Design of Wireless Electromagnetic Energy Transfer Systems

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***Abstract* – This paper presents a set of diagrams for wireless power transfer systems (WPTS) with applications in key domains such as: medical, electrical engineering, military, etc. Our research is based on original circuits working as WPTS. All the circuits are using sets of two magnetically coupled coils whose parameters were extracted by simulations using the specialized software ANSOFT Q3D Extractor. The simulations of the circuits were performed using TINA, PSpice and Simulink in MATLAB. We used existing parts libraries from Texas Instruments. The circuits were also physically built and tested and the results were very close to the numerical ones. We also compared the results with data in existing literature and we obtained an acceptable computation error. We also studied the efficiency of the power transfer and presented some practical applications for these systems such as low power battery chargers.**

Cuvinte cheie: *Sisteme de transfer a energiei fără fir (wireless), rezonatoare cuplate magnetic, extragerea parametrilor pentru structuri inductive, simulări de circuite.*

Keywords: *Wireless Power Transfer Systems (WPTS), magnetically coupled resonators, parameters extraction for inductive structures, circuit simulations.*

I. INTRODUCTION

The major sections of the system that implements Ampère and Faraday's laws are transmission and receiver of the two magnetically coupled coils, named "inductive connection" of the WPTS (Wireless Power Transfer System) (Fig. 1).

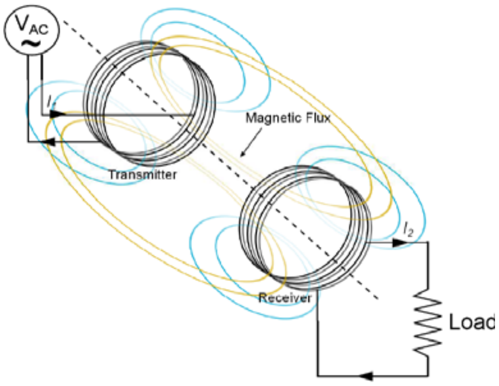


Fig. 1. WPTS functioning principle.

The coupled coils can have different shapes and sizes. The inductive components can be considered as an AC transformer with inductive high transmission. This transformer is called "weakly coupled transformer". In such a transformer, a small quantity of the magnetic flux produced by the first coil enters the second one. As a consequence, the energy to be transmitted in the weakly coupled system is in general reduced. This problem limits the use of WPTS based on inductive coupling.

WPTS are more appropriate for small distances transmission, distances up to twice the coils dimensions, because the magnetic field strength produced by the transmitter becomes very weak as the distance increases. In contrast to other WPTS methods, the efficiency of the system can reach up to 95% for short distance.

The standard diagram of a WPTS is presented in Fig. 2.

The oscillator and the power amplifier (PA) present big importance for the WPTS. The PA should produce a high frequency sinusoidal signal with the frequency equal to the resonance frequency of the two magnetically coupled resonators, TX and RX [6 – 20]. The power source circuit of the transmitter contains a tuning device for adjusting the frequency at the input of the transmitter TX at the resonance frequency of the two resonators which varies as the distance between the two coils modifies. Other important blocks are the voltage rectifier and regulator which must provide constant current and voltage on the load.

The paper presents a set of diagrams for WPTS that have several applications, such as: medical implants, mobile phones batteries charging, wireless sensors networks, electrical networks monitoring, etc. The two coils' parameters were computed using the specialized software ANSOFT EXTRACTOR Q3D, [5]. To model the power source, we used on one hand Tina and Spice [1-3, 16] libraries, and on the other hand Simulink in MATLAB [4].

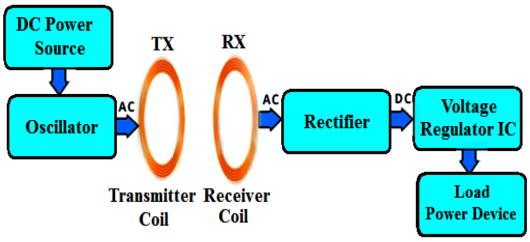


Fig. 2. Standard diagram of a WPTS

In this paper it has been designed the schematics used for building WPTS and it has been made the numerical analysis of these schematics in Tina [1 - 3], SPICE [15] and Simulink (MATLAB) [4].

