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Analysis and design of a class E current-driven rectifier for 1 MHz wireless power transfer system

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The paper presents the design of the class E current-driven rectifier, which is intended for operation in the wireless power transmission system, as well as the concept of selection of the rectifier parameters which allows the operation with high efficiency. The selection of the rectifier parameters was performed with a view to the use of the existing wireless power transmission (WPT) system. The procedure for selection of the rectifier parameters has been proposed to enable its optimal use in reference to the system parameters given already at the design stage, *ie*; load resistance and the coil magnetic coupling factor (distance between coils). In order to verify the correctness of the procedure for selection of the parameters, the numerical model of the system which consists of the class E resonance inverter, the air-core transformer and the designed E class rectifier system was developed in the LTspice environment. Simulation tests and analysis of the obtained calculation results were performed. Based on the simulation results, a prototype of the class E rectifier system which cooperates with the existing wireless power transmission system supplied from the class E inverter was developed. The obtained results of laboratory measurements demonstrated a high compliance with the simulation results, thus, confirming the correctness of the proposed design procedure and the high operating efficiency of the rectifier system.

Keywords: class E rectifier, wireless power transfer, high frequency, high efficiency, magnetic resonance coupling, soft switching, class E^2 DC-DC converter

1 Introduction

At present, the Wireless Power Transfer (WPT) technology, which uses the mechanism of magnetic resonance coupling, is used to charge batteries of various electronic devices (eg. wearable devices [1], medical implant devices [2, 3]) and power systems, especially electric vehicles [4, 5]. The high frequency of operation of the WPT systems (at the megahertz level) is desirable in the construction of light-weight, compact systems capable of transferring energy to a medium distance, which is usually no longer than one meter. From the other hand these systems are expected to ensure as highest as possible efficiency of energy processing, improvement in electromagnetic compatibility and higher power densities (*ie* fast charge) rather than to increase the distance of the power transmission. In the WPT systems, it is possible to distinguish three subassemblies: an inverter, an air-core transformer (circuit of magnetically coupled coils) and a rectifier. The effective power transfer by means of coupled coils is possible only after the leakage inductance compensation, which is obtained through the serial or parallel connection of resonance capacitors. In order to improve the efficiency of processing of energy by transformers, designs which allow the application of the soft switching technique is used, *ie* the inverters of class E [6–8], DE [9, 10], EF [11, 12] and Φ rectifiers [13]. The soft switching of the transistor and/or diode enables the reduction in switching losses which increase together with an increase in the operating frequency. Whether the optimal operation of the inverter, *ie* the operation under the conditions of soft commutation is obtained depends strongly on the parameters of the air-core transformer and the rectifier.

In the high-frequency wireless power transmission systems, a class E rectifier is used most frequently. The E class rectifiers can be divided into rectifiers supplied from the source of current [14, 15] or voltage [16, 17]. The choice of the appropriate rectifier topology (powered from the source of current or powered from the source of voltage) should be adapted to the structure of the receiving coil coupled with the compensation capacitor. In the case of the serial connection of these elements, the value of the compensation capacitor is adapted based on the voltage resonance condition in a manner which enables the voltage compensation on the secondary coil self-inductance. This means that the rectifier, from the point of view of its terminals, is powered from an equivalent current source. In the case of the parallel connection of the circuit, the value of the compensation capacitor is selected based on the current resonance condition. This, in turn, means that the rectifier is powered from an equivalent voltage source (voltage induced in the receiving coil). The optimal operation of the class E rectifier is characterized by switching on the diode under the Zero Voltage Switching (ZVS) and Non-Zero Current Switching (NZCS) conditions and switching it off under the zero voltage switching (ZVS) and zero current switching (ZCS) conditions. The correct selection of parameters of the circuit allows for the soft diode commutation to be achieved, thus, the operation with megahertz frequencies, maintaining the appro-

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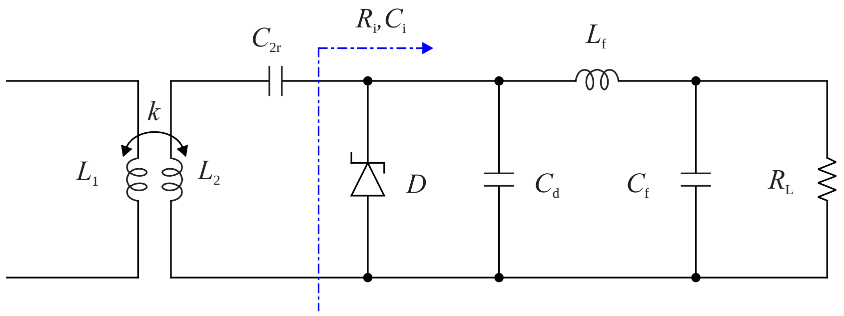

Fig. 1. Diagram of a considered class E rectifier

priately high efficiency. The drawback of E class rectifiers concerns the values of the maximum voltage and current of the diode which almost reach four times the value of load voltage and current. In other words E class rectifiers can be applied in small or medium power systems.

