Design and Simulation of Wireless Power Transfer Systems

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***Abstract* – This paper presents a set of diagrams for wireless power transfer systems (WPTS) with a lot of applications in key domains such as: medical, electrical engineering, military etc. Our research is based on 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, SPICE and SIMULINK in MATLAB. We used existing parts from Texas Instruments libraries. 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 when the distance increases. In contrast to other WPTS methods, the efficiency of the system can reach up to 95% for short distance. 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 a bound of the error of less than 5%. We also studied the efficiency of the power transfer and presented some practical applications for these systems such as low power battery chargers. The results done by simulations were almost identical with the experimental ones and those in existing literature, the error being less than 5%.**

Keywords: *Wireless Power Transfer Systems, coupled resonators, circuit simulations, power transfer efficiency, wireless battery charger.*

I. INTRODUCTION

The major sections of the system that implements Ampere 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).

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 when the distance increases. In contrast to other WPTS methods, the efficiency of the system can reach up to 95% for short distance.

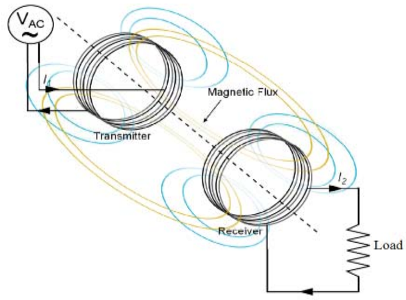


Fig. 1. WPTS functioning principle.

The set of diagrams for WPTS presented in this paper are suitable for applications such as: medical implants, mobile phones batteries charging, wireless sensors networks, electrical networks monitoring etc. 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]. The two coil parameters were computed using the specialized software ANSOFT EXTRACTOR Q3D, [5].

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

The oscillator and the power amplifier (PA) are plying important roles for the WPTS. The oscillator should produce a high frequency sinusoidal signal with the frequency equal to the resonance frequency of the two magnetically coupled resonators, TX and RX,[6-9,11-15,18,19]. 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 to modify. Other important blocks are the voltage rectifier and regulator which must provide constant current and voltage on the load.

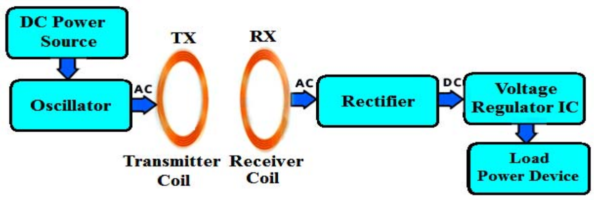


Fig. 2. Standard diagram of a WPTS.

In this paper we designed the schematics used for building WPTS and we made the numerical analysis of these schematics in Tina, SPICE [15] and SIMULINK (MATLAB).

The results we obtained with the aforementioned software were compared with the experimental ones and with those in 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 Fig.3 we present the first WPTS that was designed and built in our research laboratory from UPB.

We took into considerations two sets of coils built in University Politehnica of Bucharest (UPB) electrical engineering laboratory.

A. *Case 1.*

Input data: Two identical coils; Shape: helicoidally; Parameters:

$L_1 = L_2 = 1.4$ μH, $C_1 = 22$ nF, $C_2 = 22$ nF, $R_{L1} = R_{11} = 0.0225$ Ω, $R_{L2} = R_{10} = 0.01$ Ω and $k = M/\text{sqrt}(L_1*L_2) = 0.3$.

B. *Case 2.*

Input data: Two different coils; Shape: spiral (printed coils); Parameters:

$L_1 = 3.275$ μH , $L_2 = 0.585$ μH, $C_1 = 22$ nF, $C_2 = 179$ nF, $R_{L1} = R_{11} = 0.0225$ Ω, $R_{L2} = R_{10} = 0.01$ Ω and $k = M/\text{sqrt}(L_1*L_2) = 0.5$.