The results obtained with the aforementioned software were compared with the experimental ones and with those reported in the existing literature. By the end we inferred that the results done by simulations were almost identical with the experimental ones, the error being less than 5%.

II. WPTS DESIGN AND ANALYSIS USING TINA AND SPICE

In Figure 3 we present the first WPTS, corresponding to two printed different coils (Case 2).

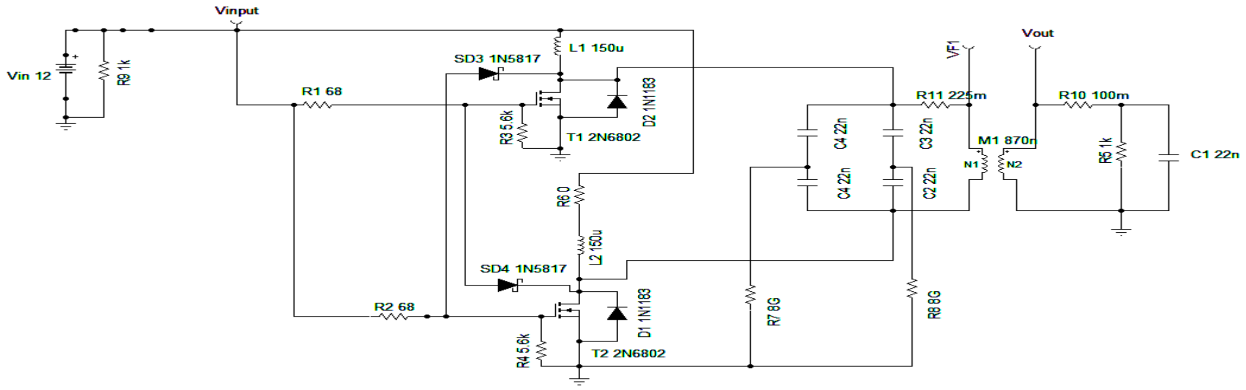


Fig. 3. WPTS for two different coils, spiral shaped (Case 2).

Two sets of coils built in the electrical engineering laboratory from University Politehnica of Bucharest (UPB), with the corresponding descriptions given below, were taken into consideration.

A. Case 1.

Input data:

- Two identical coils.
- Shape: helicoidally
- Parameters: $L_1 = L_2 = 0.87$ μH, $C_1 = 22$ nF, $C_2 = 22$ nF, $R_{L1} = R_{11} = 0.225$ Ω, $R_{L2} = R_{10} = 0.225$ Ω, $k = 0.3$.

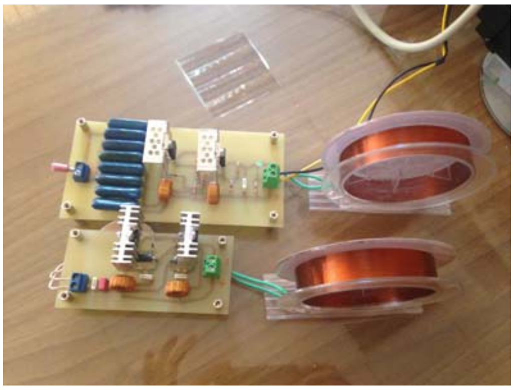


Fig. 4. Case 1. WPTS with Helicoidally coils

Figure 4 presents a photo of the WPTS built in our laboratories for Case 1 (two identical helicoidally coils).

B. Case 2.

Input data:

- Two different coils.
- Shape: spiral (printed coils)
- Parameters: $L_1 = 2.875$ μH , $L_2 = 0.575$ μH, $C_1 = 22$ nF, $C_2 = C_3 = C_4 = 22$ nF, $R_{L1} = R_{11} = 0.225$ Ω, $R_{L2} = R_{10} = 0.1$ Ω, $k = 0.5$.

