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Chapter 9 The numerical analysis of the influence of geometry planar coil systems on the efficiency of the WPT system

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The article presents results for a numerical analysis of a Wireless Power Transfer (WPT) system consisting of transmitting and receiving plane coils. The analysis takes into account different variants of WPT system geometry (distance between the transmitting-receiving coils, number of turns). The influence of variable system geometry and the frequency on system efficiency is observed. The analysis is based on the Finite Element Method (FEM) with antiperiodicity boundary conditions. The obtained results indicate at which system parameters wireless energy transfer is possible.

Index terms: Finite Element Method (FEM), magnetic field, numerical methods, wireless power transfer (WPT).

Introduction

In recent years, there has been a clear increase in energy demand in wireless and mobile devices. Their computing power and the number of supported sensors (e.g. fingerprint sensor or iris scanner) grew [1–9, 14–20]. These factors affect the increasing demand for batteries with increased capacity, extend the charging time and determine the mobility of devices. One way to supply mobile devices with energy is charging using wireless power transfer (WPT).

However, the topology of parallel flat coils, working as a group of transmitters and receivers, is still not fully developed. This article presents one of such systems which includes non-periodic structure arranged transceivers and receivers coils. The proposed WPT system could be used to charge electric devices as a wireless power transfer system. An analysis of the influence of system parameters is carried out, including number of turns, distance between coils and frequency of system operation on the efficiency of energy transmission. The article presents and describes the results of numerical analysis.

Wireless power transfer systems

One way to supply mobile devices with energy is charging using WPT, which becomes more accessible in scattered grids of many interdependent sources and loads. Due to the concept of inductive power transfer wireless charging of modern technology (smartphones, laptops) [1, 6] is possible. WPT is increasingly used, among others in the automotive industry in solutions for hybrid and electric cars [4–5, 9]. Charging an Audi car with WPT was first proposed in 2007 (Fig. 9.1).

FIGURE 9.1. Audi wireless charging for electric vehicles [9]

Wireless charging is also considered in lighting in hard-to-reach places [10] or intelligent buildings with sensors inside the walls and in the systems of beacons in hard-to-reach places [3, 14–18, 20]. WPT is also used in LED-based lighting. 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. 9.2).

FIGURE 9.2. The use of WPT for LED lighting [12]

The authors [12, 19] presented a WPT charging solution for e.g. laptops or smartphones. They found that in the next 10 years, such a solution would account for 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 [12].

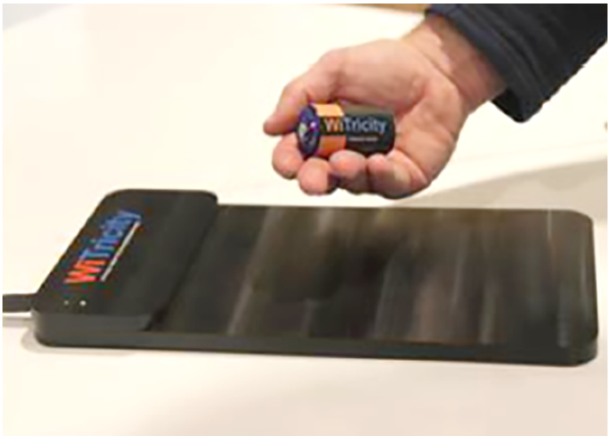

FIGURE 9.3. Wireless battery charger [12]

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

Analyzed model of wireless power transfer

The article proposes a method of wireless charging through the use of a periodic system containing a plane made of transmitting coils and a plane of receiving coils (Fig. 9.4). The pair: transmitter-receiver, consisting of coils with a radius $r = 30$ mm and number of turns n_t is treated as a WPT cell with dimensions $d \times d$, where $d \approx 2r$. The transmitting and receiving coils are placed at a distance h (Figs. 9.4, 9.5). The turns are placed on a plastic carcass. The compensating capacitor connected with the coil is settling. A configuration of WPT cells on the plane leads the occurrence of energy transmission. The system here is aperiodicity – different directions of winding the turns (Fig. 4). The transmitting surface is powered so that each transmitter is connected in parallel with a sinusoidal voltage source with the effective value U. The analyzed model of the WPT system guarantees an increase in the density of transmitted power in the area between the receiving and transmitting surfaces. Each WPT cell is connected with a separate load ($\underline{Z}$).