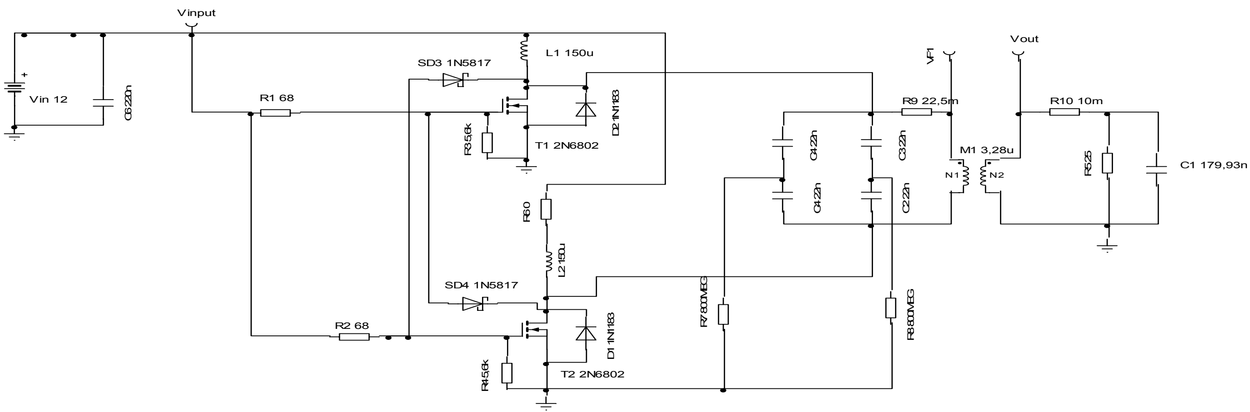


Fig. 3. WPTS corresponding to the parameters from Case 2.

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

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

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

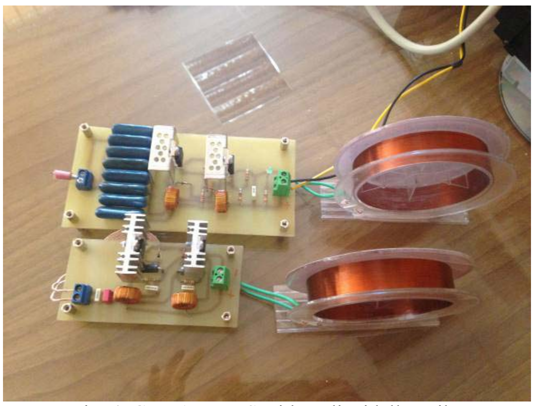


Fig. 4. Case 1. WPTS with Helicoidally coils.

Fig. 5 presents a photo of the WPTS built in our laboratories for Case 2 (different shaped coils).

From Fig. 6, b we notice that the main frequency of 905 kHz is very close to the resonance frequency of 907.33 kHz, and the error is of -0.257%.

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

The time dependencies of the currents i_{L1} and i_{L2} for Case 1, respectively Case 2, are given in Fig. 6, respectively Fig. 7, a.

Fig. 8 presents a WPTS with the following specifications: a constant output voltage $U_{out}t = 11.347$ V; a constant output current $I_{out} = 453.899$ 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}.

