An Analysis on Efficiency of Wireless Transfer Energy Due to a Misalignment of Two Coils

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***Abstract*–Function of the alignment of the two magnetic coupled coils, a procedure, to choose the proper structure of the two coils used in the wireless power transfer systems (WPTS's), is presented. The deviation in the alignment of coils can be made in two ways – the angular displacement and the lateral displacement. For the lateral displacement, the two coils are located in parallel planes with their centres misaligned, respectively in the case of angular displacement there is an angular deviation between the receiver and transmitter coils having aligned centres. The main target is to compare the obtained results and select the best solution with the great value for mutual inductance. The main focus was on the influence of lateral displacement of two coils, for two configurations: transmitter and receiver coils are circular type; transmitter coil is pancake type and receiver coil is circular type. After the simulations, we shown that there is a smaller deviation from initial value of the mutual inductance for the second case (transmitter coil is pancake type and receiver coil is circular type). Combining the two effects (angular and offset side) we get a surface where if the receiving coil is located on it, the coupling factor of the wireless system has the same value**

Cuvinte cheie: *transfer fără fir (wireless) de energie, inductivitate mutuală, bobine cupplate magnetic, optimizare.*

Keywords: *wireless energy transfer, mutual inductance, magnetic coupled coils, optimization.*

I. INTRODUCTION

The majority of the telecommunication applications use the propagation of electromagnetic waves. For power transfer antenna radiation technology, this approach is not suitable, because in radiated electromagnetism, most part of the energy is lost by dispersion into the free space. Therefore, this technology is more suitable to transfer information rather than transfer power [1, 15-19].

The most successful technologies in wireless transfer of electromagnetic energy are: inductively coupled and resonant magnetic coupling. The aim is to improve the power transfer process [2, 8, 21]. This can be done using the following possibilities:

1. the coils' design
- at this stage the parameters that can be modified are: the geometry of the coil and material of the coil [1];
2. the coils' alignment
- the modification of the alignment of coils can be performed by modifying:
  - o the angular displacement: there is an angular deviation between the receiver and transmitter coils having aligned centres;
  - o the lateral displacement: the two coils are located in parallel planes with their centres misaligned;
3. the design of the circuit
- this is highly connected to the operating frequency, because a frequency too high can cause losses by increasing resistance in conductors due to skin effect and depth of penetration of the electromagnetic field [2-5];
4. the analysis of the environment
- two key factors in wireless transfer are temperature and humidity; for example, if there are used different material (ferrites), they can influence the transfer by concentrating the magnetic field lines and sending them to the receiving coils;
5. multiple transmitter/receiver coils

- the process efficiency can suffer modifications if the number of transmitters/receivers is being modified [6]

In this paper there is presented a procedure to choose the proper structure of the two coils used in the wireless power transfer systems (WPTS's). The analysis of the two magnetic coupled resonators is performed function of the alignment of the coils.

There are two forms of deviation in the alignment of coils – the lateral displacement and the angular displacement with a detailed description given in Section II.

Finally, by comparing the obtained results, the procedure is to select the solution which gives the greatest vale for the mutual inductance.

II. THE STUDY OF THE LATERAL DISPLACEMENT AND THE ANGULAR DISPLACEMENT

The influence of the lateral displacement between two coils (transmitter coil – TC and receiver coil – RC) is studied by taken into consideration two configurations:

I. TC and RC are both circular type (Fig. 1,a);
II. TC: pancake type, RC: circular type (Fig. 1,b).

We considered the following geometric data:

- *for circular coil*
  - o the number of turns $N = 10$
  - o the diameter of the coil $D = 1.2$m
  - o the distance between transmitter and receiver $z = 0.1$m;

- *for pancake coil*
    - the turn number $N = 10$
    - outer diameter of the coil $D_{ext} = 1.2$m
    - inner diameter of the coil $D_{int} = 0.3$m.

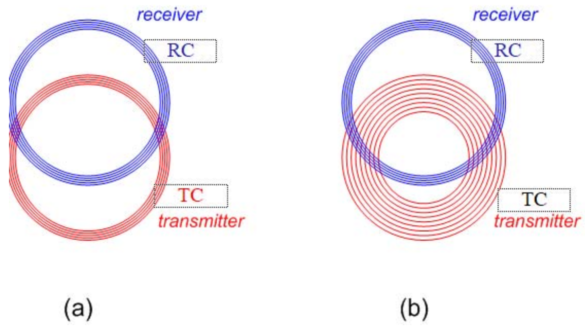


Fig. 1. Structures of the two magnetic coupled coils: a) TC and RC are circular type; b) TC is pancake type and RC is circular type.