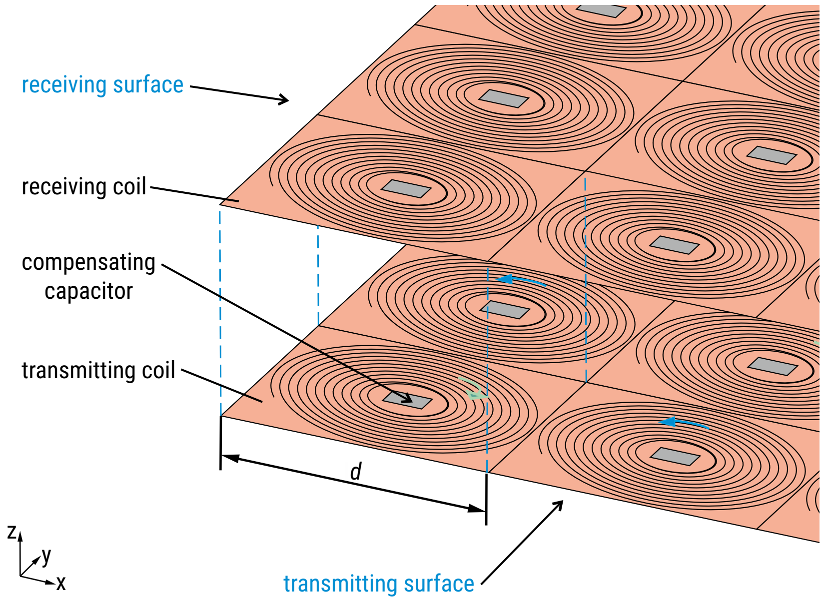

FIGURE 9.4. **Analyzed WPT system**

Numerical analysis of WPT system

In the analysis of the proposed WPT system the Finite Element Method (FEM) was used. This numerical method allows to analyze energy transfer in a system composed of many WPT cells. The following need to be taken into account: coil turns distribution, coil geometry, WPT cell number and elements of the electric circuit connected to each coil.

The analysis omits the carcass in the model, assuming that it is made of non-conductive and non-magnetic material ($\mu = \mu_0$). The capacitor is modelled as an element with a concentrated capacity C. Each transmitting coil was connected to a voltage source with an effective value U and frequency f, forcing the flow current transmitter $\underline{I}$.

In the analysis all cells forming the transmitting and receiving surfaces are taken into account. Due to the application of system periodicity, the analysis of the WPT system can be reduced to a set of transmitting-receiving coils (Fig. 9.5).

In this case, the WPT system will be simplified to a single cell filled with air and containing a pair of transmitting and receiving coils (Fig. 9.5). PML absorption conditions were used on the surfaces parallel to the XY surface. On the side surfaces, the antiperiodicity boundary option built into the Comsol program was used, which allowed for the analysis of the system with variable winding of the coils.

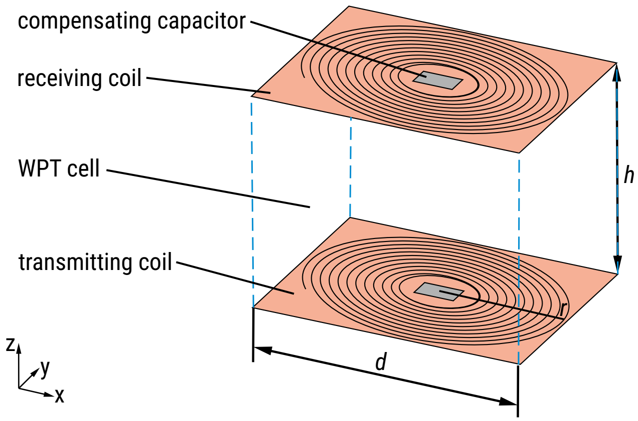

FIGURE 9.5. A single WPT cell containing a transmitting and receiving coil

Using magnetic vector potential could solve the problem of energy transport in the analyzed model

