extensive periodic network was reduced to the case of a single WPT cell. The solution of analytical model in frequency domain can be performed using methods of circuit analysis. The main problem in this type of analysis is to determine the values of the lumped parameters, taking into account the influence of adjacent segments on the equivalent inductances of the transmitting coil L_{tr} and receiving coil L_{re} and their mutual inductance M_{tr}.

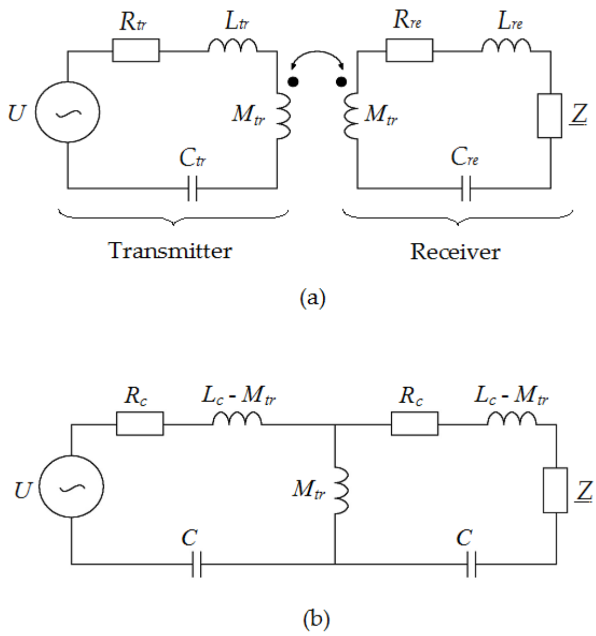


Fig.3. Analytical model of the periodic WPT cell: (a) overall model of periodic cell, (b) replacement model of the cell for identical transmitting and receiving coil

Resistance of a coil can be determined by replacing spiral structure of windings converging circles of equal width (w+i). Whole length of all circles is defined as

$$l_{sum} = 2\pi n\left[r - (n-1)(w+i)\right] \quad (4)$$

Taking into account equation (4), the formula determining resistance of a conductor is described by

$$R_c = \frac{l_{sum}}{\sigma\pi \frac{\left(w^2\right)}{4}} \quad (5)$$

If coils (transmitting and receiving) are identical the calculated resistances is $R_c = R_{tr} = R_{re}$ and not dependent of frequency. Self-inductance of a spiral planar coil is calculated using formula [23]

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

where d_m is a mean diameter

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

and wsp is a fill factor

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

Coefficients c_1, c_2, c_3, c_4 used in the equation (6) are depending on shape of a coil [23] and equal: c_1=1, c_2=2.5, c_3=0, c_4=0.2 [10].

For identical transmitting and receiving coils calculated inductances are equal $L_c = L_{tr} = L_{re}$. In the periodic system the coils are adjacent and for this reason it is necessary to include magnetic coupling between them. Mutual inductance M_{pe}, which is directly from periodic distribution of coils arranged on the surface, is a sum of all mutual inductances [23, 24]

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

where: $M_{x+i,y+j}$ is mutual inductance between coil and coil at i-th column and j-th row, $M_{x,y}$ = L_{self} is 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 formula

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

where: $M_{x,y+1}$ is mutual inductance between coil and an edge adjacent coil and is calculated from the formula

(11)

$$M_{x,y+1} = \frac{\mu_0 p^2}{4\pi} \int_{\Phi_i}^{\Phi_o} \int_{\Phi_i}^{\Phi_o} \frac{\left[(1+\varphi_1\varphi_2)\cos(\varphi_2-\varphi_1) - (\varphi_2-\varphi_1)\sin(\varphi_2-\varphi_1)\right]\mathrm{d}\varphi_1\,\mathrm{d}\varphi_2}{\sqrt{(d + p\varphi_2\cos\varphi_2 - p\varphi_1\cos\varphi_1)^2 + (p\varphi_2\sin\varphi_2 - p\varphi_1\sin\varphi_1)^2}}$$

where: p = (w+i)/(2π), Φ_i = [r – (w+i)n]/p, Φ_o = r/p.
Assuming equation (10), the inductance of the considered coil in the segment $A_{x,y}$ take a form

$$L_c = L_{self} + M_{pe} = L_{self} + 8M_{x,y+1} \quad (12)$$

After calculations of self-inductance L_{self} and $M_{x,y+1}$ it is possible to find compensating capacity C at definite frequency