The paper proposes the procedure for selection of parameters of the E class current-driven rectifier allowing on the convert a high-frequency alternating current to direct current (DC) in the WPT system. The parameters of the rectifier are selected with a view to using the existing wireless power transmission system. In order to verify the correctness of the procedure for selection of the rectifier parameters, simulation tests of the low power WPT system were conducted. The system operates with the frequency of 1 MHz. The tested system consisted of the class E inverter, the circuit of magnetically coupled coils and the E class rectifier – the DC-DC E^2 class converter. The verification covered the impact of the operation of the rectifier system on the operation of the inverter system and the air-core transformer (ATr). The laboratory measurement results were presented for the wireless power transmission system which cooperates with the developed rectifier. The authors would like to make a remark that the method of selection of the E class inverter parameters will not be discussed in this paper as it has been discussed in detail in [18].

2 Class E current-driven rectifier for WPT system

2.1 Design procedure

The diagram of the class E current-driven rectifier is presented in Fig. 1. The rectifier consists of the diode, capacitor C_d which supports the process of rectification, the $L_\mathrm{f} - C_\mathrm{f}$ branch which fulfils the role of a filter and load R_L. In the system, the time interval during which the diode and C_d capacitor depends on the value of diode switch-on duty ratio D_d.

The procedure of selection of parameters presented in this paper is a modification of the concept given in [19]. The approach proposed by the authors consists of the assumption of the value of diode switch-on duty ratio $D_\mathrm{d}(1)$, which ranges between 0.3 and 0.5, and the determination of the remaining parameters of the rectifier. It must be mentioned here that a change in the value of ratio D_d and load R_L affects the value of the equivalent resistance of rectifier $R_\mathrm{i}(3)$. This way, the possibility of simple selection of the value of equivalent resistance of rectifier R_i has been obtained by means of two parameters, *ie* D_d and R_L.

$$D_\mathrm{d} = \mathrm{const.} \tag{1}$$

Angle Φ_d understood as the shift between the voltage on the diode and current flowing through receiving coil L_2 of the WPT system (Fig. 1) can be determined based on

$$\Phi_\mathrm{d} = \arctan \frac{1-\cos(2\pi D_\mathrm{d})}{2\pi(1-D_\mathrm{d})+\sin(2\pi D_\mathrm{d})}\,, \tag{2}$$

then, the equivalent value of the rectifier resistance is determined as

$$R_\mathrm{i} = 2R_\mathrm{L}\sin^2\Phi_\mathrm{d}\,. \tag{3}$$

The value of capacitor capacity C_d is, on the other hand, calculated based on the following formula

$$C_\mathrm{d} = \frac{1}{2\pi\omega R_\mathrm{L}}\Big\{1 - cos(2\pi D_\mathrm{d}) - 2\pi^2(1-D_\mathrm{d})^2 + \frac{[2\pi(1-D_\mathrm{d})+\sin(2\pi D_\mathrm{d})]^2}{1-cos(2\pi D_\mathrm{d})}\Big\}, \tag{4}$$

inductance value of the filter choke is a consequence of the following relationship

$$L_\mathrm{f} > \frac{1-D_\mathrm{d}}{0.1\,\mathrm{f}}R_\mathrm{L}, \quad C_\mathrm{f} > \frac{25}{\pi^2\mathrm{f}^2L_\mathrm{f}} \tag{5,6}$$

value of capacity of the filtering capacitor is based on and the value of equivalent capacity of the rectifier seen from the input side of the system is based on the following relationship

$$C_\mathrm{i} = 4\pi C_\mathrm{d}\Big/\Big[4\pi(1-D_\mathrm{d}) + 4\sin(2\pi D_\mathrm{d}) - \sin(4\pi D_\mathrm{d})\cos(2\Phi_\mathrm{d}) - 2\sin(2\Phi_\mathrm{d})\sin^2(2\pi D_\mathrm{d}) - 8\pi(1-D_\mathrm{d})\sin\Phi_\mathrm{d}\sin(2\pi D_\mathrm{d}-\Phi_\mathrm{d})\Big]. \tag{7}$$