Fig. 5. Case 2. WPTS with printed coils.

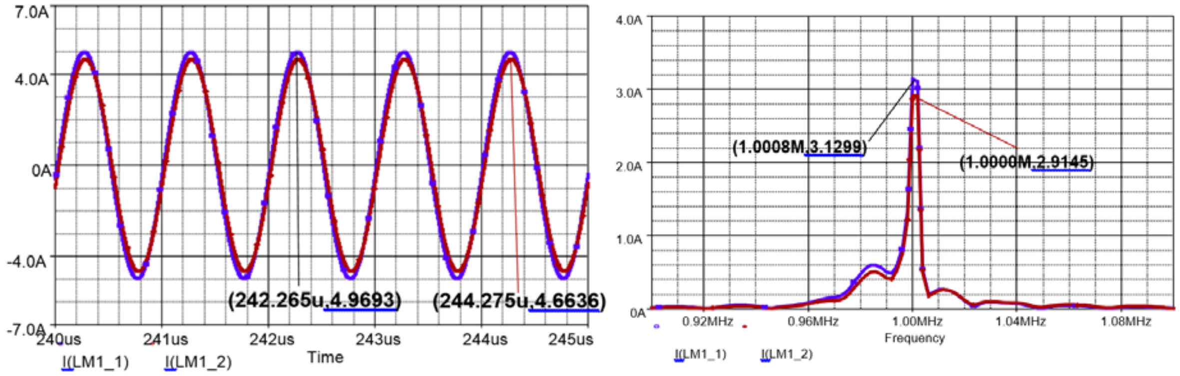
Fig. 5 presents a photo of the WPTS corresponding to Case 2 (different shaped coils).

The parameters of the two coils sets were estimated using the software ANSOFT EXTRACTOR Q3D, [5].

The schematics of the WPTS from Figure 3 was simulated in Tina, [1 – 3], and SPICE [16], which uses as input file, the .cir file exported from Tina.

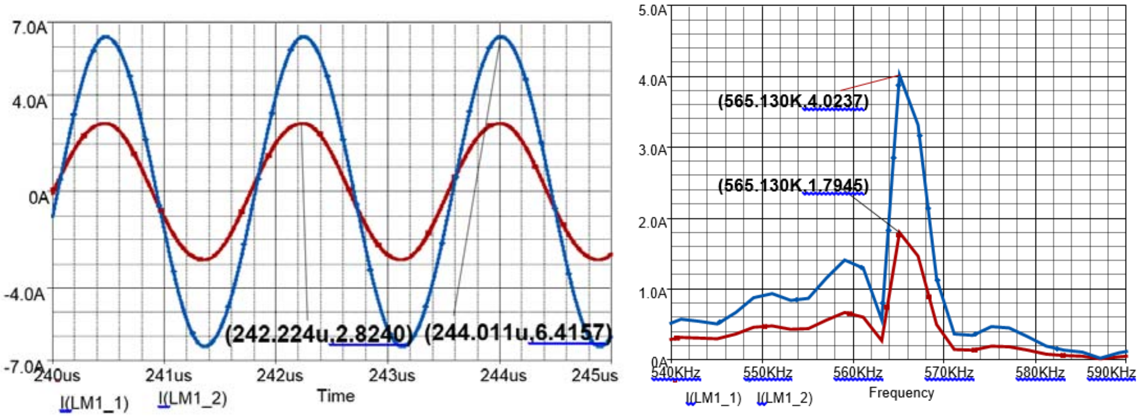
The time dependencies of the currents for Case 1, respectively Case 2, are given in Figure 6a respectively Figure. 7a.

The dependencies on frequencies are for the two cases are given in Figure 6b (Case 1), respectively Figure. 7b (Case 2).



(a) (b)

Fig.6. Dependencies of currents i_{L1} and i_{L2}, for the first set of coils on: a) vs time; b) vs frequency



(a) (b)

Fig.7. Dependencies of currents i_{L1} and i_{L2}, for the second set of coils on: a) vs time; b) vs frequency.

