SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 18, No. 2, June 2021, 171-192

UDC: 621.311:621.391; 007 DOI: https://doi.org/10.2298/SJEE2102171K

Development of the Structure and Circuit Solution of a Bidirectional Wireless Energy Transmission System for Swarm Robots

Konstantin D. Krestovnikov[1], Ekaterina O. Cherskikh[1]

Abstract: This paper presents development of a circuit solution design for a bidirectional wireless energy transfer system, based on a resonant self-oscillator. The operation principle of the developed circuit solution in receiving and transmitting mode is described and the elementary circuit diagram is presented together with design ratios. Coil parameters for the resonant circuit are calculated, optimal number of turns in coils is presented, based upon the specified limit value of permissible current. The dependencies of system efficiency from transmitted power, maximum transmitted power, and energy transmission distance are obtained. The developed design, which includes the step-up DC-DC converter, allows to obtain the voltage on the output of the receiving system, equal to or higher than the voltage of the power source of the transmitting system. The specific feature of the proposed system is that it does not require a dedicated control system for operation in resonant mode and changing direction of power transfer. Resonance in transmitting and receiving coils can be maintained, even when their mutual layout is changed, due to utilization of identical resonant circuits and a self-oscillator. Application of the proposed solution is relevant for energy transfer among autonomous robots with limited positioning accuracy, as well as for energy transfer from power supply to robot or in reverse direction.

Keywords: Bidirectional wireless power transmission system, Current fed push-pull inverter, Swarm robotics, Synchronous rectifier.

1 Introduction

In the course of operation, autonomous robotic systems need to routinely recharge batteries [1, 2]. The most common power source for autonomous robots is an accumulator battery. In this case, the energy replenishment process is equivalent to battery recharging [3], what is, essentially, energy transfer from the external power source to the robot. Among common solutions of this problem

[1]Laboratory of Autonomous Robotic Systems, St. Petersburg Federal Research Center of the Russian Academy of Sciences (SPC RAS), St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences, 14-th Linia, VI, No. 39, St. Petersburg, 199178, Russian Federation;
E-mails: k.krestovnikov@iias.spb.su; cherskikh.e@iias.spb.su.

various wired and contact energy transfer methods have to be mentioned. Both approaches assume presence of connection sockets or terminal pairs and often require human involvement in the workflow of robot system operation, which imposes certain constraints. If the robot is used in a corrosive medium or in open air, additional protective measures are necessary to isolate the sockets and contact pairs from contamination and moisture. To reduce human involvement in robot operation process and simplify the processes of battery positioning and subsequent recharge, wireless energy transfer systems (WETS) can be used. The most common solutions in this domain are conceptually based on energy transfer between inductively coupled elements and provide for unidirectional energy transfer from the source to the sink.

Development and real-world testing of WETS with planar magnetically coupled coils are presented in [4]. The system shown here, consists of a DC-AC inverter, magnetically coupled coils, rectifier, and switched mode regulator of output power. The circuitry of the transmitting part of the system is implemented as a two-channel E-class receiver. The dimensions of the receiving and the transmitting coils are 13×13 and 21×21 cm, 10 and 5 turns respectively.

WETS can also be used for charging of a robot group, such as m3Pi [5]. The receiving part of the system consists of a rectifier and a step-up DC-DC converter for power adjustment in battery charging process. The transmitted power can be controlled by adjusting the output voltage of the step-down converter.

Wireless charger presented in [6, 7] is intended for charging of an EDLC-capacitor (supercapacitor), which is a power supply for a hybrid bicycle. The transmitting part of this system is a parallel resonant circuit, connected to an alternator. The receiving part contains an uncontrolled rectifier and a DC-DC converter. Load resistance of the system is 50 Ω, outer diameter of the transmitting and receiving coils is 200 mm.

Using unidirectional WETS for power redistribution among the robots is an inefficient solution because the transmitting and receiving units have to be installed on each robot to implement inter-agent power transfer. More practical solution of this task assumes implementation of bidirectional WETS, where each part of the system can be used as a transmitter, as well as a receiver.

An example of WETS is the solution, presented in [8]. In the transmitting part of this system a half-bridge current inverter is used, whereas in the receiving part there is the MOSFET-based rectifier with voltage doubling. Being operated in reverse energy transfer mode, the MOSFET-based rectifier is used as inverter. In case of direct energy transfer from the transmitting part to the receiving one, it acts as an uncontrolled rectifier. To achieve smooth switching of inverter keys by zero-voltage switching values, the duty cycle of the converter is maintained on the 50% level, and transmitting power is controlled via adjustment of operational frequency of the system. To compensate for pulsations on power switches of the transmitting part, an extra capacitor is installed serially with a parallel LC transmitting circuit; thereby an additional serial-parallel resonant circuit is established.

The bidirectional energy transfer system enables to transmit power from one transmitter to several receivers simultaneously [9]. The resonant circuits of each part of energy transfer system have a series-parallel design. The circuits of the system are set to operate on a resonant frequency, and each reversible rectifier operates either in inverter mode, or in rectifier mode, depending on energy transfer direction. The value and direction of energy transfer are defined by opening angle of the power switches of the controlled rectifier. The value and direction of energy flux among several systems are controlled via phase and amplitude modulation of voltage, whereby two these approaches can be used together or separately.