$$\mathbf{A} = [\mathbf{A}_x \ \ \mathbf{A}_y \ \ \mathbf{A}_z \ ]. \tag{9.1}$$

The use of the Helmholtz equation could provide a description of magnetic phenomena in the frequency domain

$$\nabla \cdot \left(\mu^{-1}{}_0 \nabla \cdot \mathbf{A}\right) - j\omega\sigma\mathbf{A} = \mathbf{J}_{ext}, \tag{9.2}$$

where:

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

The values used in numerical analysis are presented in Table 9.1. Analysis connected with frequency domain from f_{min} = 100 kHz to f_{max} = 1000 kHz.

TABLE 9.1. Values used in the calculations

parameter	symbol	value
wire with a diameter	w	250 μm
conductivity of wire	σ	$5.6{\cdot}10^7$ S/m
source with an effective value	U	5 V
thickness of wire insulation	i	10 μm
load	Z	50 Ω

The influence of the model coils of radius (r = 30 mm) and different number of turns (n_t) and distance between the transmitter and receiver coil (h) on the efficiency of the system was analyzed (Tab. 2).

TABLE 9.2. Considered variants of the WPT system

r [mm]	*n_t*	*h* [mm]
30	35	15 (*r* /2) and 30 (*r*)
30	70	15 (*r* /2) and 30 (*r*)
30	105	15 (*r* /2) and 30 (*r*)

Results of the analysis

The results of the analysis of the WPT system were obtained by the numerical method. The norm of the current intensity of the transmitting (I_z) and receiving coil (I_o) and the transfer efficiency (η) were analyzed, depending on the structure of the model. The numerical model was created in the *Comsol Multiphysics program*, using included coil approximation models with an attached circular part and boundary conditions (PML and antiperiodicity), and solved using the FEM method. The analyzed model contained 652140 degrees of freedom.

Figures 9.6–9.11 present comparisons of WPT efficiency (Figs. 9.10, 9.11), the transmitter current (Figs. 9.6, 9.7), the receiver current (Figs. 9.8, 9.9) for different values of the number of turns of the transmitting and receiving coils and different distances between these coils.

The characteristics for the model, where the distance between the coils was half the radius (h = 15 mm), are shown in Figs. 9.6, 9.8, 9.10. On the other hand, Figs. 9.7, 9.9, 9.11 show the characteristics for the model, where the distance between the coils was equal to the radius (h = 30 mm).

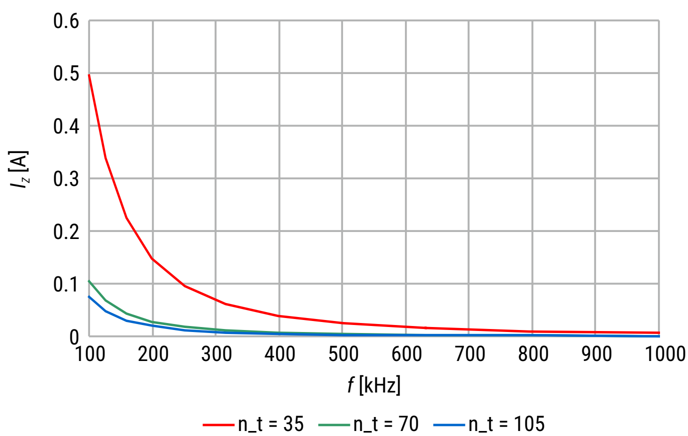

FIGURE 9.6. Results comparison of transmitter current (I_z) dependent on the number of turns (*n_t*) for the case *h* = 15 mm.