(13) $$C(f)=\frac{1}{4\pi^2 f^2 L_c}=\frac{1}{4\pi^2 f^2\left(L_{self}+M_{pe}\right)}=\frac{1}{4\pi^2 f^2\left(L_{self}+8M_{x,y+1}\right)}$$

where: with the assumption that transmitting and receiving coils are identical, $C(f) = C_{tr} = C_{re}$.

Mutual inductance M_{tr} between transmitter and receiver is presented in a form

(14)

$$M_{tr}=\frac{\mu_0 p^2}{4\pi}\int_{\Phi_i}^{\Phi_o}\int_{\Phi_i}^{\Phi_o}\frac{\left[(1+\varphi_1\varphi_2)\cos(\varphi_2-\varphi_1)-(\varphi_2-\varphi_1)\sin(\varphi_2-\varphi_1)\right]\mathrm{d}\varphi_1\,\mathrm{d}\varphi_2}{\sqrt{h^2+p^2\varphi_1^2+p^2\varphi_2^2-2p^2\varphi_1\varphi_2\cos(\varphi_2-\varphi_1)}}$$

Analysed models

The analytical model taking into account a number of phenomena and the geometry of the system is characterized by a high accuracy of solving the problem of power transport. The presented analytical model enables simplification and acceleration of calculations of periodic WPT systems (Table 1). The results obtained using the proposed analytical solution were verified with one, which is obtained by the numerical model (on the Figures 4-9. marked by FEM).

Table 1. Geometrical parameters for analysed models

radius (r [mm])	number of turns (n)	distance between coils (h [mm])
25	40	12.5 and 25
	50	12.5 and 25
	60	12.5 and 25

On the basis of obtained results for periodic WTP system was verified the validity of proposed analytical model by comparing active power of receiver

(15) $$P_o = R_o I_{re}^2$$

and power on the transmitting coil

(16) $$P_z = U I_{tr}$$

Using equations (15) and (16) the power transfer efficiency was described by equation

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

The comparison concerned the determination of P_z and P_o and efficiency. The results concerned the appropriate selection of impedance to obtain the maximum efficiency of the system Z_e by equation

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

The following parameters were adopted for multivariate calculations: wire thickness $w = 200$ μm, insulation thickness $i = 5$ μm, conductivity of wire $\sigma = 5.6\cdot 10^7$ S/m, voltage $U = 1$ V and frequency from $f_{min} = 0.1$ MHz to $f_{max} = 1$ MHz. Lumped parameters of analytical model were found using previously designated equations and were presented in Table 2. Transmitter and receiver power and power transfer efficiency were calculated for both models (analytical and numerical) within frequency range $f_{min} \div f_{max}$.

Table 2. Calculated parameters

n	M_{pe} (μH)	C (pF)	Z_e (Ω)		M_{tr} (μH)	
			$h = 0.5\,r$	$h = r$	$h = 0.5\,r$	$h = r$
40	2.59	293	93	21.37	14.8	3.37
50	3.37	219	137	31.54	21.7	4.99
60	4.12	178	180	42.07	28.6	6.61

In order to determine the maximum efficiency, the impedance 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 also presented values of mutual inductance M_{tr} between transmitter and receiver for 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 a four-fold decrease the values of mutual inductance.

