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Chapter 5. Analysis of the influence of load resistance on the efficiency in WPT systems

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Streszczenie. W rozdziale przedstawiono analizę systemu bezprzewodowego przesyłu energii (WPT) z wykorzystaniem okresowo rozłożonych cewek planarnych. Celem analizy było zbadanie wpływu rezystancji obciążenia na sprawność tych systemów. Sprawdzono, dla jakich rezystancji dany system może osiągnąć maksymalną sprawność i moc obciążenia. W analizie uwzględniono liczbę zwojów. Do analizy wykorzystano dwa podejścia (analityczne i numeryczne). Analizę numeryczną przeprowadzono z wykorzystaniem Metody Elementów Skończonych (MES). Metoda analityczna została odniesiona do rozwiązania równoważnego obwodu elektrycznego. Wyniki analizy wykazały, że większe wartości maksymalnej sprawności osiągnięto dla modelu z cewką kołową niż dla cewki kwadratowej, a różnica nie przekroczyła 19%. Wraz ze wzrostem liczby zwojów rosną wartości rezystancji obciążenia, dla których osiągnięto maksymalną sprawność i moc odbiornika. Wyniki pozwolą na projektowanie systemów WPT z odpowiednim doborem rezystancji obciążenia w celu osiągnięcia maksymalnej sprawności.

Abstract. The chapter presents an analysis of a Wireless Power Transfer (WPT) system with the use of periodically distributed planar coils. The aim of the analysis was to investigate the impact of the load resistance on the efficiency for these systems. Tests were carried out to understand for which resistances a given system can achieve maximum efficiency and load power. The analysis took into account the number of turns. Two approaches (analytical and numerical) were used for the analysis. The numerical analysis was performed using the Finite Element Method (FEM). The analytical method was related to the solution of the equivalent electric circuit. The results of the analysis showed that greater values of maximum efficiency were achieved for the model with a circular coil than for a square coil, and the difference did not exceed 19%. With the growth in the number of turns, the values of the load resistance grow, for which the maximum efficiency and power of the receiver were achieved. The results will allow the design of WPT systems with the proper selection of load resistance in order to achieve maximum efficiency.

Słowa kluczowe: bezprzewodowe przesyłanie mocy, indukcyjne przesyłanie mocy, rezystancja obciążenia, analiza numeryczna

Keywords: wireless power transfer, inductive power transfer, load resistance, numerical analysis, circuit analysis

Introduction

Nowadays, there is a growing number of devices using Wireless Power Transfer (WPT) technology [1, 2]. Current trends, visible in wireless vehicle charging systems [5, 6] and modern electronics [3, 4, 5], have also led to the extension of the concept of the so-called inductive power transfer (IPT). Among others, in the case of the growing number of mobile devices, or remotely operated sensors [6, 7], a constant supply of energy is necessary to ensure continuous operation. In this context, WPT is considered as an alternative method of fast charging wireless devices.

In order to implement IPT, a pair of coils [6, 8] is used together with, for example, additional intermediate coils [9, 10], or a system of coils [11, 12]. Technological solutions with multiple coils usually operate at high frequencies [13]. At low frequencies ($f < 1000$ kHz), systems of resonating coils (resonators) are considered [14, 15]. In these solutions, in the space between the transmitter and receiver, several additional resonators support energy transfer. So far, a detailed analysis of the series configuration of the resonators has been carried out. However, the analysis of the series-parallel distribution of planar coils working as a group of energy transmitters and receivers is not yet fully developed. In addition, wireless charging is considered in systems located in hard-to-reach places, e.g. in the case of groups of beacons [16], or in buildings with sensors inside walls and ceilings [17]. This technology is widely developed in medicine [18]. A very important aspect in WPT systems is also the impact of the environment on the quality of system operation and achieving high efficiency of the system [19].