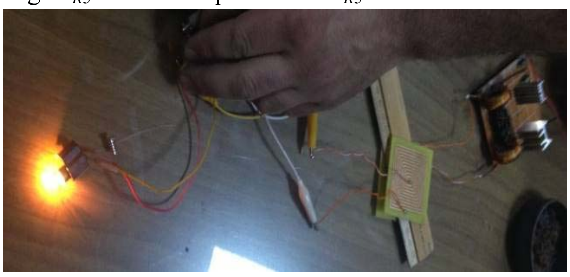
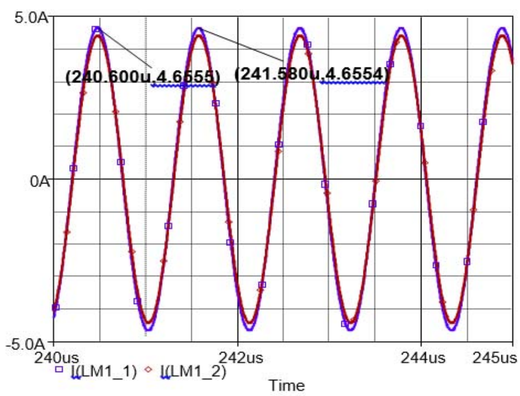
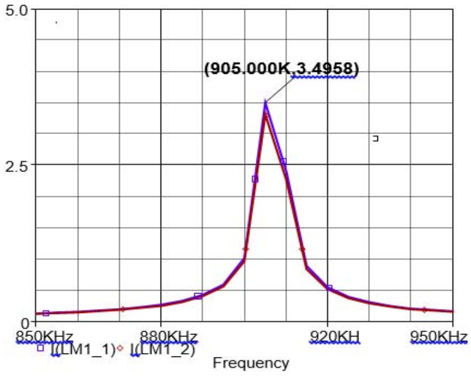


Fig. 5. Case 2. WPTS with printed coils.



(a)



(b)

Fig. 6. Dependencies of currents iL1 and iL2, for the first set of coils: a) vs time; b) vs frequency.

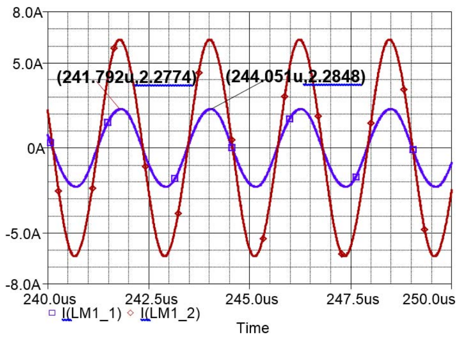


Fig.7.a Dependencies of currents i_{L1} and $i_{L2,}$ for the second set of coils vs. time;

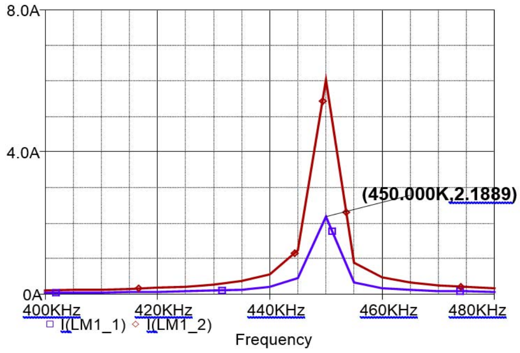


Fig.7.b Dependencies of currents i_{L1} and $i_{L2,}$ for the second set of coils vs frequency.

The two sets of magnetic coupled coils from Fig. 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, $k = M / \sqrt{L_1 \cdot L_2} = 0.22619.$

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 Fig. 9. From Figs. 9, a, and b as a conclusion, we notice the considered dependencies are almost the same for both versions of the two resonators.