From Figure 7b we notice the main frequency of 565.130 kHz is very close to the resonance frequency of 567.092 kHz.

Figure 8 presents a WPTS with the following specifications:

- a constant output voltage $U_{out} = 11.352$ V
- a constant output current $I_{out} = 554.065$ mA.
- on the branch of coil L_2 we connected a voltage rectifier with diodes.

The output of the bridge is connected to a RC filter for regulating the ripples in the time dependency of the output voltage u_{R5} and the output current i_{R5}.

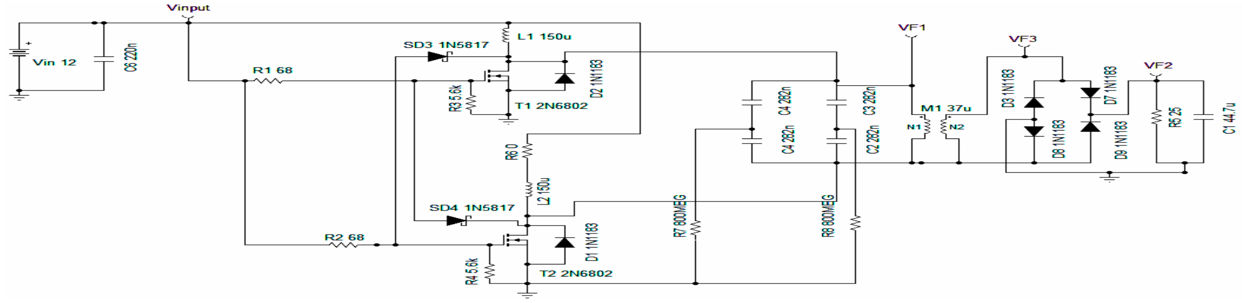


Fig.8. Wireless Power Transfer System (WPTS) which produces constant output voltage and current (dc).

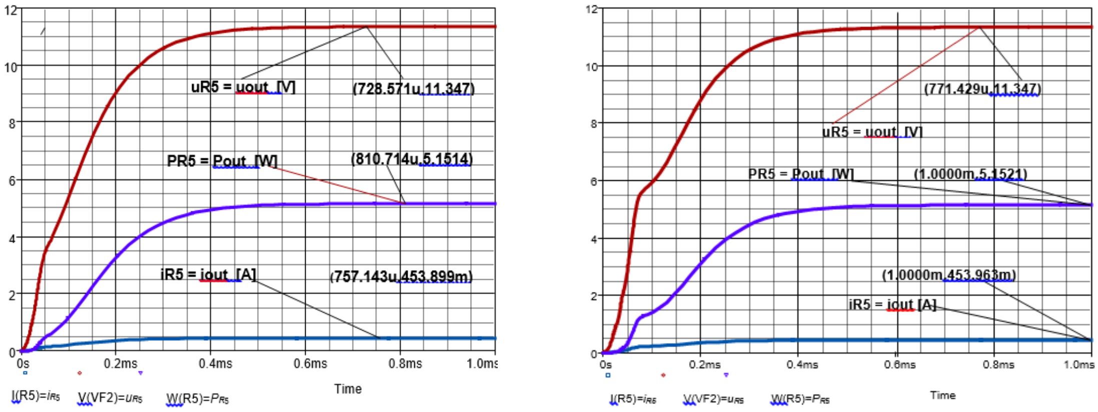
The two sets of magnetic coupled coils from Figure 8 have the parameters:

1. $L_1 = 2.265$ µH,
   $L_2 = 0.54655$ µH,
   $k = M/\sqrt{L_1 \cdot L_2}$;
2. $L_1 = 37$ µH,
   $L_2 = 23.15$ µH,
   $k = 0.22619$.

The dependencies on time of the output voltage u_{R5}, the output current i_{R5} and the output power on the load P_{R5} are depicted in Figure 9. From Figure 9a, and Figure 9b.

As a conclusion, we notice the considered dependencies are almost the same for both versions of the two resonators.