A hybrid bidirectional WETS system is proposed in [10]. The system consists of two pairs of coils, where one pair act as a transmitting part, and another one as a receiver. Both transmitting and receiving parts of the system have two circuits, connected by common wire. One of the two circuits follow the serial pattern, and another one has the serial-parallel pattern. Such a hybrid design provides for usage of LCL and LC circuits to compensate for decrease in the transmitted power flux, caused by axial shear of the receiving and transmitting parts of the system, as the combined output power of both circuits remains approximately constant. The receiving and transmitting resonant circuits are supplied from the half-bridge converter, which acts as a source or as a load, depending on the direction of power flux. The converter operates at the required frequency, and the voltage amplitude generated in the receiving circuit is controlled by phase modulation. When the converter is used as a unidirectional energy transfer system, the device can be used as a rectifier to obtain direct current at output.

The controller for the bidirectional energy transfer system [11] provides for adjustment of transmitted power and can be used both in unidirectional and in bidirectional WETS with one or several loads. Control of amount and direction of the transmitted power is performed using phase shift of control signals and switch opening. The WETS is equipped with a sensor for measurement of voltage and frequency in the receiving and transmitting coils via magnetic field, generated by the transmitting part during operation. The controller compares the measured values with the reference ones. Obtained error values are processed using a PI-controller. The proposed controller alters the operational frequency of the system to control the transmitted power, therefore, the energy transfer system is not always operated in resonant mode, what causes reduction of its efficiency.

The systems with similar power range are also considered in [12, 13], and [14]. Low power wireless system [15] is employed for battery charging of portable devices. In the receiving and transmitting parts of this system serial resonant circuits are used. Also, there is a half-bridge circuit for power transistor switching to provide for bidirectional energy transfer. The receiving and transmitting coils are round and consist of 18 turns each, with internal diameter of 21.7 mm and outer diameter of 32 mm. As axial shears during system operation can occur, and air gap between the coils can increase, the operational frequency adjustment is proposed. The resonant circuit is controlled via frequency modulation.

The authors of [16] developed an original integral circuit, which includes a control system for a bidirectional WETS and implements a system for battery-to-battery energy transfer, with serial topology of the resonant circuit. Because the output current of the charger system gradually decreases, and its maximum value is lower than nominal charging current permissible for the majority of mobile devices, the prototype does not require a control system for adjustment of output voltage or current. To increase the WETS efficiency, direct energy transfer in battery-to-battery mode is employed, bypassing the power supply circuits of the mobile device. Each coil has 4 turns with internal diameter of 19 mm and outer diameter of 33 mm.

Bidirectional WETS can also include a data transfer system, embedded into the energy transfer controller [17]. The design of the proposed WETS is based on a serial resonant circuit with a bidirectional up/down converter. In energy transfer mode, the controlled switches connected in a bridge perform inverter functions in the transmitting part, whereas in the transmitting mode the internal diodes of the MOSFEET transistors act as an uncontrolled rectifier together with the bidirectional DC-DC converter.

To summarize the review of state-of-the-art solutions, the characteristics of some WETS are compared in **Table 1**.

Developed models of considered devices are usually assembled on the basis of half-bridge or bridge inverters, which assume dedicated control system. One of the common downsides of most of them is the need to adjust their operational frequencies depending on mutual layout of the receiving and transmitting parts of the system and actual load, what requires additional equipment. The majority of the bidirectional WETSs are characterized by high levels of transmitted power (greater than 1 kW), as they are intended for electrical vehicles and other industrial appliances. The systems from this range of transmitted power characteristics are redundant for the most autonomous robotic systems. The next common solution is low-power energy transfer systems, developed for various applications in mobile electronics. Their transmitted power is in the range up to 10 W, which is sufficient only for small-size robot in case that there is enough time for battery charging. The systems of moderate transmitted power, intended for use in autonomous robotic devices, are featured primarily by unidirectional systems and are insufficiently covered in research literature.

Table 1

The characteristics of unidirectional and bidirectional systems.

Efficiency [%]	Transmitted power [W]	Frequency [kHz]	Distance between parts of the system [mm]	Reference
Unidirectional wireless charging systems				
75	1.8	140	3	[20]
50	5	6780		[18]
66	5	6780	30	[19]
43	7	40		[5]
72-73	100	1100	50	[6, 7]
70	100	1100	50	
74	69			[4]
77	295			
Bidirectional wireless charging systems				
58.6	1.55	678		[16]
70	2.5	110-205	2	[15]
70	2.5	90-205	2	
60	2.7			[21]
62.5	2.7	6780	23	[22]
85	1000	20	55	[11]
92	1200			[8]
85	1500	20	40	[9]
91	3300	85	120	[10]

Our research is dedicated to development of medium-power bidirectional WETS in the range between 10 W and 100 W, that operates in resonant mode and shows high operational efficiency and transmitted power, irrespective of mutual layout of the receiving and transmitting parts of the system. This contributes to autonomy increase and resource redistribution in swarm autonomous robotic sets, as well as to reducing human involvement into the operation process.

2 Principal Design of a Bidirectional WETS

The developed principal design of a bidirectional WETS consists of several main units (Fig. 1).