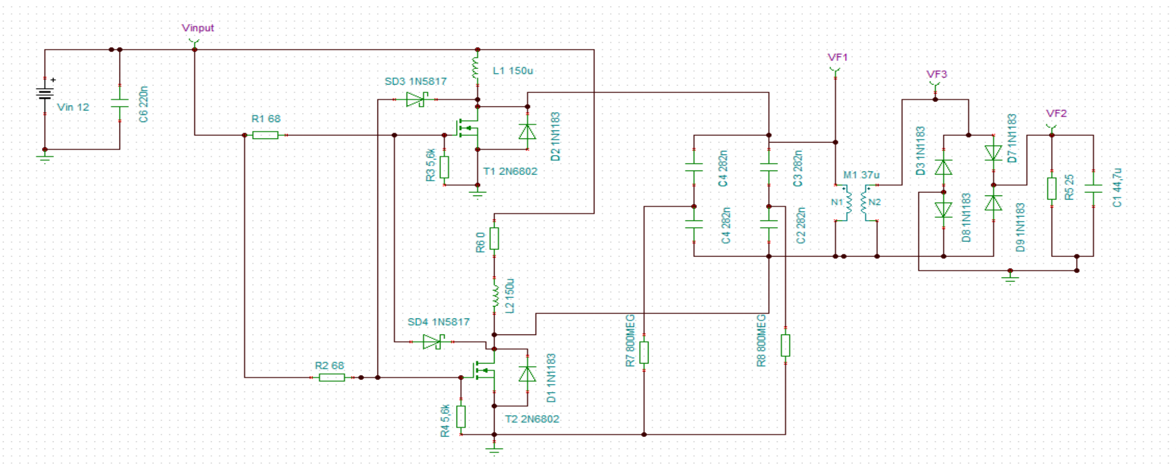
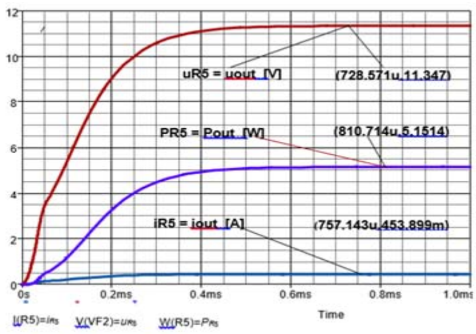
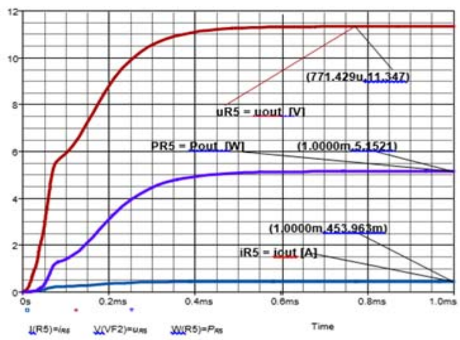


Fig.8. Wireless Power Transfer System (WPTS) which produces constant output voltage and current (dc).



(a)

Fig. 9.a Time dependencies of the output voltage uR5, the output current iR5 and the output power on the load PR5: the parameters of the two coils as variant 1;



(b)

Fig. 9.b Time dependencies of the output voltage uR5, the output current iR5 and the output power on the load PR5: the parameters of the two coils as variant 2

In Fig. 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.

We build in our lab the coils for the two variants and the parameters were identified using ANSOFT EXTRACTOR Q3D, [5]. For the system in Fig. 10 we considered two variants for the two magnetic coupled coils:

1. $L_1 = 0.674$ μH, $L_2 = 1.235$ μH, $k = M/\sqrt{L_1 \cdot L_2} = 0.3$;
2. $L_1 = 2.265$ μH, $L_2 = 0.54655$ μH, $k = M/\sqrt{L_1 \cdot L_2} = 0.5$

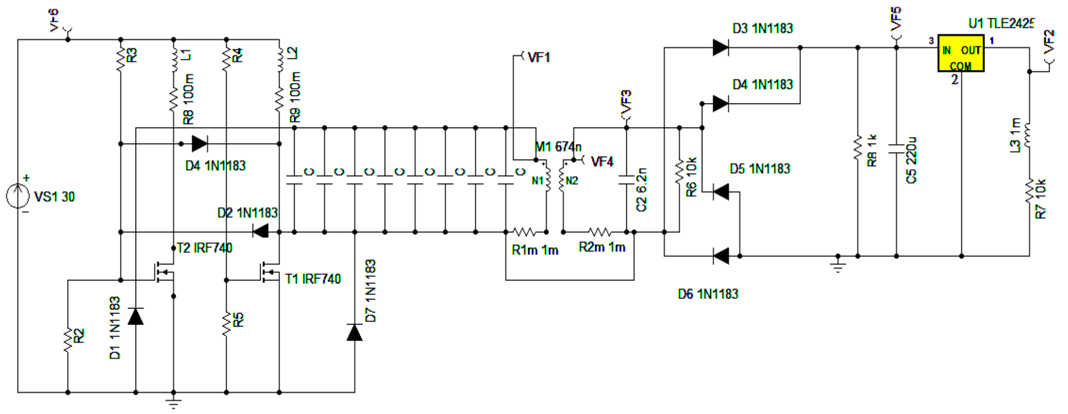


Fig. 10. Wireless electromagnetic energy transfer used for low power battery charging.