In Figure 9.6, it can be seen that the transmitter current decreases with increasing frequency. A similar dependence is observed for the receiver current, as shown in Figure 9.7. The smaller the number of turns causes, the greater the value of the current intensity.

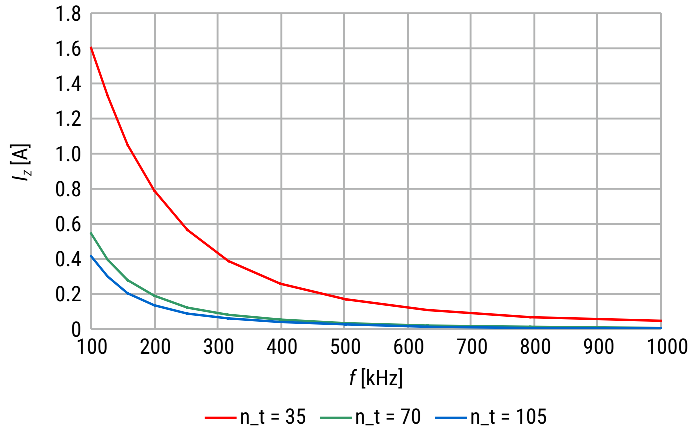

FIGURE 9.7. Results comparison of transmitter current (I_z) dependent on the number of turns (*n_t*) for the case h = 30 mm.

The efficiency of energy transfer increases with increasing frequency and already at approx. 200 kHz, it reaches the maximum value of approx. 96%, as shown in Figure 9.10.

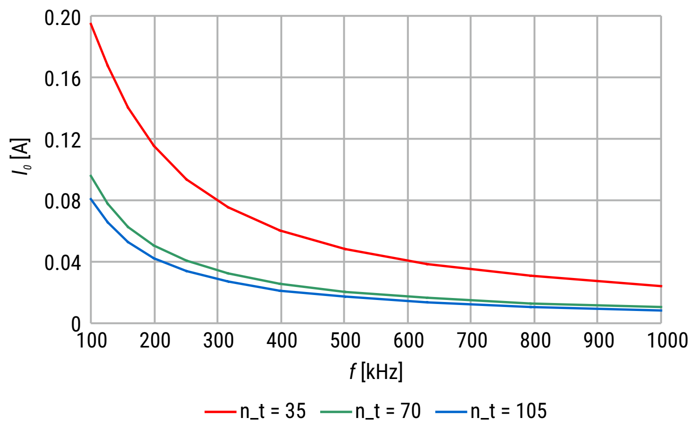

FIGURE 9.8. Results comparison of receiver current (I_o) dependent on the number of turns (*n_t*) for the case h = 15 mm.

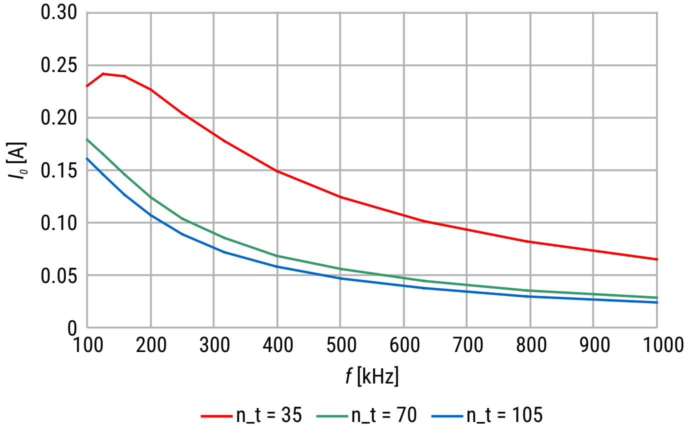

FIGURE 9.9. Results comparison of receiver current (I_o) dependent on the number of turns (*n_t*) for the case *h* = 30 mm.