In Figure 10 we present a WPTS used for charging low power batteries which need a constant voltage 0.565 V dc and a constant current 30 mA on all charging time.



(a) (b)

Fig. 9. Time dependencies of the output voltage i_{R5}, the output current i_{R5} and the output power on the load P_{R5}: a) The parameters of the two coils as Case 1; b) The parameters of the two coils for Case 2.

For the system in Fig. 10 we considered two variants for the two magnetic coupled coils:

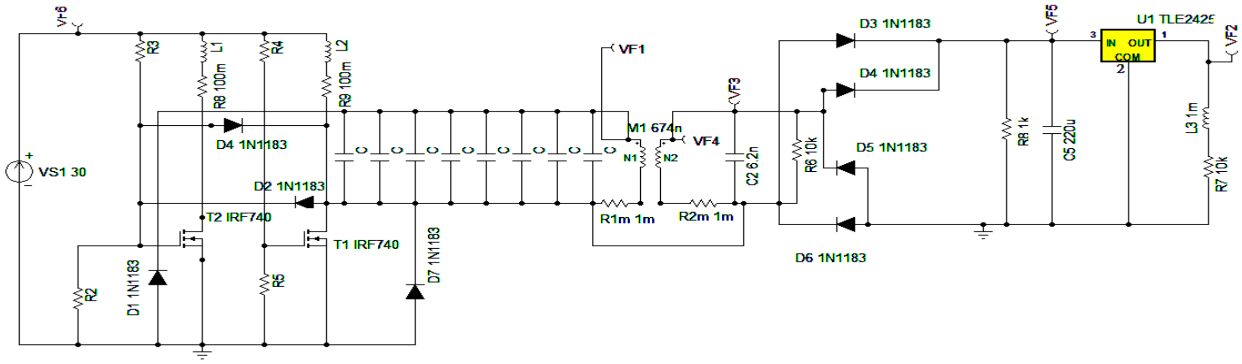


Fig. 10. Wireless electromagnetic energy transfer used for low power battery charging.

We build in our lab the coils for the two variants and the parameters were identified using ANSOFT EXTRACTOR Q3D, [5].

1. $L_1 = 0.674\ \mu\text{H}$

$$L_2 = 1.235\ \mu\text{H}$$

$$k = 0.3\,;$$

2. $L_1 = 2.265\ \mu\text{H}$

$$L_2 = 0.54655\ \mu\text{H}$$

$$k = 0.5\,.$$

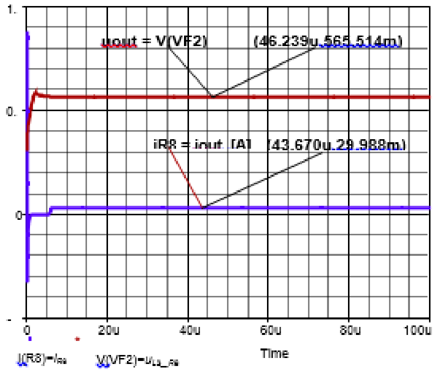


Fig.11 Time dependency of the current $i_{R8} = i_{out}$ and of the voltage $u_{R8} = u_{out}$, for the variant $L_1 = 0.674\ \mu\text{H}$, $L_2 = 1.235\ \mu\text{H}$, k=0.3.

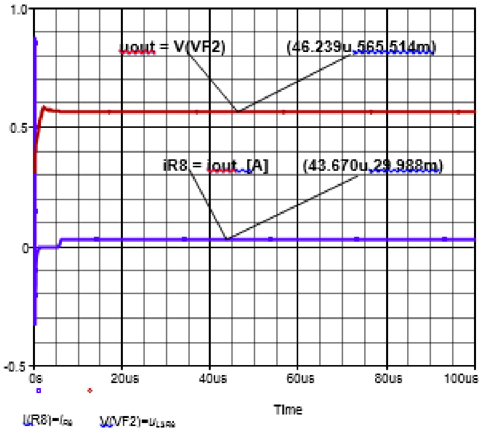


Fig.12. Time dependency of the current $i_{R8} = i_{out}$ and of the voltage $u_{R8} = u_{out}$, for the variant $L_1 = 2.265\ \mu\text{H}$, $L_2 = 0.54655\ \mu\text{H}$, k=0.5

We built in our lab the coils for the two variants and the parameters were identified using ANSOFT EXTRACTOR Q3D [5].