The study of the lateral displacement and the angular displacement was performed by taking into considerations the following:

- both coil systems are placed in air;
- the vertical distance between TC and RC is preserved;
- the horizontal alignment of the centres of two coils is modified; the modification can be up to 25% from the coils' diameter.

Using the procedure developed in [20], the results are presented in Figures 2 and 3.

In Table 1 we present the mutual inductance values for the two considered configurations (TC and RC have the circular type; TC is pancake type and RC is circular type).

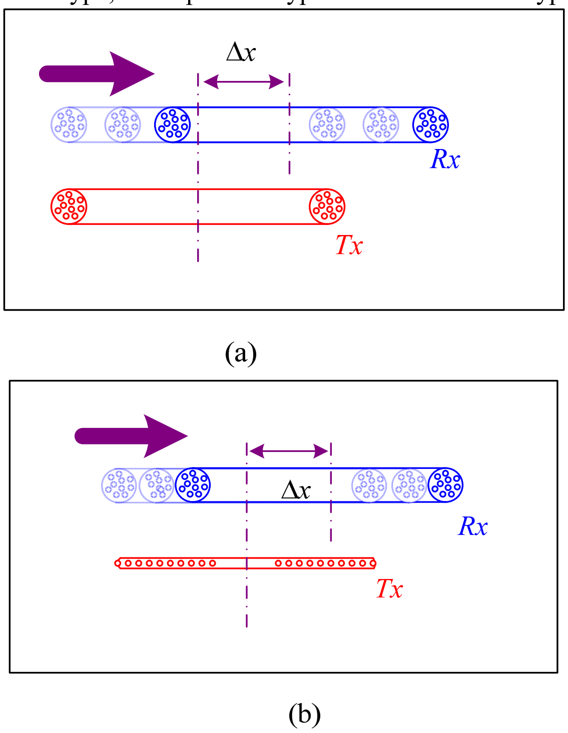


Fig. 2 Coils alignment modification: a) The two coils have the circular type; b) TC is pancake and RC is circular.

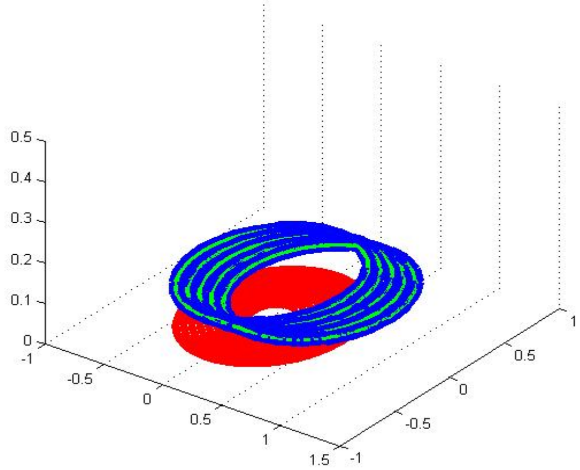


Fig. 3. Horizontal alignment modification of the coils' centres.

The mutual inductance between two circular coils with different geometrical parameters and relative positions, based on Neumann's formula [7, 9, 10] has the following expression:

$$M = \left.\frac{\Phi_{21}}{i_1}\right|_{i_2=0} = \frac{\mu_0}{4\pi}\int_{C_1}\int_{C_2}\frac{\overline{dl_1}\cdot\overline{dl_2}}{R_{12}}. \qquad (1)$$

To compute the mutual inductance a procedure has been implemented in MATLAB by using two grids for each coil - one of them circumscribed and the other inscribed. In this way the values between a maximum and a minimum can be limited and by choosing the average value of the mutual inductance for the two grids, the minimum mesh density can be used.