Figs. 9.7, 9.9, 9.11 show the effect of the number of turns and frequency on the transmitter current, receiver current and system efficiency for the model, where the distance between the coils was the same as the radius, i.e. 30 mm.

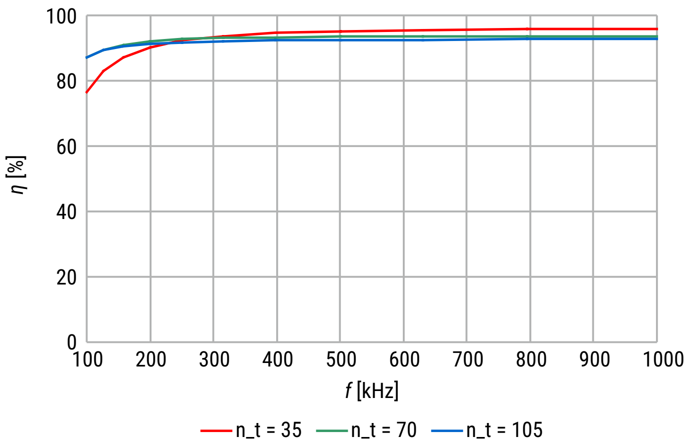

FIGURE 9.10. Results comparison of power transfer efficiency (η) dependent on the number of turns (*n_t*) for the case *h* = 15 mm.

The waveform of the transmitter and receiver current is similar to the previous case, i.e. the currents decrease with increasing frequency. With one difference. As can be seen in Figure 9.9, for the number of turns equal to 35, the receiver current increases with increasing frequency and reaches its maximum value when the efficiency of the system is 50%, and then decreases. The efficiency of energy transfer increases with increasing frequency and reaches the maximum value of approx. 94% only at approx. 600 kHz, which is noticeable in Figure 9.11.

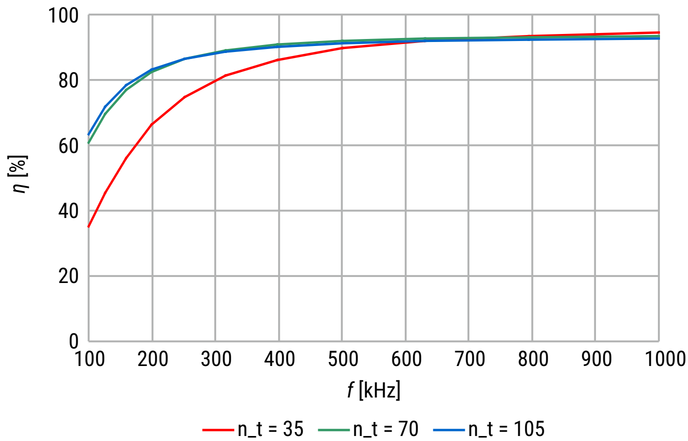

FIGURE 9.11. **Results comparison of power transfer efficiency (η) dependent on the number of turns (n_t) for the case h = 30 mm.**

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. 30 mm, than for the model where the distance between the coils is half the radius, i.e. 15 mm. However, for higher frequencies, the efficiency values for both models are similar.

Conclusions

The presented non-periodic wireless power transfer system was investigated using the 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. the distance between the transmitter and the receiver, the number of turns on the efficiency of the WPT system was analyzed. 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. 30 mm, than for the model where the distance between the coils is half the radius, i.e. 15 mm. However, for higher frequencies, the efficiency values for both models are similar.

The numerical analysis of energy transfer in the system consisting of many WPT cells requires consideration of the details of the model structure, such as: geometry of the coils, winding distribution, number of WPT cells, as well as elements of the electric circuit connected to each of the coils and the adopted boundary conditions. An 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 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 to shape the distribution of the magnetic field. Due to the FEM method, it is possible to analyze the influence of the number of turns, radius of the coil, distance between coils, and size of the WPT cell on the efficiency of the system. The presented results of the numerical analysis can be helpful with the use of optimization algorithms in order to obtain maximum efficiency of the WPT system.

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