The main part of the system is the resonant self-oscillator, that can be operated in synchronous rectifier mode. The energy transfer is performed via electromagnetic inductance through magnetically coupled parallel resonant circuits. The resonant circuit is the frequency-setting component (1) here for the self-oscillator, provided that the overall system is operated in energy transfer mode. The operational frequency of the system is calculated as follows:

$$f = \frac{1}{2\pi\sqrt{LC}}, \tag{1}$$

where L is inductance of the resonant circuit coil, C is capacitance value in the resonant circuit.

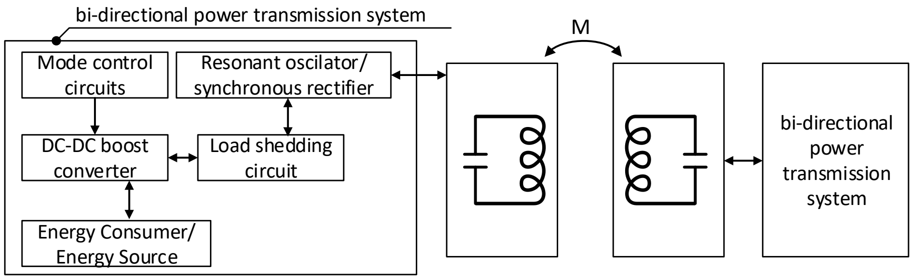


Fig. 1 – *Principal design of a bidirectional WETS system.*

Resonant circuits are identical; therefore, the system is symmetrical about air gap. A DC-DC step-up converter is used here because the EMF induced in the receiving coil will have the lesser amplitude than in the transmitting coil. This is due to the active losses in the resonant circuits and the fact that the air gap has high resistance against the magnetic flux. The EMF amplitude in the transmitted coil is calculated according to (2) [23 – 25]:

$$U_m = \pi V_{dc}, \tag{2}$$

where V_{dc} is power supply voltage.

Using the step-up converter, we can obtain at the output of the receiving system the voltage, equal or higher to that in the power supply of the transmitting system. This feature enables to use the system for redistribution of energy among the autonomous robotic devices with batteries with equal operational voltage, namely in swarm robotics [26].

3 Circuit Solution of the Bidirectional WETS

Circuit solution of the bidirectional WETS (Figs. 1 and 2) is based on the earlier research, where the WETS with coreless coils [27, 28] and synchronous rectifier are described. Also, the losses in synchronous rectifier applied for the receiving part of WETS were calculated [29, 30].

The first part of the circuit includes a self-oscillator which can operate as a synchronous rectifier, and a circuit for smooth load acceptance (Fig. 2).

The self-oscillator is implemented on transistors VT1 and VT2. Its frequency-setting loop is the transmitting/receiving resonant circuit L1C1. The circuit of smooth load acceptance works according to edge delay on triggering of VT3 transistor, the duration of this process is defined by C3 and R6 values and VT3 parameters.

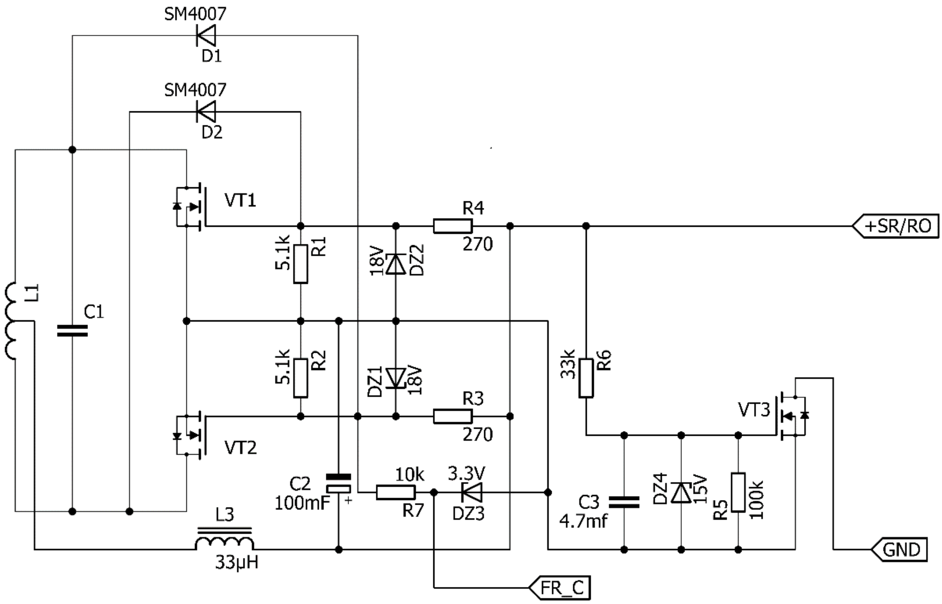


Fig. 2 – *Principal circuit diagram of the bidirectional WETS, part 1.*

The second part of the principal circuit is presented in Fig. 3.