The power supply or charging of many devices located in close proximity to each other can be simplified by using WPT systems, made as networks with periodically arranged coils that form surface elements for transmitting or receiving energy. This solution increases the density of the transmitted power, and also enables the simultaneous powering of many devices fromone source. Potential applications of this type of WPT systems focus mainly on the simultaneous charging of a number of sensors [20]. From the point of view of applications in high-power systems, the periodic WPT elements proposed in the chapter can be considered for the design of distributed vehicle charging systems in large parking lots.

The design and analysis of the mentioned WPT systems involves the use of three-dimensional numerical models used to calculate the distribution of the magnetic field in the system. In order to minimize the complexity of the problem and the number of degrees of freedom of the model, the chapter proposes two ways of analyzing the system based on the structure and parameters of a single segment. Numerical analysis and a solution based on the electrical circuit were considered. The use of numerical modeling methods significantly simplifies the problem of engineering calculations of the proposed systems, introducing the possibility of their design using software for numerical calculations. Both proposed approaches reduce the size and complexity of commonly utilized numerical and circuit models.

Analyzed models

The presented analysis was focused on selected configurations of planar systems, enabling wireless energy transfer (through inductive coupling between the energy source and receiver), in which it is possible to process and transfer it. The considered systems were based on multi-segment surfaces, composed of identical components with selected geometry (periodically distributed over these surfaces) acting as a source and receiver with a dispersed but ordered distribution of elementary energy sources/receivers. This configuration requires taking into account the frequency range of the power source, as well as the geometry of the system.

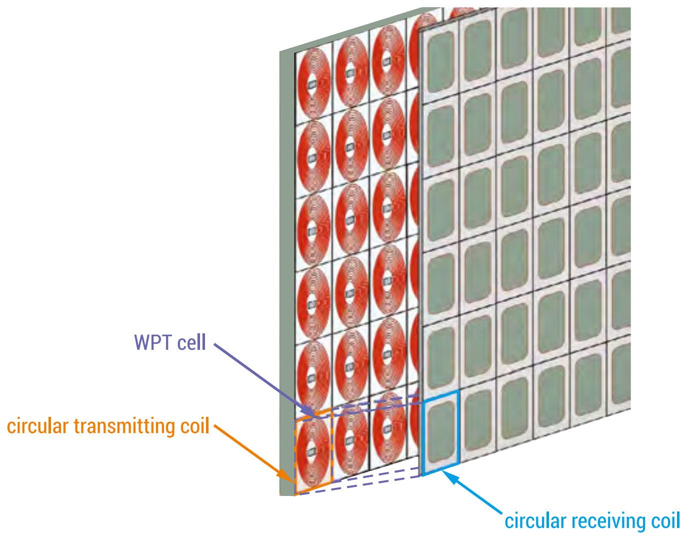

FIGURE 1. The analyzed periodic WPT system with planar coils

Each coil has a compensation capacitor in series with the coil. The Tx coils create the transmitting surface, and Rx coils the receiving surface. Between those surfaces, wireless energy transfer takes place. The transmitting surface has a sinusoidal voltage source (U_{sc}). The receiving coils are combined to the loads (Z_l). Multiple receivers can be supplied simultaneously.

Methods analysis

Each of the methods (analytical, numerical, experimental) has advantages and disadvantages. Knowledge of the methods and needs imposed by the analyzed system allows for the appropriate selection of the method of task implementation and elimination of errors. Knowledge of numerical methods enables the proper use of calculation packages (e.g. Matlab, Maple, Mathematica), as well as provides the necessary basis for independent solving of specific, increasingly complex, engineering problems. This requires, on the one hand, the awareness of the essence of the problems to be solved, and on the other hand, knowledge of the methods of solving them.

The Finite Element Method (FEM) is one of the numerical methods for solving differential equations. These equationsdescribe phenomena and processes known in nature, physics and technology. The use of FEM in solving technical problems results from the possibility of achieving the result of an equation that cannot be solved analytically or is too complex and time-consuming.