The impact of equivalent capacity C_i may be compensated by changing the value of capacity of capacitor $C_{2\mathrm{r}}$ (8) appropriately, so that the resultant capacity is equal

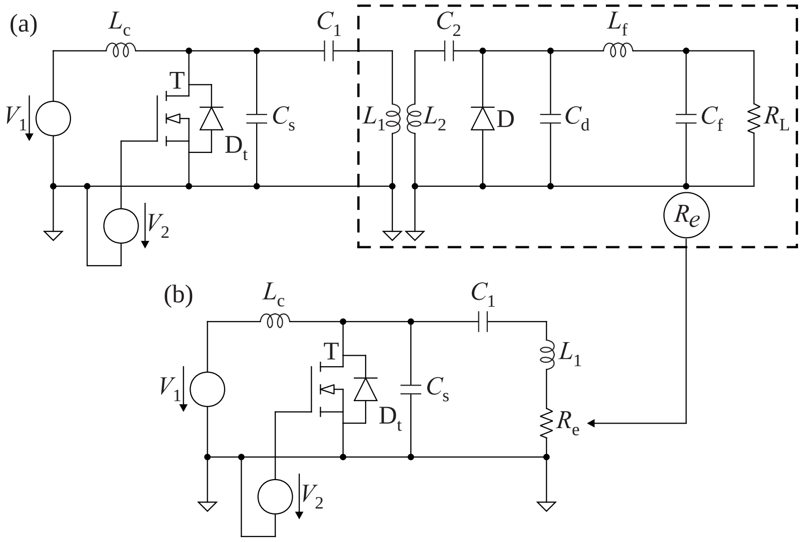

Fig. 2. (a) – A equivalent-circuit model of the wireless energy transmission system, (b) – equivalent circuit of the inverter part

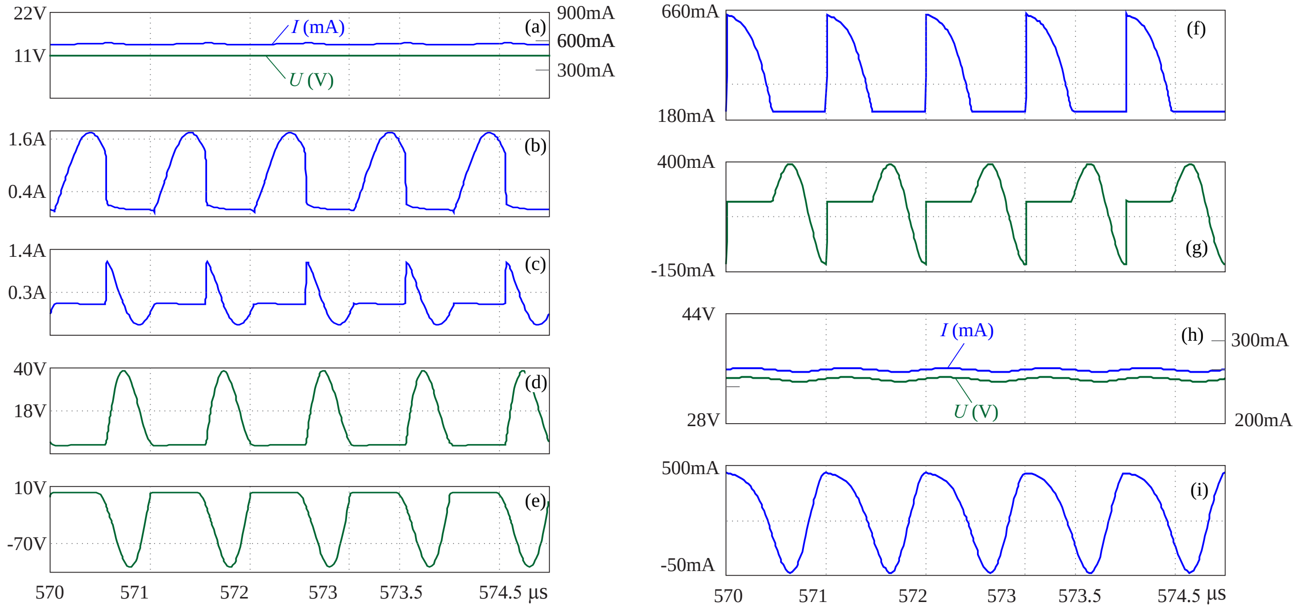

Fig. 3. The currents and voltages waveforms of the tested system: (a) - current and voltage supplied inverter, (b) - current of transistor T, (c) - current of capacitor C_s,(d) - voltage on capacitor C_s, (e) - voltage on diode rectifier D,(f) - current of diode D, (g) - current of the capacitor Cd, (h) - current and voltage on the resistance R_L, (i) - current of the secondary coil L_2