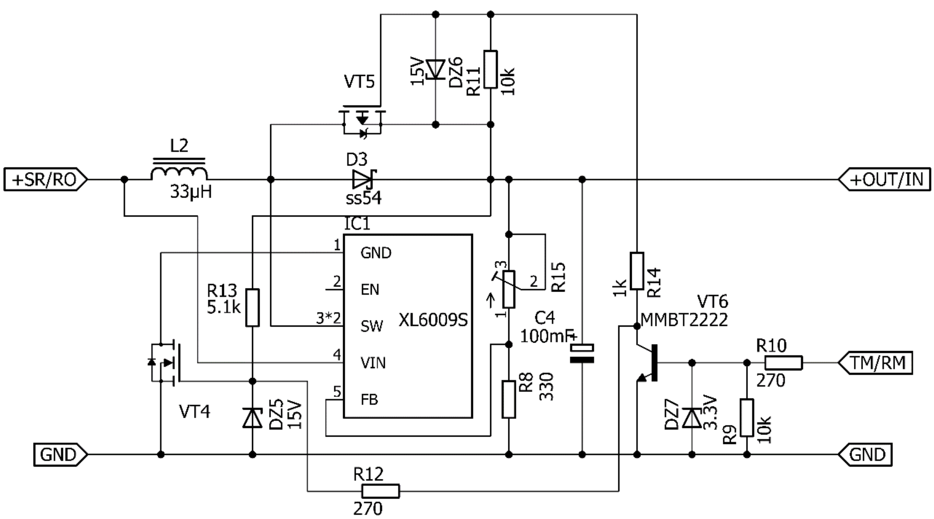


Fig. 3 – *Principal circuit diagram of the bidirectional WETS, part 2.*

The parts of the principal circuit diagram of the bidirectional WETS are connected in the points «+SR/RO» and «GND». The second part of the principal diagram includes the step-up DC-DC converter based on the XL6009 circuit, and the switching circuits based on transistors VT4 and VT5.

4 WETS Operation in Energy Transfer Mode

Switching the system into energy transfer mode is performed by supplying high signal into the circuit «TM/RM»; thereby the power supply is connected to the system between the points «+OUT/IN» and «GND». Prior to this we have to ensure that there is no rectangular-shaped signal in the frequency control point «FR_C». If the rectangular-shaped signal of the operating frequency is detected, it means that the system works in receiver mode, and switching into transmitting mode is prohibited. High signal in the circuit «TM/RM» is supplied through the current-limiting resistor R10 to the base of the transistor VT6 and triggers it. Triggering of VT6 causes locking of VT4 and triggering of VT5. Locking of VT4 shuts down the internal circuits of DC-DC converter, and VT5 bypasses the diode D3. Therefore, the «+» of power supply is connected to the point «+SR/RO». After the supply voltage has been initiated between the points «+SR/RO» and «GND», the current begins to flow to the VT3 gate triggering it and bypassing its internal diode; it flows as well to the gates of the field MOSFEET transistors VT1 and VT2 charging the gate capacities through resistors R3 and R4, what triggers the self-oscillator. To ensure reliable triggering of transistors and decrease of dynamical losses, it was empirically revealed that calculation of the necessary value of the gate resistors $R_{3,4}$ could be performed according to (3):

$$R_{3,4} = \frac{1}{30 C_g f}, \tag{3}$$

where C_g is the gate capacity of transistors in use.

The formula (3) is obtained based on the premise that the gate capacity charging should occur within 1/10 period. The self-oscillator operation principle is more thoroughly described in [27]. The loss calculation is performed as follows:

$$P_{LC} = \sqrt{2} I_m^2 (R_l + E_{sr}), \tag{4}$$

where R_l is effective resistance of the loop coil, and E_{sr} is equivalent series resistance of the loop capacitor. The methodology for calculation of the losses in the self-oscillator in energy transfer mode is presented in [29].

5 WETS Operation in Energy Reception Mode

Switching the system into energy transfer mode is performed by supplying low signal into the circuit «TM/RM». In this case the VT5 transistor is locked, and its internal diode is connected in parallel with D3. The VT4 is triggered, as the necessary voltage level arises in the «+SR/RO» point, and the current flows through the throttle of the step-up DC-DC converter and the D3 diode. After triggering the bidirectional WETS, the EMF is induced in the coil L1, and the electrolytic capacity C2 begins to charge through the internal diodes of the MOSFEET transistors. As in the C2 capacity the minimum voltage required to open the MOSFEET channel of the transistor (VT1, VT2) arises, the transistor triggers and bypasses the internal diode through the open channel, whose resistance is much lower than the dynamic resistance of the diode. To exclude the through current in the transistors VT1 and VT2, the diodes D1 and D2 are used. The diode D1 locks the VT2 transistor on the opposite part of the bridge, as long as the transistor remains open. The R1 and R2 resistors are intended for discharge of gate capacity and transistor locking if the EMF in the receiving coil is absent. The circuits DZ1-R3 and DZ2-R4 act as a parametric stabilizer, intended to limit voltage in the gate-drain circuit of the transistor. The gate capacity is also charged through the resistors R3 and R4 by transistor triggering. The C2 and L3 form the rectifier filter. The C2 capacity is needed to store energy required for power switch control. When the system is operated in energy reception mode, the voltage on the capacitor C2 is calculated according to (5):

$$U_m = k_{cв} \frac{\pi V_{dc}}{\sqrt{2}}, \tag{5}$$

where $k_{cв}$ is coupling coefficient between the inductively coupled receiving and transmitting coils.