Results of the analysis

The calculation results of WPT system obtained by the numerical and analytical methods were compared. For this purpose the source power, receiver power and also the transfer efficiency (η) were compared. It was taken into account the structure of the WPT system (e.g. number of turns, distance between cells, size of WPT cell). Transmitter and receiver power and power transfer efficiency were calculated within frequency range from f_{min} = 0.1 MHz to f_{max} = 1 MHz (for both methods: analytical and numerical).

The numerical model was created in the *Comsol Multiphysics program* using boundary conditions (PML and periodicity). Numerical analysis was performing by using FEM method. Analyzed model contained 292630 degrees of freedom.

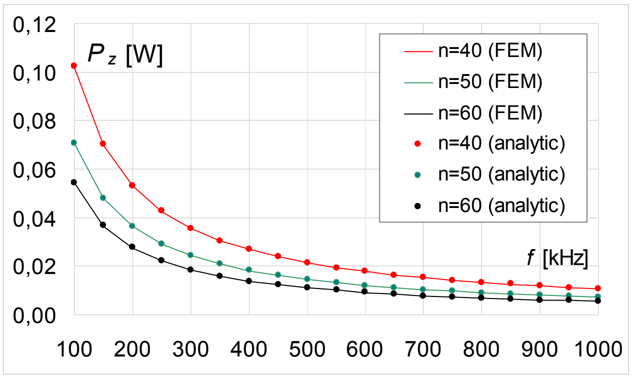


Fig.4. Results comparison of source power (P_z) dependent of number of turns for the case h = 12.5 mm

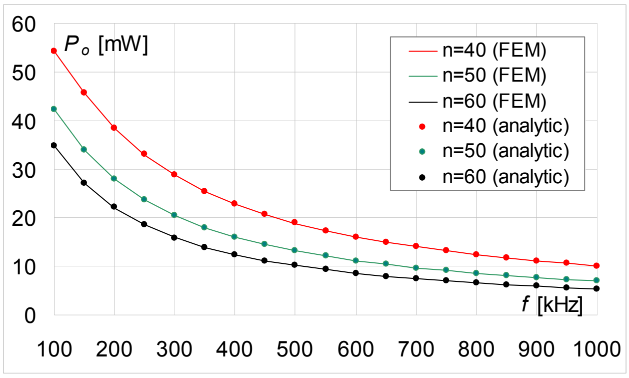


Fig.5. Results comparison of receiver power (P_o) dependent of number of turns for the case h = 12.5 mm

Figures 4-9 present comparisons of WPT efficiency (Figs. 6, 9), the source power (Figs. 4, 7), the receiver power (Figs. 5, 8) for different values of the number of turns of the transmitting and receiving coils and different distances between these coils.

Figures 4 and 7 show the variability of the source power (P_z) depending on the frequency and number of turns. With the increase in frequency, the P_z decrease regardless of the number of turns or the distance between the transmitting and receiving coils. In the whole frequency range the P_z is larger for h = 25 mm than for h = 12.5 mm.

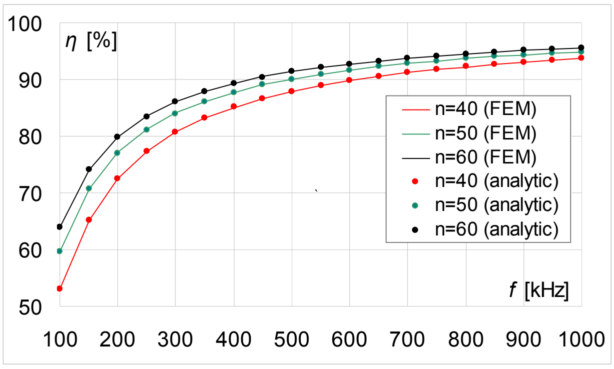


Fig.6. Results comparison of power transfer efficiency dependent of number of turns for the case h = 12.5 mm

Figures 5 and 8 show the variability of the receiver power (P_o) depending on the frequency and number of turns for different distances between the coils. For h = 12.5 mm, with the increase in frequency, the P_o decrease regardless of the number of turns. For h = 25 mm, the value of the receiver power reaches its maximum value when the efficiency reaches approximately 50%. After that, the receiver power decreases for all number of turns.