Table 1. Values and ranges of component parameters of the studied system used in the simulation

Inverter		Transformer		Rectifier	
Parameter	Value	Param.	Value	Param.	Value
V_1	11 V	L_1	17.7 μH	C_d	799 pF
f	1 MHz	L_2	17.9 μH	L_f	886 μH
L_c	278 μH	rL_1	0.3 Ω	C_f	2.86 nF
C_s	2.83 nF	rL_2	0.3 Ω	C_i	2.06 nF
C_1	1.565 nF	k	0.196	R_i	47.67 Ω
R_e	10 Ω	C_{2r}	4.48 nF	R_L	150 Ω
				D_d	0.410

to the value of the capacity necessary for the compensation of leakage inductance of coil L_2 of the air-core transformer. It is worth emphasizing that in the case of the serial connection of capacitors, such compensation is possible if value C_i is greater than value C_2

$$C_{2r} = \frac{C_2 C_i}{C_i - C_2}, \tag{8}$$

where, C_2 is the capacity of the capacitor, which compensates the coil leakage inductance of the secondary side, selected on the basis of resonance, *ie* $C_2 = \frac{1}{(2\pi f)^2 L_2}$.

2.2 System model for wireless power transfer

The circuit model of the WPT developed in the LTspice environment is presented in Fig. 2a. The analysed

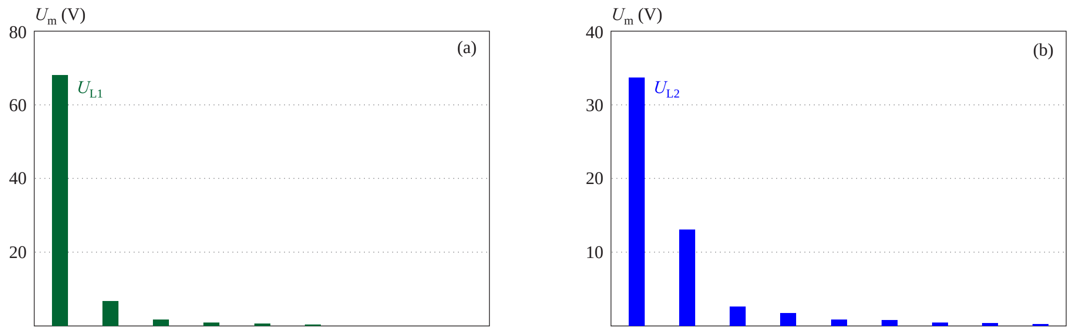

Fig. 4. Share of higher harmonics in waveform of: (a) – coil voltage of transformer ATr for the primary side, (b) – coil voltage of transformer ATr for the secondary side

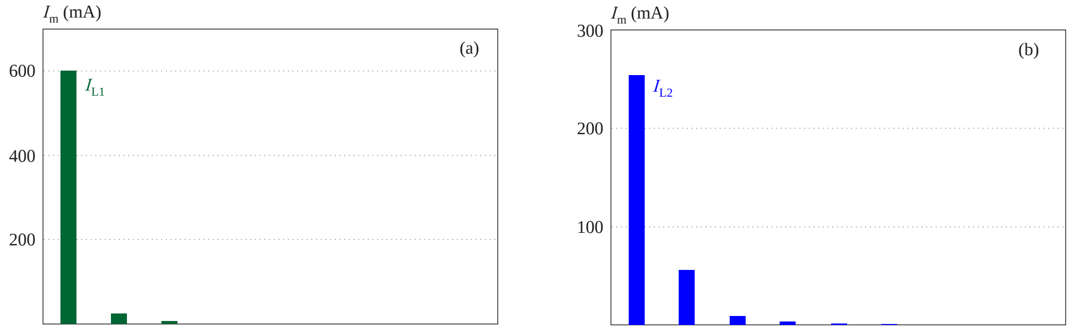

Fig. 5. Share of higher harmonics in waveform of: (a) – coil current of transformer ATr for the primary side, (b) – coil current of transformer ATr for the secondary side