After the rectified voltage occurs in the point «+SR/RO», the capacitor C3, as well as parallelly connected gate capacitance of the transistor VT3 begin to charge through the resistor R6. The transistor VT3 triggers smoothly, connecting the DC-DC converter to the resonant self-oscillator, which operates in the synchronous rectifier mode. Then the transistor VT4 triggers and the step-up DC-DC converter starts. Then an output voltage occurs at the output of the bidirectional wireless energy transfer system in the point «+OUT/IN», whose value is set by the variable resistor R15.

6 Determination of Parameters of Transmitting and Receiving Coils

Efficiency of WETS performance significantly depends on correct selection of parameters for loop coils of the receiving and transmitting units. The WETS provide for integration of various types of coils in the resonant circuit. The most common ones are planar helical coils due to their high diameter-thickness ratio, what positively influences their coupling coefficient. Planar helical loop coil (Fig. 4) has the following relevant design parameters: number of turns *N*, coil pitch *d*, and initial turn radius *r*.

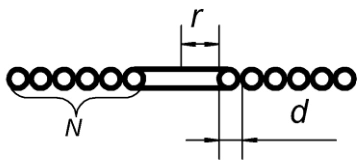


Fig. 4 – *Design parameters of the planar helical coil.*

Efficiency of energy transfer and transmitted power are influenced by the coupling coefficient between the receiving and transmitting coils, which depends on their parameters and mutual layout. Increase of flux inducing EMF in the receiving coil and consequently the increase of coupling coefficient can be achieved via improvement of mutual coil layout or via boosting the flux generated by the transmitting coil. According to the Biot–Savart–Laplace law, the value of the magnetic inductance vector generated by elementary current in every point of space is proportional to this current. The magnetic flux Φ is proportional to magnetic inductance value B, which is in turn proportional to current I in the wire. This leads us to the conclusion that $\Phi \sim I$, and the inductance value L acts as proportionality coefficient here. Hence, to achieve maximum transmitted power and energy transfer distance, the maximum current value in the loop coil should be maintained.

Initial parameters for calculation of coil number N by specified initial coil radius and coil pitch are: U_m – amplitude of alternating voltage, supplied to the resonant circuit, f – operational frequency of the loop coil, r – initial turn radius, d – coil pitch, ρ – specific resistance of the conductor stuff, S – wire cross-section, and j – permissible current density in the wire.

Electrical parameters of the coil are inductance and effective resistance. The value of effective resistance of the homogeneous conductor with uniform cross-section without accounting for skin effect is calculated according to (6):

$$R_{con} = \frac{\rho l_{con}}{S}, \tag{6}$$

where ρ is specific resistance of the conductor stuff, l_{con} is conductor length, and S is cross-section area of the conductor.

For subsequent calculations, the resistance of the coil conductor with round cross-section (6) is applicable, provided that $D/\delta < 2$ [31], where D is wire diameter and δ is thickness of conductive layer. If this inequation does not hold, other equations applicable for wire resistance calculation accounting for skin effect must be used, e.g., ones proposed in [31, 32].

The length of the conductor of the helical planar coil is calculated according to (7):

$$l_{con} = 2\pi(Nr + d(0.5N^2 - 0.5N)). \tag{7}$$

Using (6) and (7), we can calculate the effective resistance of the conductor, depending on the number of turns of the helical coil.

Calculation of inductance value of a planar helical coil can be performed with decent accuracy using the empirical Wheeler formula [33, 34], normalized to metric units and specified geometrical parameters of the coil (8):

$$L = \frac{\mu_0}{4\pi}\frac{1000}{2.54}\frac{(2r + Nd)^2 N^2}{32r + 60Nd}, \tag{8}$$

where μ_0 is magnetic constant.

Magnetic flux generated by the transmitting coil can be increased by increasing the amperage of the current in this coil or its inductance value. The parameters L and I_m of the coil included into the LC loop operating at the resonant frequency are related according to the (9):

$$I_m = \frac{U_m}{\sqrt{(2\pi f L)^2 + R_{con}{}^2}}. \tag{9}$$

We use crest value of the current (9) to calculate the losses caused by effective resistance P_d (10):

$$P_d = \left(\frac{I_m}{\sqrt{2}}\right)^2 R_{con}. \tag{10}$$

For coil comparison and turn number selection, we introduce a parameter that could be correlated with the loss parameter P_d. It characterizes the amount of magnetic field energy being accumulated in the loop coil per unit of time (11):

$$P_m = 2Lf\left(\frac{I_m}{\sqrt{2}}\right)^2. \tag{11}$$

To illustrate the difference between loop coils with various number of windings more clearly, the γ parameter is used. It represents the ratio of magnetic field energy being accumulated in the coil per unit of time to losses in it:

$$\gamma = \frac{P_m}{P_d}. \tag{12}$$

Values of γ less than 1 show that the losses in the coil are greater than magnetic field energy accumulated in it per unit of time. With increase of the windings number, if voltage applied to the parallel LC circuit remains constant, the losses in the coil decrease. This is because the coil inductance and effective resistance grow, and, therefore, the idle current value decreases. The γ parameter also increases, because with the greater number of windings the reactance grows more actively than the effective resistance.

Table 2 shows the initial parameters for calculation and selection of the optimum number of turns for receiving and transmitting coils of low-power WETS to be employed within a swarm robotic system for energy redistribution among swarm agents [35, 26].