TABLE 1

	M [H] case (a)	error case (a)	M [H] case (b)	error case (b)
Δx=0	1.43e-4	0%	6.25e-5	0%
Δx=0.1m	1.28e-4	10.5%	6.03e-5	3.5%
Δx=0.2m	1.05e-4	26.6%	5.25e-5	11.68%
Δx=0.3m	8.43e-5	41.1%	4.81e-5	23.2%

Although a greater value for mutual inductance is obtained when the two coils are circular type (case (a) M = 0.143mH) compared to the case (b) M = 0.063mH and the coils centres are aligned vertically, it can be seen for configuration (b) a smaller deviation from initial value when there is a lateral displacement of the centres of the two coils (23.2% vs. 41.1%).

In Figure 4 there is presented the error variation versus $\Delta x / D$ deviation.

As shown in [20], an angular displacement in a certain range produces an increase in mutual inductance, combining the two effects (angular and offset side) we get a surface where if the receiving coil is located on it, the coupling factor of the wireless system has the same value.

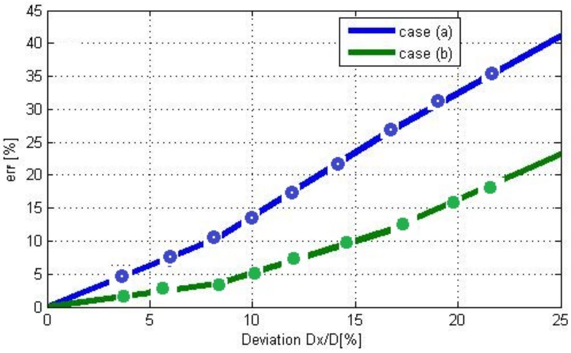


Fig. 4. Error vs. $\Delta x / D$ deviation.

Using the ANSYS Q3D Extractor Program, [11], the **R**, **L**, **G**, and **C** matrices were computed for the frequency of 10 MHz for two spiral coils.

The dependencies of the coupling coefficient on the angle of the planes of the two coils are shown in Figure 5.

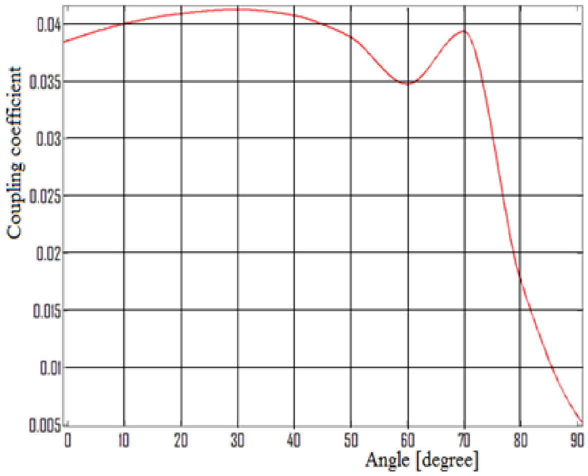


Fig. 5. The dependency of the coupling coefficient on the angle of the planes of the two coils.

ANSYS Q3D Extractor, after the process of parameter identification, can export data into a .cir file, such that to allow a further analysis in SPICE [11-13].

These files also contain the parameter values of the circuit elements that simulate the two magnetic coupled coils, as depicted in Fig 6.

The two coil parameters were determined by the ANSOFT EXTRACTOR Q3D [11], and have the following values:

$L_1 =$ 2.317 μH; $L_2 =$ 2.3098 μH;
$R_{L1} = 0.5971\ \Omega$; $R_{L1} = 0.57186\ \Omega$;
$R_i = 1.5\ \Omega$, $R_L = 30\ \Omega$; k = 0.3793.

Efficiency, active input power and active load power function of frequency is given in Figure 7.