Table 2. Values of component parameters of prototype system

Parameter	Value	Param.	Value	Param.	Value
V_1	11 V	L_1	17.7 μH	C_d	785 pF
f	1 MHz	L_2	17.9 μH	L_f	1000 μH
L_c	330 μH	rL_1	0.3 Ω	C_f	3.3 nF
C_s	2.87 nF	rL_2	0.3 Ω	R_L	150 Ω
C_1	1.65 nF	d	7.5 cm		
		C_{2r}	4.4 nF		

system consists of the circuit of the E class inverter system, magnetically coupled coils and the E class rectifier. The parameters of the rectifier have been determined for the existing inverter system and the air-core transformer. This means that the starting point, to calculate of rectifier parameters, is the known value of equivalent resistance R_e for which the inverter was designed for optimal operation, here equal to $10\,\Omega$. Here, the value of the equivalent resistance R_e should be understood the effective load resistance seen by inverter (see, Fig. 2b). It follows from (9) that the adaptation to resistance R_e requires the identification of the appropriate value of the coil magnetic coupling factor k, diode switch-on duty ratio $D_d(\Phi_d)$ and load resistance R_L. By assuming value $R_L = 150\,\Omega$, $D_d = 0.41$ and saving equation (9) to form (10) value $k = 0.196$ was obtained. This way, one of the possible configurations of parameters R_L, k and D_d, which allows the adaptation of the rectifier system to the existing wireless power transmission system, was obtained. In accordance with the given parameters R_L and D_d, using the relationships (1) - (8) the remaining rectifier parameters were determined.

$$R_e = \frac{\omega^2 k^2 L_1 L_2}{R_i + rL_2} = \frac{\omega^2 k^2 L_1 L_2}{2R_L \sin^2 \Phi_d + rL_2}\,, \tag{9}$$

where, L_1 and L_2 – self-inductances of the primary and secondary coil, ω – pulsation, rL_2 – secondary coil resistance, k – coupling factor between coils L_1 and L_2.

$$k = \sqrt{\frac{2R_L R_e \sin^2 \Phi_d + rL_2}{\omega^2 L_1 L_2}}\,. \tag{10}$$

Table 1 lists the parameters used for the circuit simulation of the system, marked in accordance with Fig. 2.

3 Simulation results and analysis

Figure 3 presents the obtained waveforms of currents and voltages for the selected elements of the system. The obtained waveforms are characteristic for the optimal operation of both the inverter and the rectifier. The transistor operates under the conditions of switching on ZVS and ZCS, switching off ZVS and NZCS, while the diode operates under the conditions of switching on ZVS and NZCS, switching off ZVS and ZCS, confirming at the same time the correct selection of parameters. The output current and voltage waveform from the rectifier

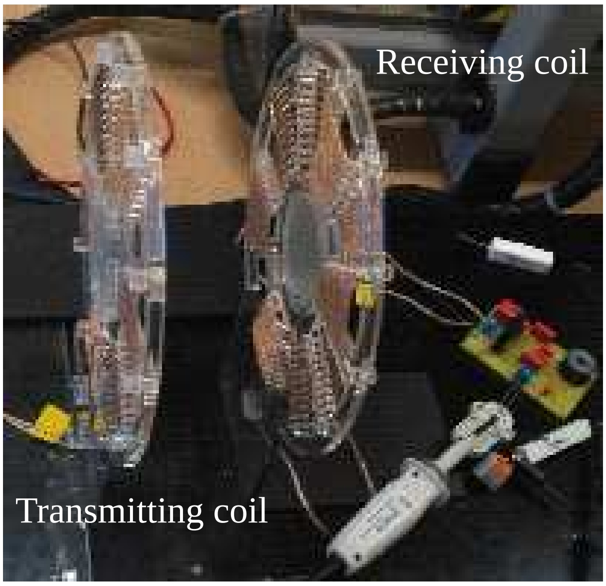

Fig. 6. View of the measuring stand of an elaborated prototype of a wireless energy transmission system

(Fig. 3g) is approximately constant. What deserves attention is the waveform of current collected by the rectifier (secondary coil current - Fig. 3h), which clearly deviates from the sinusoidal waveform. What is interesting, the non-sinusoidal waveform of current on coil L_2 does not have a negative impact on the operation of the rectifier and on the resultant efficiency of the WPT system, which, in this case was 91 %. In the work, the efficiency of WPT system was calculated as the ratio of the power output on the load resistance R_L to the input power delivered to the inverter system.