Discretization is the first step in creating the FEM model. It consists in dividing the area into smaller elements. Elements have common nodes (points) and additionally contain information about mutual proximity. Discretization is crucial in FEM issues, because it determines the length of the calculations and the accuracy of the results. Simulation of physical processes using the Finite Element Method, in the final stage, consists in solving a system of algebraic equations. The number of unknowns is closely related to the number of nodes that make up the mesh and the number of unknowns in each node. By increasing the mesh density, we increase the calculation time and at the same time increase the accuracy of the solution. The Comsol Multiphysics 4.3b package was used to prepare a numerical model presenting the proposed solution and to perform computer simulations (Fig. 2). Comsol can model wave problems in the frequency domain using the additional *Radio Frequency* module. A detailed description of the boundary conditions can be found in the Comsol documentation [22, 23]. The compensation capacitor (C_{cp}) was modelled as a lumped element. To model the infinite dielectric background, two layers (PML) were used at the top and bottom of the WPT cell [24].

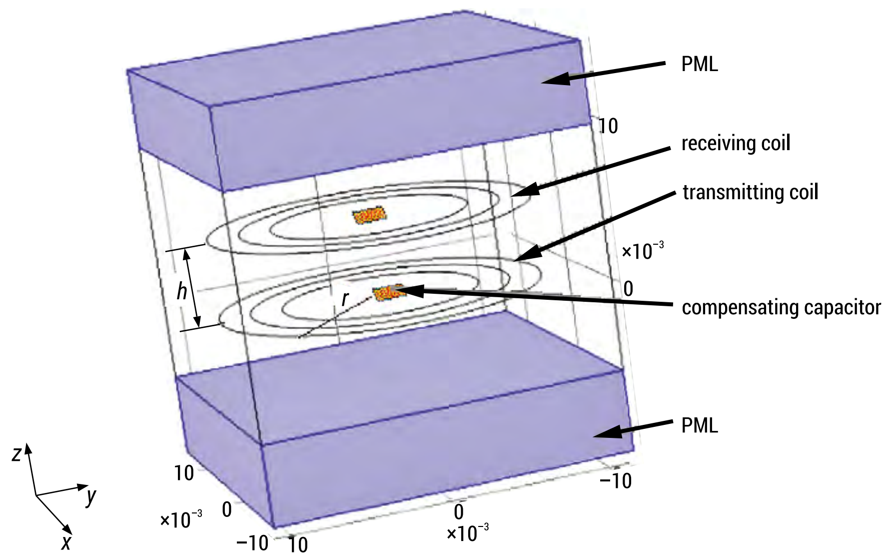

FIGURE 2. **Geometry of the numerical model**

In the calculations, a magnetic vector potential (Equation (1)) and the Helmholtz equation (Equation (2)) were used:

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

$$\nabla \cdot \left(\frac{1}{\mu} \nabla \cdot \mathbf{A} \right) - \mathrm{j}2\pi f \sigma \, \mathbf{A} = \mathbf{J}_{ex} \tag{2}$$

$\mathbf{J}_{ex}$ – an external current density [A/m^2] results from a voltage supply (U_{sc}). Equations (1)–(2) by FEM were solved.

The power transfer efficiency is calculated from:

$$\eta = \frac{P_{ld}}{P_{sc}} \cdot 100\% \tag{3}$$

where: the active power of the Rx coil is represented by Equation (4) and the power of the Tx coil is calculated form Equation (5):

$$P_{ld} = R_o \left| \underline{I}_{ld} \right|^2 \tag{4}$$

$$P_{sc} = U_{sc} \cdot \underline{I}_{sc} \tag{5}$$

Results

Calculations were made at the frequency of 1000 kHz, at the distances $h = r/2$ and $h = r = 10$ mm, for the small and large coils, $U_{sc} = 1$ V, number of turn coils $n = 10$ and 30. The influence of the load resistance ($Z_l = R_o$) on the power and efficiency of the WPT system was investigated.

Characteristics η, P_{sc} and P_{ld} powers are shown on the graphs (Figs. 3–6). The numerical analysis results are represented as solid lines (marked as numerical in the legend). The results of the analytical analysis [21] are represented by dots (marked as analytical in the legend).