Table 2
Initial parameters for calculation.

Parameter	U_m [V]	R [mm]	D [mm]	P [(Ω·mm²)/m]	S [mm²]	j^p [A/mm²]
Value	26.37	19	0.74	0.0171	0.374	6.5

When using in the transmitting part of WETS a self-oscillator whose frequency-setting loop is the transmitting LC loop, more convenient approach consists in selection of an optimum coil with fixed capacitance of the resonant circuit and variable operation frequency which depends on inductance of loop coil. As a limiting condition the permissible value of current in the conductor was set. This parameter is calculated according to permissible current density j and specified conductor cross-section S:

$$I_m^p = j^p S\,. \tag{13}$$

In the **Table 3**, the calculated parameters for the resonant circuit capacitance are given: C = 0.47 µF.

Table 3
Calculation results by f = var, C = const.

N [turn]	f [kHz]	I [A]	P_d [W]	P_m [W]	γ	N [turn]	f [kHz]	I [A]	P_d [W]	P_m [W]	γ
1	771.4	42.4	9.8	252	25.6	11	76.3	4.2	1.2	24.9	19.6
2	391.1	21.5	5.1	127.8	24.7	12	70.2	3.8	1.1	22.9	19.2
3	263.9	14.5	3.5	86.2	24.0	13	65.0	3.5	1.1	21.2	18.9
4	200.1	11.0	2.8	65.4	23.3	14	60.6	3.3	1	19.8	18.5
5	161.6	8.9	2.3	52.8	22.6	15	56.7	3.1	1	18.5	18.2
6	135.8	7.4	2.0	44.4	22.0	16	53.2	2.9	1	17.4	17.9
7	117.3	6.4	1.7	38.3	21.5	17	50.2	2.7	0.9	16.4	17.6
8	103.3	5.6	1.6	33.7	21.0	18	47.5	2.6	0.9	15.5	17.3
9	92.4	5	1.4	30.1	20.5	19	45.0	2.5	0.9	14.7	17.
10	83.5	4.6	1.3	27.3	20.1	20	42.8	2.3	0.8	14	16.8

As per (13), for the specified initial parameters the permissible current value for the conductor I_m^p is 2.43 A. Consequently, possible choices here are the coils with number of turns 19 and 20. According to the criterion of maximization of magnetic flux generated by the transmitting coil, the best choice is the 19-turn coil. Loop coil with 19 turns has effective current value 2.5 A, what is greater than the calculated value I_m^p by 2,8%; hence this choice is acceptable. Considering the specified current constraint, the 19-turn coil is the best one.

7 Experimental Testing of the Developed WETS Solution

For empirical test of the developed circuit solution, the assembled experimental prototypes of WETS were mounted on the mobile robotic platforms (Fig. 5), and a series of experiments was performed.

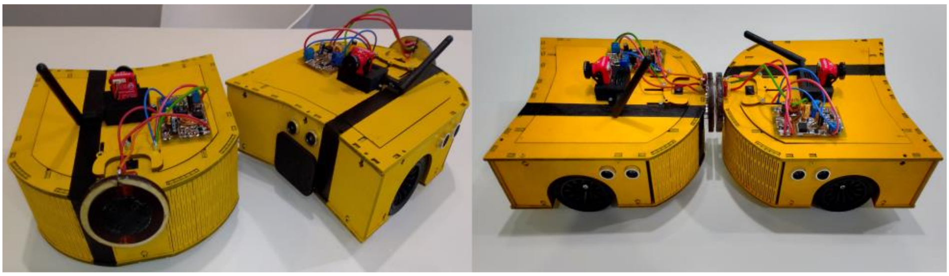


Fig. 5 – *Experimental prototypes of the developed system, mounted on the mobile autonomous platforms.*

The coils of the resonant circuit have 19 tap-off windings each and consist of 0.69 mm thick wires. Using the methodology proposed in [31], the conductor resistance accounting for skin effect was calculated. With operational frequency of 45 kHz, the skin effect leads to increase of the conductor resistance in 19 windings copper coil with wire diameter of 0.69 mm by 3.12%, what is negligible in prototype, used for approbation of the proposed design and circuit solution. As resonant circuit capacitors the film MPP capacitors with low ESR value were used.

During the first experiment, the following dependency of efficiency from transmitted power was obtained in the resonant circuit of WETS with fixed capacitance C = 0.47 µF (Fig. 6).

Maximum efficiency of the system reaches 59.91% by transmitted power of 10.09 W. Maximum transmitted power is 15.4 W.

During the second experiment, the maximum transmitted power of WETS was measured by variable distance between the receiving and transmitting coils (Fig. 7).