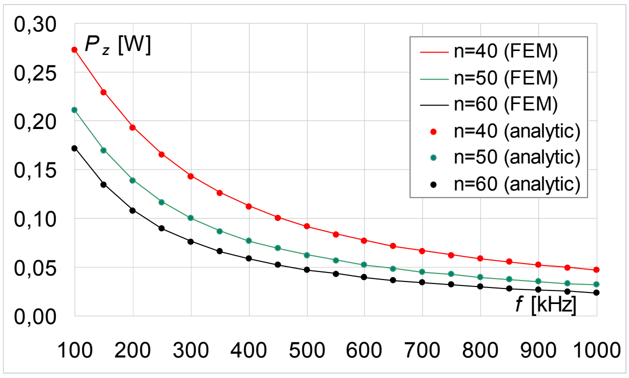


Fig.7. Results comparison of source power (P_z) dependent of number of turns for the case h = 25 mm

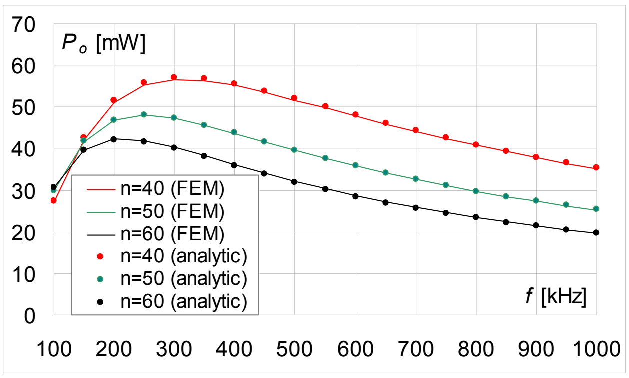


Fig.8. Results comparison of receiver power (P_o) dependent of number of turns for the case h = 25 mm

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. 6, 9). The highest efficiency of WPT system (96%) was observed for f = 1000 kHz, n = 60 and h = 12.5 mm. However, for n = 40 the efficiency of the system was slightly lower (94%). Twice increasing the distance between the coils (h = 25 mm) reduced the efficiency of the system. The maximum efficiency value equal 82% was observed for n = 60 (Fig. 9).

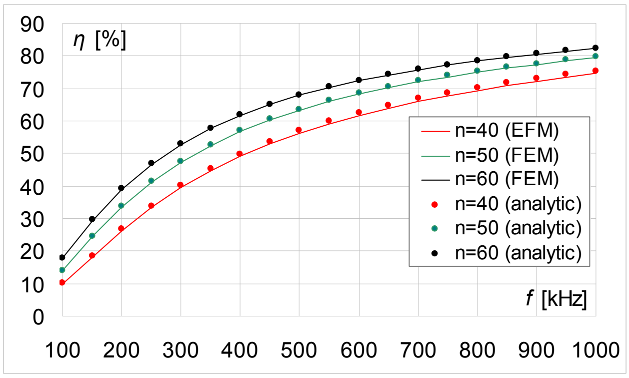


Fig.9. Results comparison of power transfer efficiency dependent of number of turns for the case h = 25 mm

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

Conclusions

The article contains e.g. analytical solution that allows to determine, for example: efficiency, load power at the design stage and preliminary analysis of the system properties. In the article also proposes model of the transmitter-receiver system, taking into account the parameters calculated on the basis of analytical equations concerning the influence of magnetic couplings, structure geometry and the type of loads.

The model used for solving considered structures, arranged of many spiral planar coils, was developed. The purpose was to quickly determine the output parameters (e.g. power, efficiency) both with analytical model and by using equivalent numerical model. The use of electrical circuit, representing a single cell of the WPT system eliminated the need to make very complex models, which are solved using numerical methods. Also in the article presented the structure of the numerical model and conditions that help to reduce its complexity.