Then, a comparative analysis of the spectrum of voltage (Fig. 4) and current (Fig. 5) was conducted on the primary and secondary coil. It was noticed that the higher current and voltage harmonics on the primary side are significantly limited in relation to their content on the secondary side; hence the optimal operation of the inverter is not disturbed.

4 Experimental results

The stand for laboratory measurements of the wireless power transmission system is presented in Fig. 6. Parameters of the real subassemblies were selected in such a manner as to make their values correspond as closely as possible to the parameters used during the simulation (Tab. 2). The coil magnetic coupling factor $k = 0.196$ determined at the design stage corresponds to the setting of the distance between coil symmetry centres $d = 7.5$ cm.

Polypropylene capacitors, intended for operation with high frequencies and characterised by the low ESR resistance value were used to build the system. The main element of the rectifier system is the C3D04060A Schottky diode, while in the case of the inverter it is the IRFB4620PBF transistor. It must be added that the own output capacity of the transistor and the diode must be taken into account in the parallel capacity connected to them – C_s and C_d (Fig. 2). During the measurements, the I-PROBER 520 measuring probe attached to the oscilloscope was used (BNC plug), it is characterised by the DC – 5 MHz bandwidth. The recorded current and voltage waveforms on selected elements are presented in Fig. 7. The efficiency of the WPT system (including the inverter and rectifier system) amounted to a satisfactory value, *ie* 86 %.

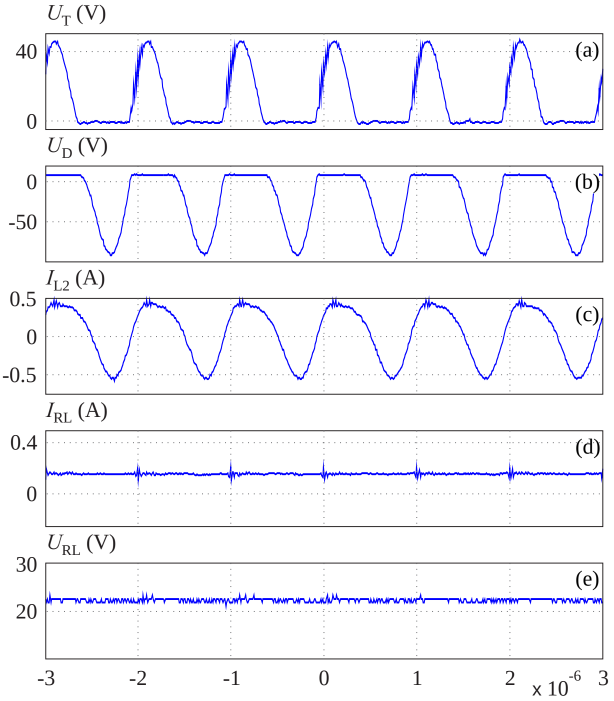

Fig. 7. The waveform of currents and voltages obtained at the laboratory stand: (a) – voltage on the transistor, (b) – voltage on the diode, (c) – rectifier input current, (d) – current on the resistance load,(e)voltage on the resistance load

5 Conclusions

The paper presents the concept of selection of parameters for the E class current-driven rectifier. Based on the obtained results of simulation calculations, a prototype of the E class rectifier, which cooperates with the existing wireless power transmission energy was developed, and then constructed and tested. Particular attention was paid to the verification of the proposed concept of parameter selection. The energy processing efficiency of high frequency wireless power transmission systems (*ie* the systems which use the magnetic coupling mechanism) strongly depends on the operation of transformers (E class inverter, E class rectifier). It is known that the efficiency of the E class inverter depends primarily on the matching of the value of equivalent resistance R_e, for which it was designed, to the optimal operation. In turn, the value of equivalent resistance of the inverter depends on the equivalent resistance R_i of the rectifier including load and on parameters of the magnetically coupled coil circuit. This means the necessity of the careful design of the rectifier and the accurate determination of its input parameters. The presented concept of selection of the E class rectifier parameters enables the flexible optimisation of the system parameters, *ie* the load resistance, the magnetic coupling factor and the diode switch-on duty ratio. The circuit models developed in the LTspice environment of wireless power transmission systems are used for the verification of the optimal operation of converters. A conclusion has been drawn that the appearance of higher harmonics in the current and voltage waveform of the secondary coil, *ie* in the input current of the rectifier, does not have a negative effect on the operation of the transformers and the system efficiency value. The observed compliance of the obtained results of simulation calculations with the measurement results was satisfactory

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