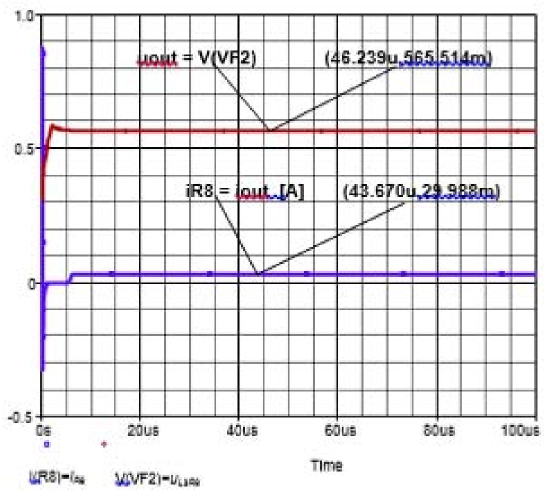


Fig.11. Time dependency of the current $i_{R8} = i_{out}$ and of the voltage $u_{R8} = u_{out}$, for the variant $L_1 = 0.674$ μH, $L_2 = 1.235$ μH,

$$k = M / \sqrt{L_1 \cdot L_2} = 0.3$$

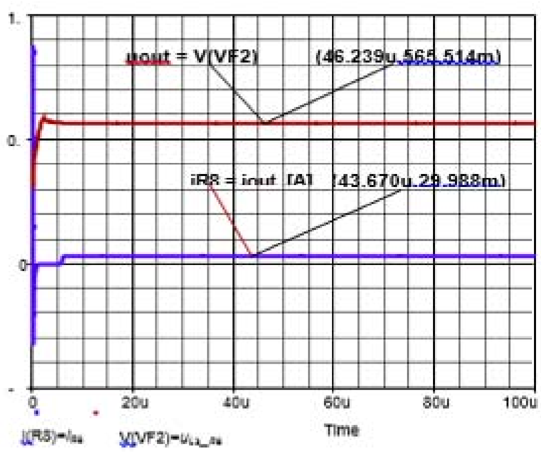


Fig.12. Time dependency of the current $i_{R8} = i_{out}$ and of the voltage $u_{R8} = u_{out}$, for the variant $L_1 = 2.265$ μH , $L_2 = 0.54655$ μH,

$$k = M / \sqrt{L_1 \cdot L_2} = 0.5.$$

We build 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. 9). Fig. 11 presents the WPTS for Case 1, while Fig. 12 presents the WPTS for Case 2.

As a conclusion, we notice from Figs. 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

WPTS requires a wide range of electronic parts, so, at a first glance, it's very useful and natural to use MALAB 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 shown in Fig. 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	C1=54.4e-09;	L2m=1.235e-06;
close all	C2=6.2e-9;	R2m=0.001;
%Datele initiale	C3=47e-06;	M=0.2737e-06;
U_DC=12;	L1=8.6e-06;	hist=0.001;
R1=1e+03;	L2=8.6e-06;	Up=2;
R2=0.2;	L3=1e-4;	Us=5;
R3=1e+06;	L4=1.0e-06;	T=1e-06;
R4=0.01;	L1m=0.674e-06;	%mex -v -g redr_bifazat.c;
R5=5;	R1m=0.001;	END
R6=1e+04;		