The results show that as the number of turns n grows, this difference becomes smaller and smaller. The shape of the characteristics is maintained regardless of n. As n grows, the range of the load resistance R_o, for which η exceeds 50% grows. η or the load power P_{ld} grows with the growth of R_o, and then, after reaching the maximum value, they begin to drop. As n grows, the maximum value of P_{ld} power or η is achieved at increasingly greater R_o values.

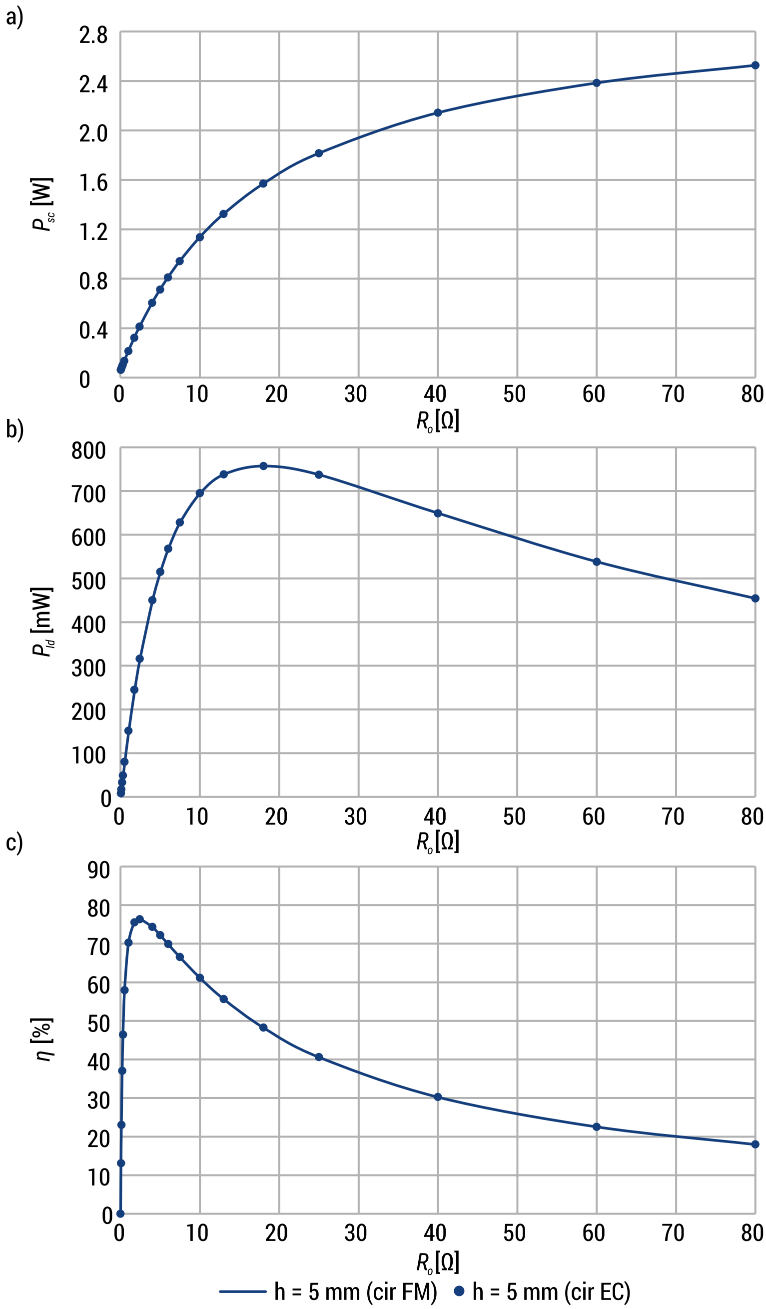

FIGURE 3. Results for r = 10 mm, n = 10, h = 5 mm: (a) P_{sc}, (b), P_{ld}·, (c) η

Doubling the distance between the coils h causes a growth in the maximum power P_{sc}, and a drop in the maximum power P_{ld}, regardless of the analyzed case. η also drops, the largest drop in value occurs for n = 10. In this case, η does not exceed 50%.