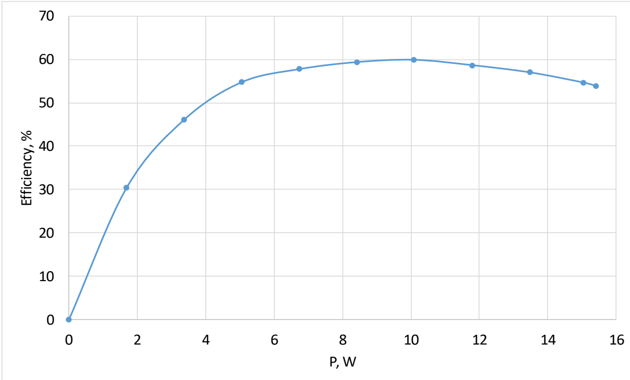


Fig. 6 – *Dependency of the system efficiency from transmitted power.*

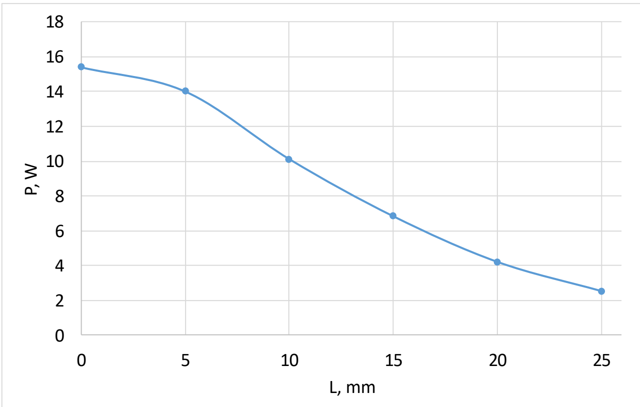


Fig. 7 – *Dependency of the maximum transmitted power in the system from the energy transfer distance.*

When the gap between the coils increases, the mutual inductance decreases, thereby the transmitted power decreases too. The curve follows the descending pattern; the maximum value of transmitted power is reached when the receiving and transmitting parts of the system are in close proximity to each other. By the gap of 25 mm the transmitted power drops by 6.1 times and makes up 2.5 W.

Fig. 8 shows the dependency of the WETS performance efficiency from the distance between the receiving and transmitting coils by maximum transmitted power.

As follows from the curve in the Fig. 8, the maximum efficiency value by maximum transmitted power for the specified distance reaches 56.58 %, when the gap between the receiving and transmitting parts is 5 mm. This is because of comparatively well consistency between the load resistance with WETS for these values of transmitted power and distance.

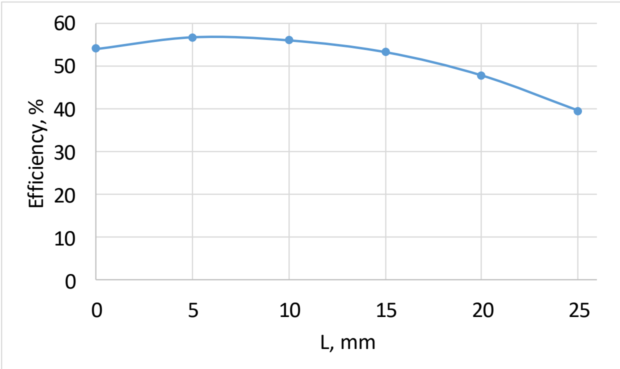


Fig. 8 – *Dependency of the system efficiency from the energy transfer distance.*

For system performance mode with maximum efficiency of 59.91% and transmitted power 10.09 W, the power loss calculation was performed based on the parameters of the components utilized in the prototype. The calculation results are given in the **Table 4**.

Table 4

Calculation results power losses in the system.

Element	Transmitting part, W	Receiving part, W
LC-circuit	0.90	0.90
Leakage field	1.68	
resonant self-oscillator / synchronous rectifier	0.78	0.62
C2, C4		0.35
VT3, VT4, VT5	0.16	0.16
L2	0.25	0.25
D3		0.32
XL6009		0.22
Sum of power losses	3.77	2.82
Total losses	6.59	

For calculation of power losses, the value of losses over the leakage fields was taken to be equal 10% of the transmitted power. The consumed power of the transmitting part of the system in this operational mode is 16.84 W. The power losses in the receiving part of the system can be significantly reduced with the aid of a more efficient DC-DC boost converter.

In the next experiment, the system prototypes were connected to Li-ion accumulator batteries of robotic platforms with operational voltage 7.4 V and capacitance 2500 mA/h. One of the prototypes was operated in transmitting mode, and another one in receiving mode. Fig. 9 features an oscillography of the voltage form on the transmitting and receiving coils, when the accumulator battery connected to the receiving prototype is charged, and the value of the output current is minimal, i.e., the system operates without load.

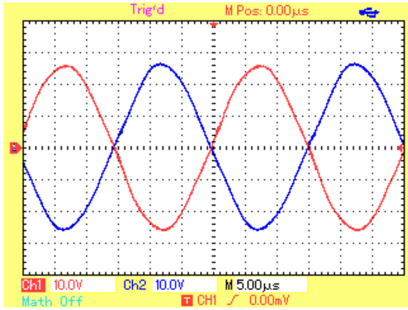
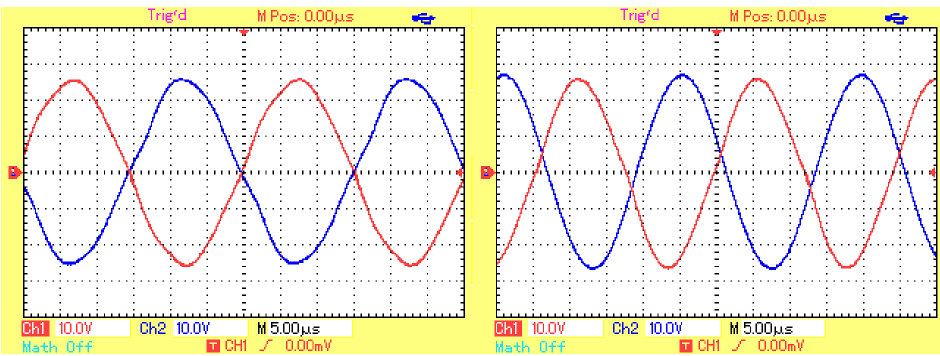