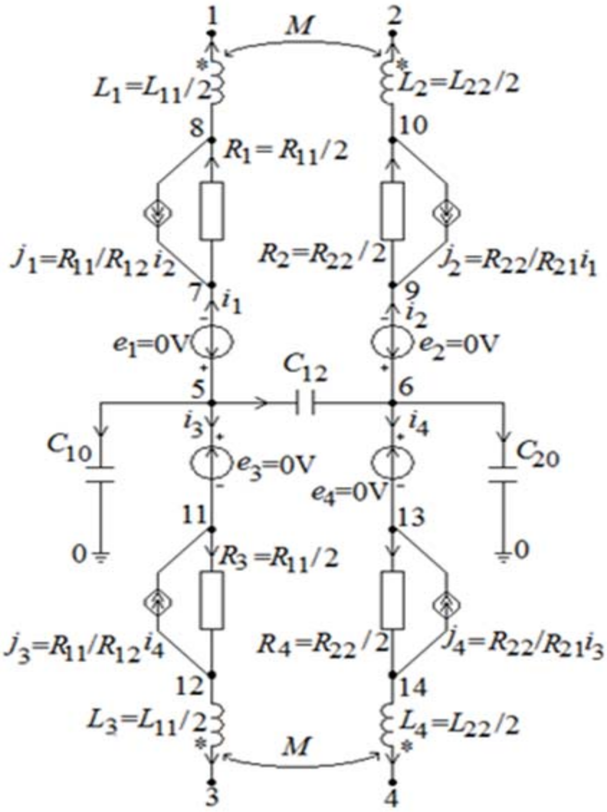


Fig. 6. SPICE equivalent circuit for two magnetic coupled coils.

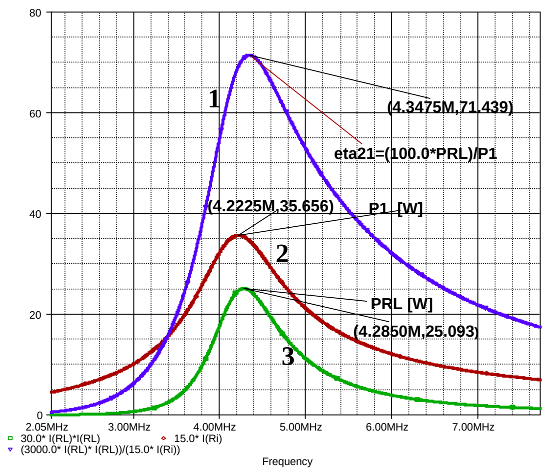


Fig. 7. The efficiency (1), the active input power (2) and active load power (3) vs. frequency.

In practice, the TC and RC are not always in parallel planes (Fig. 8).

After simulations with various angles between the two magnetic coupled coils, one can deduce that for distances between the two coils smaller than their diameter a variation about 40 degrees of the angle α improves the value of the mutual inductance (Fig. 9, a).

For distances bigger than the diameter, in order to obtain a maximum value of the mutual inductance, the two coils have to be in parallel planes (Fig. 9, b).

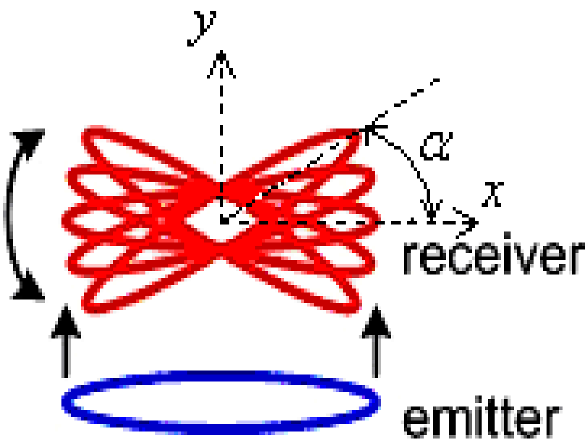
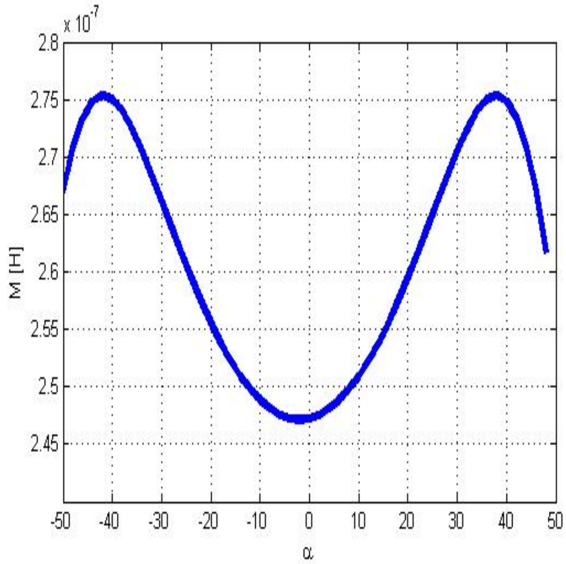
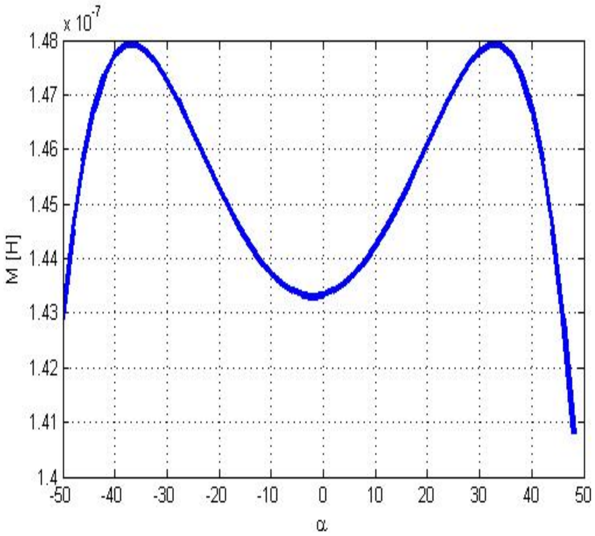