The R_o range, for which η exceeds 50%, also drops. The maximum values of η and P_{ld} are achieved for lower R_o values compared to lower h. The shape of the characteristics is preserved regardless of n.

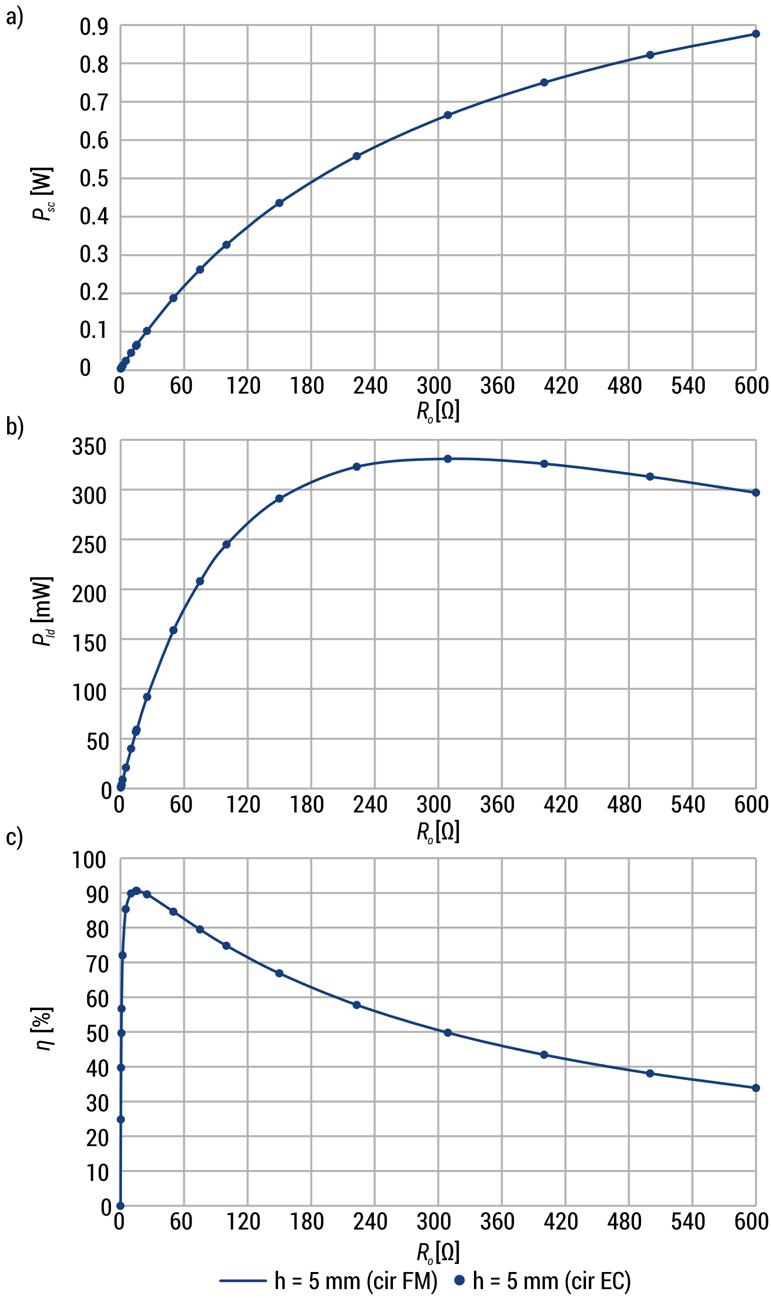

FIGURE 4. Results for r = 10 mm, n = 30, h = 5 mm: (a) P_{sc}, (b), P_{ld}., (c) η