The given solutions in the article, which were used in the numerical and analytical models, allow studying the influence of the coil geometry and distance between transmitter and receiver on the power transmission. The analysis concerned the influence of geometrical parameters of coils in the WPT cell (e.g. number of turns) on the efficiency of system and the power of transmitter and receiver in wide frequency range. By simply adjusting the number of turns and increasing frequency of a current, it was possible to obtain high efficiency of power transmission (≈95%) for the loads supplied using proposed system, without the use of intermediate coils or iron cores/bars. Even at distances equal to a radius of coil the system was still able to reach near 82% efficiency.

Additionally, the results of obtaining maximum efficiency were presented. By appropriate selection of load impedance it was possible to determine the power transferred to receiver and a corresponding efficiency. The results from analytical approach were consistent with results from numerical model. The results confirmed a correctness of the adopted assumptions and shown that the analysis of an extensive grid of periodic resonators can be simplified to a single WPT cell.

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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] Liu X., Wang G., A Novel Wireless Power Transfer System With Double Intermediate Resonant Coils, *IEEE Transactions on Industrial Electronics*, 63 (2016), 2174-2180
[3] 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
[4] Zhang Z., Pang H., Georgiadis A., Cecati C., Wireless Power Transfer-An Overview, *IEEE Trans. Ind. Electron*., 66 (2019), no. 2, 1044-1058
[5] 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
[6] 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
[7] Rim C.T., Mi C., Wireless Power Transfer for Electric Vehicles and Mobile Devices; John Wiley & Sons, Ltd.: Hoboken, United States, 2017, 473-490
[8] Fujimoto K., Itoh K., Antennas for Small Mobile Terminals, 2nd ed., Artech House: Norwood, USA, 2018, 30-70
[9] 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
[10] Steckiewicz A., Stankiewicz J.M., Choroszucho A., Numerical and Circuit Modeling of the Low-Power Periodic WPT Systems, *Energies*, 13 (2020), no. 10, 1-17
[11] 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
[12] Liu X., Wang G., A Novel Wireless Power Transfer System With Double Intermediate Resonant Coils, *IEEE Trans. Ind. Electron.,* 63 (2016), pp. 2174-2180
[13] El Rayes M.M., Nagib G., Abdelaal W.G.A., A Review on Wireless Power Transfer, *IJETT*, 40 (2016), 272-280
[14] Re P.D.H., Podilchak S.K., Rotenberg S., Goussetis G., Lee J., Circularly Polarized Retrodirective Antenna Array for Wireless Power Transmission, *In Proceedings of 2017 11th European Conference on Antennas and Propagation (EUCAP)*, Paris, France, 19-24 March (2017), pp. 891-895
[15] Nikoletseas S., Yang Y., Georgiadis A., Wireless Power Transfer Algorithms, Technologies and Applications in Ad Hoc Communication Networks, *Springer*: Cham, Switzerland, (2016), pp. 31-51
[16] Steckiewicz A., Choroszucho A., Numerical investigation of quasi-static magnetic cloak performance in time-varying magnetic field, *Romanian Journal of Physics*, 64 (2019), 606, 1-11
[17] 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
[18] Fitzpatrick D., Implantable Electronic Medical Devices; Academic Press: San Diego, United States, 2014, 7-35
[19] Kesler M., Highly Resonant wireless power transfer: safe, efficient and over distance, WiTricity Corporation, 2013
[20] 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
[21] Choroszucho A., Analysis of the influence of the complex structure of clay hollow bricks on the values of electric field intensity by using the FDTD method, *Archives of Electrical Engineering*, 65 (2016), no. 4, pp. 745-759
[22] Ping L., Qi-tao Y., Yun-liang L.: Analysis of electromagnetic propagation into reinforced concrete walls by FEM-PML methods. IEEE International Conference on Microwave and Millimeter Wave Technology, ICMMT 2008 Proceedings, s. 1-4, 2008.
[23] 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
[24] 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