To output a constant current and voltage, a voltage regulator was attached to the load (Fig. 10). Fig. 11 (Fig. 12) presents time dependencies of the current and voltage corresponding to Case 1 (Case 2).

As a conclusion, we notice from Figures. 11 and 12 that the two output variables are almost identical for both cases for the parameters of the two magnetically coupled resonators.

III. WPTS DESIGN AND ANALYSIS SIMULINK (MATLAB)

WPTS requires a wide range of electronic parts, so, at a first glance, it's is very useful and natural to use MATLAB Simulink toolbox [4].

The Simulink toolbox from MATLAB, [4], facilitates the design and dynamic analysis for wireless power transfer systems.

The first designed and analyzed WPTS is in Figure 13. The system WPTS_1_2 (WPTS_2) contains the following files: *red_bifazat.c, WPT_2_dat.m, WPT_2.mdl,* redr_bifazat.mexw64, and redr_bifazat.mexw64 pdl.

The input file WPT_2_dat.m is:

```
clear all
close all
%Datele initiale
U_DC=12;
R1=1e+03;
R2=0.2;
R3=1e+06;
R4=0.01;
R5=5;
R6=1e+04;
C1=54.4e-09;
C2=6.2e-9;
C3=47e-06;
L1=8.6e-06;
L2=8.6e-06;
L3=1e-4;
L4=1.0e-06;
L1m=0.674e-06;
R1m=0.001;
L2m=1.235e-06;
R2m=0.001;
M=0.2737e-06;
hist=0.001;
Up=2;
Us=5;
T=1e-06;
%mex -v -g redr_bifazat.c;
END
```

From Figure 13, the schematics of the WPTS allows for the power transfer efficiency computation:

$$\eta_{21\_1} = 100\cdot\frac{P_{dc\_in}}{P_{dc\_out}} = 100\cdot\frac{5.003}{18.63} = 26.85\%$$

$$\eta_{21\_2} = 100\cdot\frac{P_{ac\_in}}{P_{ac\_out}} = 100\cdot\frac{5.003}{8.248} = 60.66\%$$

The schematics of the next wireless power transfer system SWTP_3, designed and analyzed with the Simulink toolbox in MATLAB, is depicted in Figure 13.

For the WPTS in Figure 16, the two resonators have the following parameters [6]: $C_1 = 46.171$ nF, $C_2 = 46.091$ nF, $L_1 = 66.56\ \mu\text{H}$, $L_2 = 66.49\ \mu\text{H}$, $M = 13.438048\ \mu\text{H}$, $R_{L1} = 1.12\ \Omega$, $R_{L2} = 0.78\ \Omega$ and $R_L = 7.93\ \Omega$.

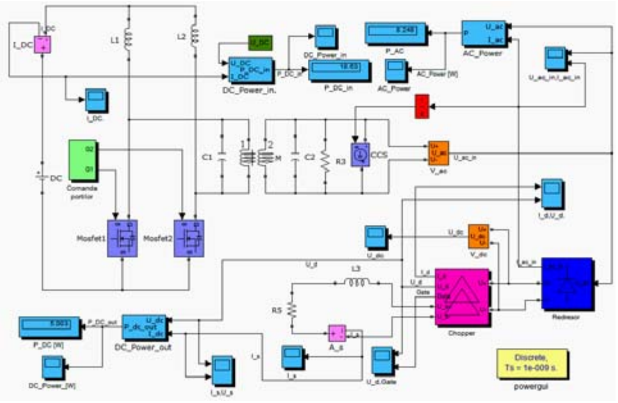


Fig.13. Equivalent diagram of a wireless electromagnetic power transfer used for charging cell phones

Figure 14 depicts the time dependencies of the output current *I_d* and voltage *U_d*. The time dependency of the output power *P_DC*_out is given in Figure 15.