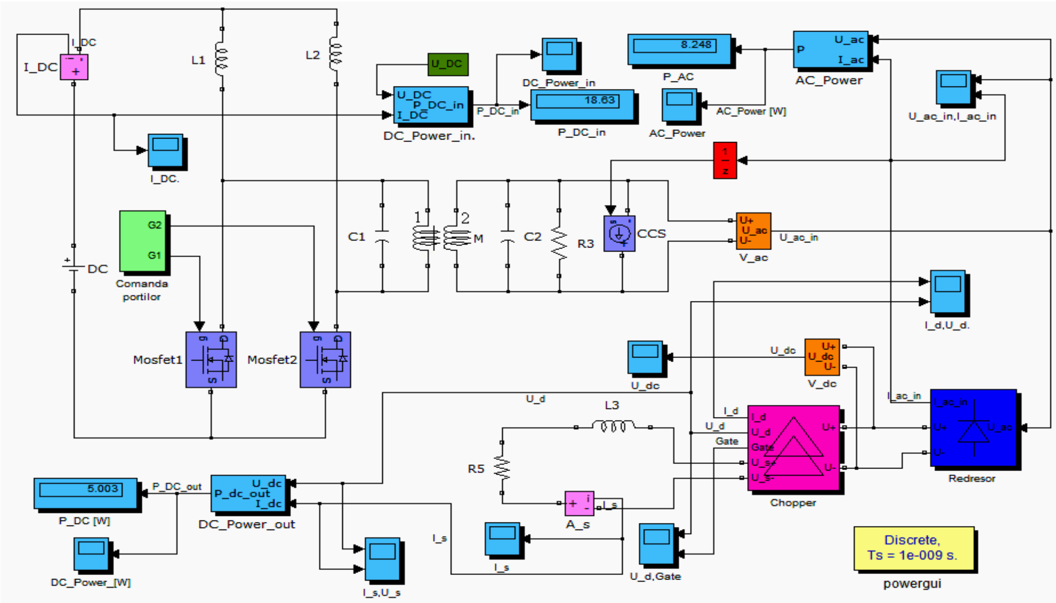


Fig.13. Equivalent diagram of a wireless electromagnetic power transfer used for charging cell phones.

From Fig. 13, we deduce that the schematics of the WPTS allows for the power transfer efficiency computation:

$$\eta_{21\_2} = 100.0 \cdot \frac{P_{dc\_in}}{P_{ac\_out}} = 100.0 \cdot \frac{5.003}{8.248} = 60.66\ \%$$

$$\eta_{21\_1} = 100.0 \cdot \frac{P_{dc\_in}}{P_{dc\_out}} = 100.0 \cdot \frac{5.003}{18.63} = 26.85\ \%$$

Fig. 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 Fig. 15.

The schematics of the next wireless power transfer system SWTP_3, designed and analyzed with the SIMULINK toolbox in MATLAB, is presented in Fig. 16. For the WPTS in Fig. 16, the two resonators have the following parameters, [6]: C_1 = 46.171 nF, C_2 = 46.091 nF, L_1 = 66.56 μH, L_2 = 66.49 μH, M = 13.438048 μH, R_{L1} = 1.12 Ω, R_{L2} = 0.78 Ω and R_L = 7.93 Ω.

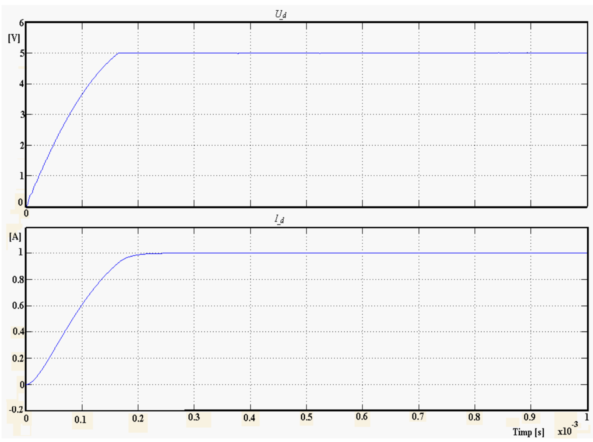


Fig. 14. Time dependencies of voltage U_d and current I_d.