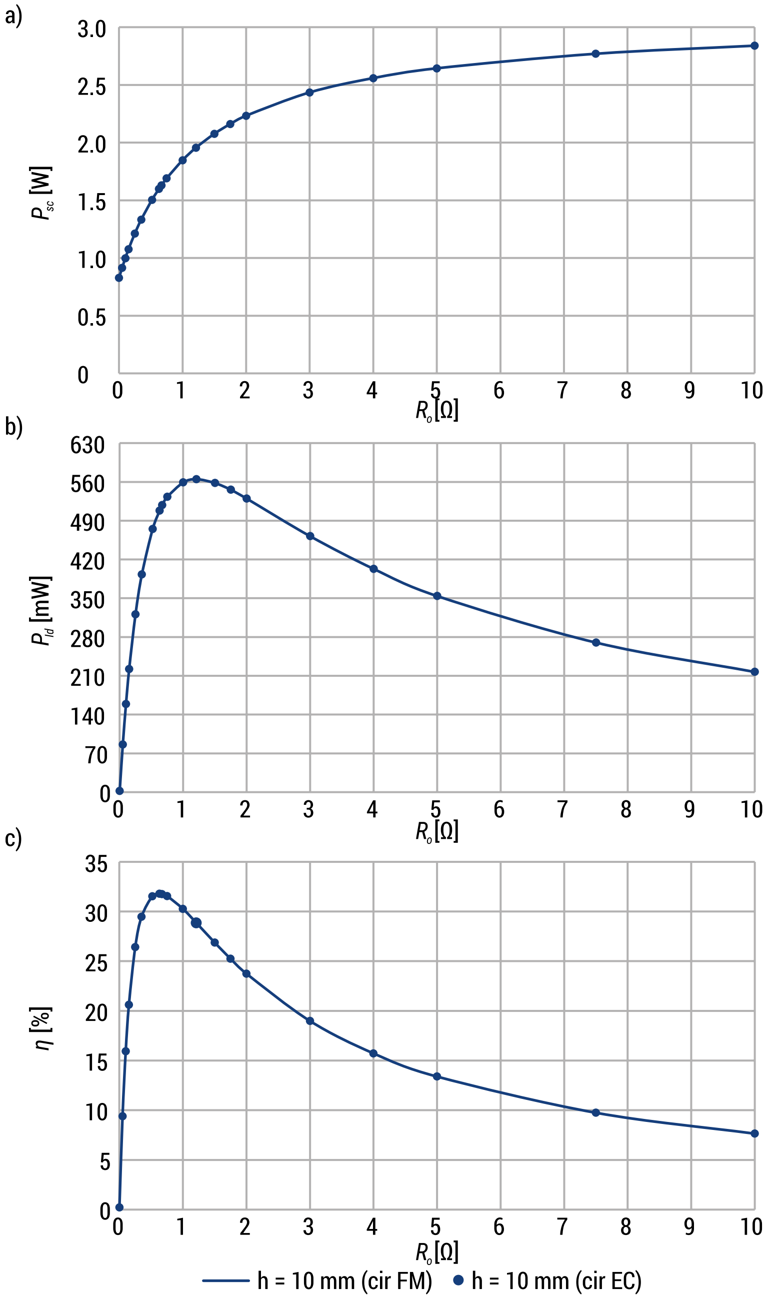

FIGURE 5. Results for r = 10 mm, n = 10, h = 10 mm: (a) P_{sc}, (b), P_{ld}., (c) η