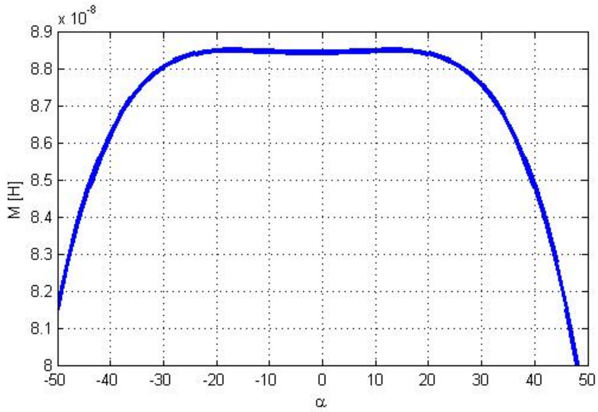
Fig. 8. The RC positions related to the TC.



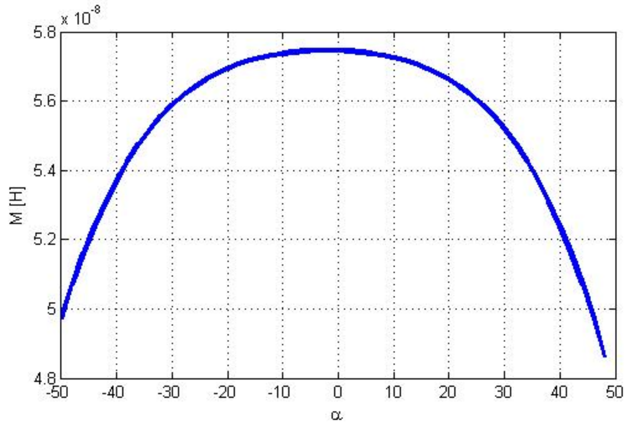
a) Δy = 50cm



b) *Δy* = 70cm



c) *Δy* = 90cm



d*) Δy* = 110cm

Fig. 9. The mutual inductance variation related to the angle between the two coils.

III. CONCLUSIONS

Wireless power transfer is a new technology, useful when electrical energy is needed but interconnecting wires are, for certain reasons, impractical or impossible. The transfer can be made over distances at which the electromagnetic field is strong enough to allow a reasonable power transfer. This paper is an extended version of a previous work [20] and it presents a procedure to choose the best structure of the two magnetic coupled coils (RC and TC) used in the wireless power transfer systems (WPTS). The deviation in the alignment of coils is analyzed for two forms – the angular displacement and the lateral displacement. For the lateral displacement, the two coils are located in parallel planes with their centres misaligned, respectively in the case of angular displacement there is an angular deviation between RC and TC having the centres aligned.

Safely and accuracy wireless energy transfer remains a challenge and an actual research theme.

The two parameters which control the amount of the transferred power by magnetic coupling and the transfer efficiency as well are the frequency and the coupling coefficient (ω, M). The main focus was on the influence of lateral displacement of two coils, for two configurations:

TC and RC are circular type; TC is pancake type and RC is circular type. After the simulations, we shown there is a smaller deviation from initial value of the mutual inductance for the second case (TC: pancake type, RC: circular).

As shown in [20] and the results from ANSYS Q3D Extractor, an angular displacement in a certain range produces an increase in mutual inductance. Combining the two effects (angular and offset side) we get a surface where if the RC is located on it, the coupling factor of the WPTS has the same value.