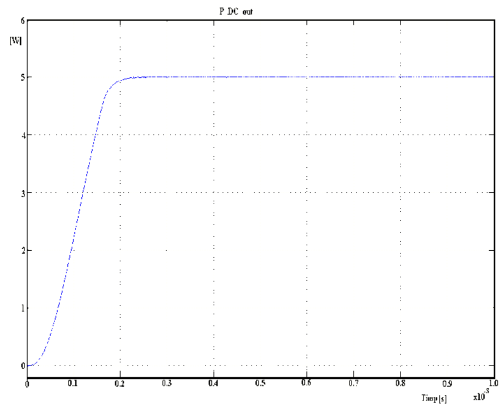


Fig. 15. Time dependency of power P_dc_out.

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 Fig. 16 the magnetic couple for the two coils L_1 and L_2 was eliminated.

In figure 17 we give the time dependencies of the voltage u_2 and current i_2 in the receptor coil. The resonance frequency is:

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

is very close to the frequency of the curves given in figures 17 and 18, f_{0_grafic} = 90.85 kHz. From Fig. 17, the diagram of the wireless power transfer system allows for calculating the efficiency of power transfer:

$$\eta_{21\_1} = 100.0 \cdot \frac{P_{ac\_out}}{P_{ac\_inp}} = 100.0 \cdot \frac{7.788}{9.788} = 79.567\ \%.$$

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

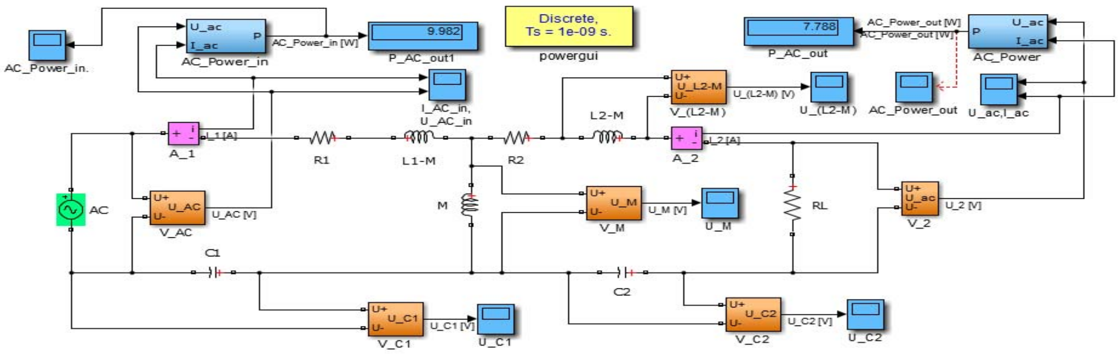


Fig. 16. Equivalent diagram of the wireless power transfer system used for checking experimental results.

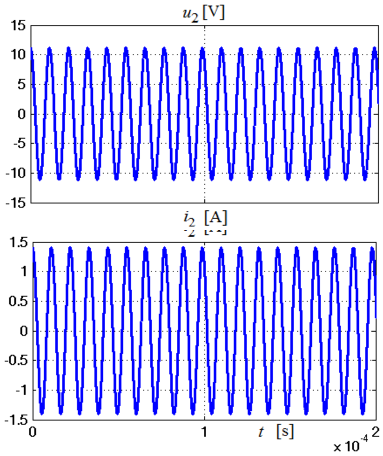


Fig. 17. Time dependencies of the voltage u2 and current i2 in the receptor coil.

IV. Conclusions

In this paper we presented a set of diagrams for WPTS with applications in many important domains. Our research used circuits working as WPTS. The originality consists of designing WPTS for which the parameters and the configuration of the two magnetically coupled resonators from the system are known. The user can impose some values for the current and the voltage corresponding to the load. These circuits use sets of two magnetically coupled coils built in our lab from UPB. The parameters of the two coils were determined using specialized software. For designing the power source circuit, the output circuit and the schematics for WPTS, electronic parts from Tina, SPICE and Simulink have been used. 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. 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 compared with those with the experimental ones and those in existing literature, the error being less than 5%.

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