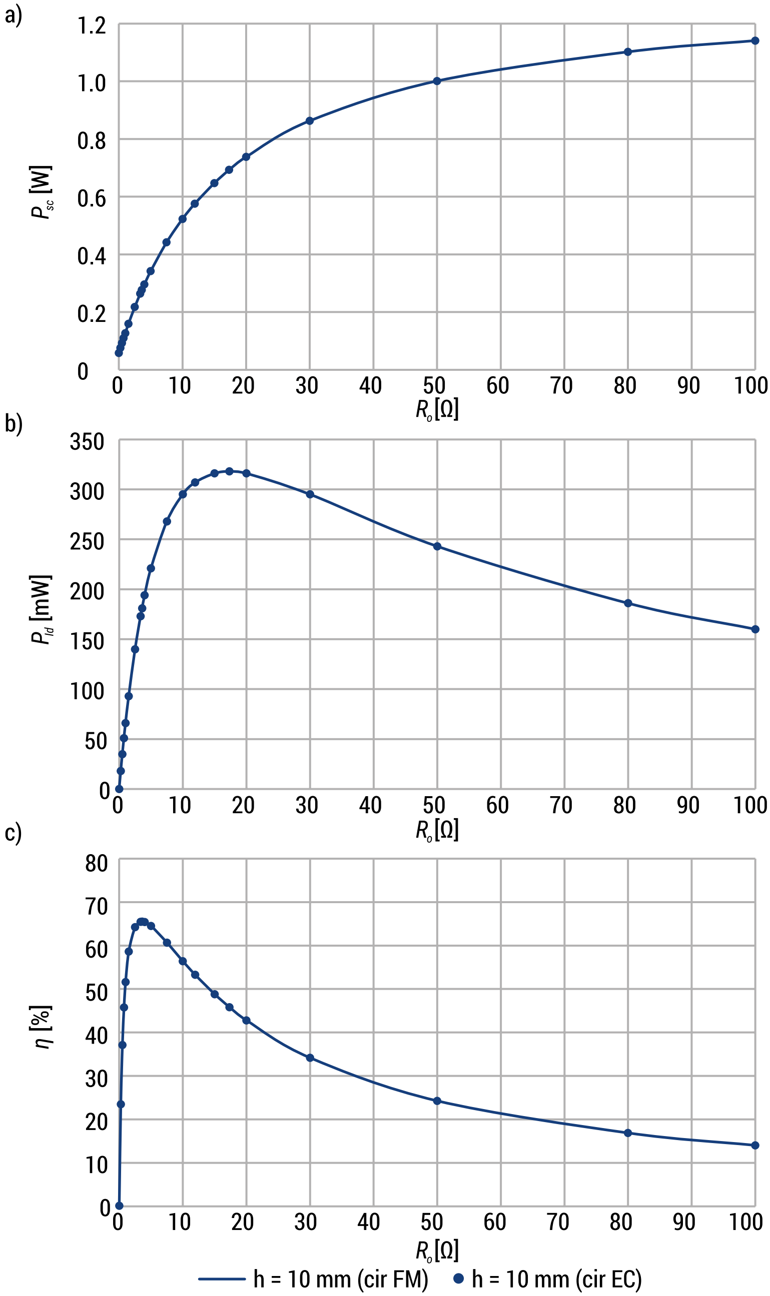

FIGURE 6. Results for r = 10 mm, n = 30, h = 10 mm: (a) P_{sc}, (b), P_{ld}., (c) η

Summary and conclusions

The idea of wireless energy transmission has been discussed for many years. In recent years, however, there is an increasing trend towards practical applications of WPT. This paper presented a WPT system with a periodic distribution of low-power planar coils. A multi-variant analysis was performed in order to find the load resistance values at which the system efficiency is the highest. The analysis took into account the variability of the number of turns, and the distance between the transmitting and receiving coils.

The proposed use of an equivalent circuit, represented by a single WPT cell, gave a simpler and faster solution. The applied analysis methods can be used to assess the properties of the WPT system and related parameters.

The paper presents a numerical and analytical analysis of the WPT system at a frequency of 1000 kHz. The impact of the load resistance change on the power and efficiency for the coils was investigated. There is an almost two-fold drop in the maximum η of the system (the maximum η then does not exceed 30% for a square coil and 50% for a circular one). This relationship was observed when the distance between the transmitting and receiving coils was doubled. Depending on the size of the coil and n, R_o values are variable. With the growth of these parameters, the values of R_o grow, for which the maximum η and P_{ld} power were achieved. Growing the distance between the coils in the WPT system reduces the value of R_o, for which the maximum η and P_{ld} power is achieved. The achieved results can be used in the design of WPT systems, selecting the R_o value in such a way as to achieve the greatest values of η or P_{ld}.

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