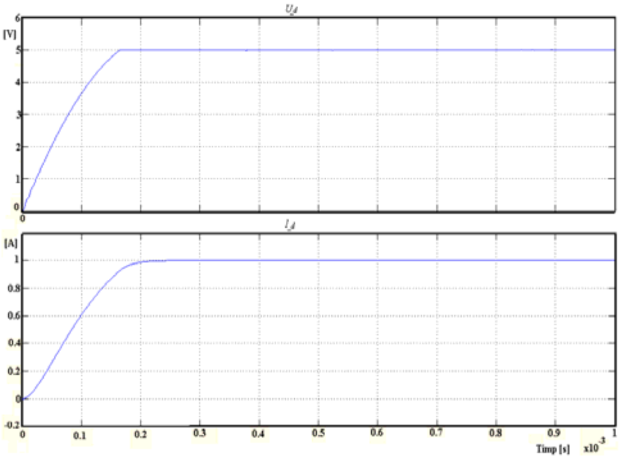


Fig. 14. Time dependencies of voltage *U_d* and current *I_d*

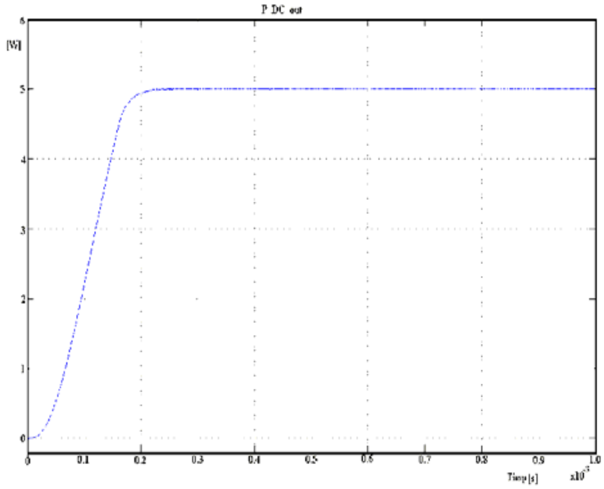


Fig. 15. Time dependency of power *P_DC_out*

We preferred to use the values of the parameters of the two coils for the system SWTP_3 identical as in [6] in order to check the results we obtained with those measured in [6]. In Figure 18 the magnetic couple for the two coils L_1 and L_2 was eliminated.

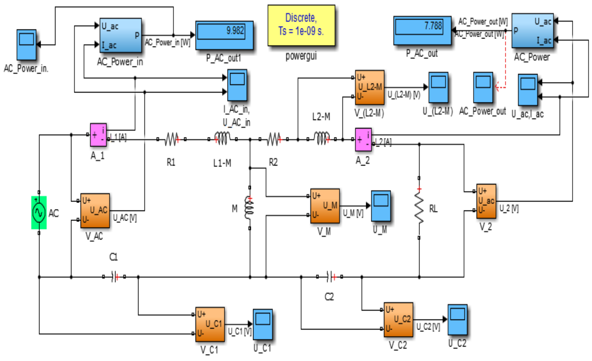


Fig. 16. Equivalent diagram of the wireless power transfer system used for checking experimental results.