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Third coauthor – 20%

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REFERENCES

[1] Andres Kurs, “Power Transfer through Strongly Coupled Resonances”, Master of Science in physics, MIT, Sept. 2007.

[2] J. I. Agbinya, “Wirelees Power Transfer”, River Publishers Series in Communications, 9000 Aalborg Danemark, 2012.

[3] www.witricity.com.

[4] Zhang, X. Liu et all, “In Vitro and In Vivo Studies on Wireless Powering of Medical Sensors and Implantable Devices”, LSSAW, IEEE Xplore, 978-1-4244-4293-5/09/2009, pp. 84-87.

[5] A. Karalis, J.D. Joannopoulos, and M. Soljačić, “Efficient wireless non-radiative mid-range energy transfer”, Annals of Physics, Vol. 323, January 2008, pp. 34-48.

[6] T. Imura, H. Okabe, and Y. Hori, “Basic Experimental Study on Helical Antennas of Wireless Power Transfer for Electric Vehicles by using Magnetic Resonant Couplings”, Proceedings of Vehicle Power and Propulsion Conference, Sept. 2009, IEEE Xplore, pp. 936-940.

[7] D. Niculae, M. Iordache, Lucia Dumitriu, “Magnetic coupling analysis in wireless transfer energy”, The 7th Int. Symp. on Advanced Topics in El. Eng. Bucharest, 12-14 May 2011.

[8] N. Tesla "Apparatus for transmitting electrical energy", U.S. patent number1119732, issued in December 1914.

[9] Ariseidis Karalis, J.D. Joannopoulos, Marin Soljacic "Efficient wireless non-radiative mid-range energy transfer", MIT 2006;.

[10] E. W. Weisstein, Nov. 2011, Quartic Equation. From MathWorld—A Wolfram Web Resource [Online]. Available: http://mathworld.wolfram. com/QuarticEquation.html.

[11] Ansoft Q3D Extractor, User Guide, www.ansoft.com.

[12] W. Q. Niu, J. X, Chu, W. Gu, and A. D, Shen, „Exact Analysis of Frequency Splitting Phenomena of Contactless Power Transfer Systems”, IEEE on CAS – 1: Vol. 60, N0. 6, June 2013, pp. 1670 – 1677.

[13] Y. Tak, J. Park, and S. Nam, “Mode-based analysis of resonant characteristics for near-field coupled small antennas”, IEEE Antennas Wireless Propag. Lett., vol. 8, Nov. 2009, pp. 1238–1241.

[14] T. Imura and Y. Hori, “Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and Neumann formula”, IEEE Trans. vol. 58, no. 10, Oct. 2011, pp. 4746–4752.

[15] S. Cheon, Y.H.Kim, S.Y. Kang,M. L. Lee, J.M. Lee, and T. Zyung, “Circuit model based analysis of a wireless energy transfer system via coupled magnetic resonances”, IEEE Trans, vol. 58, no. 7, Jul. 2011, pp. 2906–2914.

[16] A. P. Sample, D. A.Meyer, and J. R. Smith, “Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer”, IEEE Trans. Ind. Electron., vol. 58, no. 2, Feb. 2011, pp. 544–554

[17] A. J. Moradewicz and M. P. Kazmierkowski, “Contactless energy transfer system with FPGA-controlled resonant converter”, IEEE Trans. Ind. Electron., vol. 57, no. 9, Sep. 2011, pp. 3181–3190.

[18] J. Sallan, J. L. Villa, A. Llombart, and J. F. Sanz, “Optimal design of ICPT systems applied to electric vehicle battery charge”, IEEE Trans. Ind. Electron., vol. 56, no. 6, Jun. 2009, pp. 2140–2149.

[19] M. Iordache, Dragos Niculae, Lucia Dumitriu „Performance optimization in wireless transfer of electromagnetic energy”, ATEE’13, 23-25 May 2013 – Bucharest, Romania.

[20] Dragos Niculae, Mihai Iordache, Marilena Stanculescu, Lavinia Iordache, ”The influence of the alignment between receiver and transmitter coils on efficiency of wireless transfer energy, 2016 International Conference on Applied and Theoretical Electricity (ICATE), Page(s): 1 – 5.