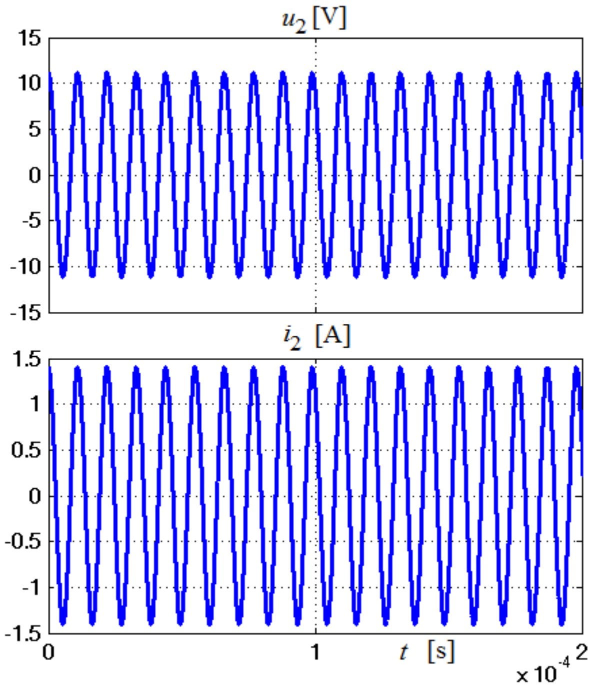


Fig. 17. Time dependencies of the voltage u_2 and current i_2 in the receptor coil

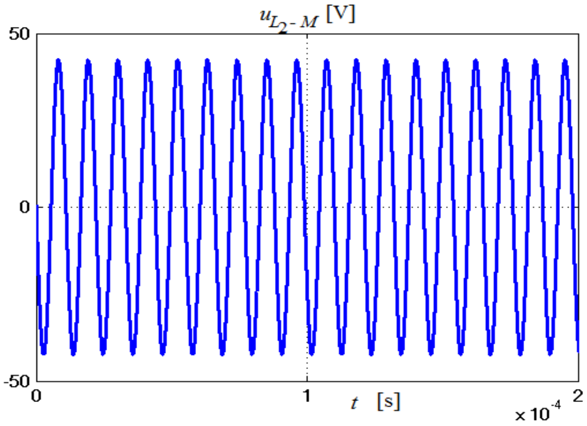


Fig. 18. Time dependency of the voltage u_{L2_M} of the coil $L_2 - M$

In Figure 17, the time dependencies of the voltage u_2 and current i_2 in the receptor coil are presented, and in figure 18 we give the time dependencies of the voltage u_2 and current i_2 in the receptor coil.

The resonance frequency:

$$f_0 = \frac{1}{2\pi\sqrt{L_1 C_1}} \cong \frac{1}{2\pi\sqrt{L_2 C_2}} = 90.9$$

is very close to the frequency obtained for checking he results f_{0_grafic} = 90.85 kHz.

The diagram of the wireless power transfer system allows for calculating the efficiency of power transfer:

$$\eta_{21\_1} = 100 \cdot \frac{P_{ac\_out}}{P_{ac\_in}} = 100 \cdot \frac{7.788}{9.788} = 79.567\%$$

The waves for the WPTS in Figure 17 are identical with those in [6].

IV. CONCLUSIONS

This paper is an improved version of a previous work of the authors [21]. In this paper we presented a set of diagrams for WPTS with applications in key domains. Our research used original circuits working as WPTS. These circuits use sets of two magnetically coupled coils built in our lab from UPB.

The parameters of the two coils were determined using the specialized software ANSOFT EXTRACTOR Q3D, [5]. For designing power source circuit and the output circuit we used electronic parts from the libraries of Tina (Texas Instruments) and SPICE, [1 - 3], and from the library of the Simulink toolbox in MATLAB [4]. Analyzing the results obtained by simulations, we can conclude that TINA, SPICE and MATLAB are suited for the design and analysis of a wide range of WPTS. The schematics used for building WPTS were designed and analyzed with many simulations in Tina, SPICE and Simulink in MATLAB. The libraries of TINA, SPICE and SIMULINK contain a wide range of electronic parts which allow for designing and building efficient wireless power transfer systems.

WPTS are more appropriate for small distances transmission, distances up to twice the coils dimensions. In contrast to other WPTS methods, the efficiency of the system can reach up to 95% for short distance.The results done by simulations were almost identical with the experimental ones and those in existing literature.

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Contribution of authors:
First author – 30%
First coauthor – 20%
Second coauthor – 20%
Third coauthor – 20 %
Forth coauthor – 10 %

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