Fig. 9 – *Voltage form on the transmitting and receiving coils by charged accumulator battery.*

In Figs. 9 – 11 the voltage curve of the transmitting coil is shown in red, whereas the same curve of the receiving coil is shown in blue. The voltage curves on the receiving and transmitting coils have sinusoidal shapes with minor distortions and similar amplitude. The curve phase is shifted by 180 degrees, as the coils have equal winding path and are installed counter-currently to each other.

Fig. 10 shows voltage curves by battery charge current of 0.5 A and variable distance between the coils.

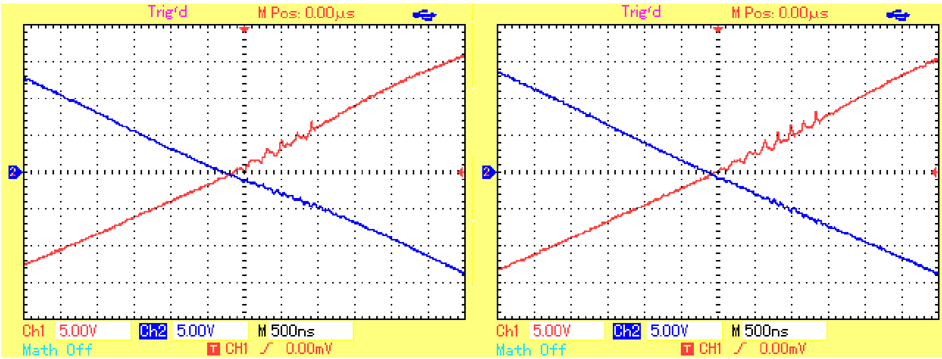


(a) (b)

Fig. 10 – *Voltage form on the transmitting and receiving coils during accumulator battery charging:*
(a) – *when the coils are in close proximity;*
(b) – *when the gap between coils is 20 mm wide.*

When the system is operated under load, sinusoidal form of voltage curve preserves, but curve form distortions are visible. Increasing the distance between coils up to 20 mm, a phase shift between voltage values occurs, thereby the distortions of curves disappear almost completely.

Scaling-up the curves on the oscillography records enabled to reveal minor distortions in voltage form at the transmitting coil, as shown in Fig. 11.



(a) (b)

Fig. 11 – *Transition process during self-oscillator transistor triggering:* (a) – *without load;* (b) – *with load current* 0.5 A.

Transition process caused by triggering of self-oscillator transistor switches is essentially vibrational one. The increase of load current in the system causes increase of duration and amplitude of oscillations. Due to this transition process, the losses on transistors grow. This can negatively influence the overall efficiency of the system in case of high levels of transmitted power. This issue can be partially rectified by decreasing the amplitude and duration of the transition process via decrease of resistance values on gate resistors R3 and R4.

8 Specifics of the Developed System

In contrast to other research works, considered above, this paper thoroughly details the circuitry and operating principle of bidirectional WETS. The majority of presented papers are aimed to develop control systems and methods and do not contain detailed description of structure, circuitry and operational principles of the system. The proposed WETS contain a power unit, assembled of bridge and half-bridge inverters with a dedicated control system, or as fully integrated solutions.

The most of research prototypes of wireless power transmission systems presented in scientific papers are equipped at output with only a rectifier; hence, their reference efficiency should be higher than in the presented prototype. It is noteworthy, that the efficiency of our system is comparable with the efficiency of the alternative solutions, considered here. For example, the systems of the Qi and PMA standards are unidirectional, thereby having efficiency in the range of 60-70% [36], whereas the efficiency of the systems of the A4WP standard is about 55%.

The advantages of the developed bidirectional WETS compared to similar solutions are the integrated system, intended to control the energy transmission process, and power unit of the system, which does not require a dedicated control system, as it is assembled as a resonant self-oscillator. Using resonant self-oscillators and identical circuits in receiving and transmitting parts of the system enables consistent system operation in resonant mode and obviates the need in operational frequency adjustment, irrespective to the gap between coils and their displacement distances. This provides for increase of efficiency and transmitted power of the system. This feature enables to use the system in case of low accuracy of alignment between the receiving and transmitting coil, what is particularly relevant in autonomous robotics.

The prototype presented in this paper has the maximum output power less than 20 W and efficiency of about 60%. In wireless power transmission systems, the efficiency increases with the power. This is explained by the fact that power losses in components and resonant circuits increase to a minor extent, compared to the transmitted power of the system. We experimented with a unidirectional system, based on the similar circuit solutions [27, 37]. Load power was limited by a secondary power source in the transmitting part of the system and amounted to 133.45 W, whereas the maximum efficiency level was 76.47%. It should be noted that these parameters were achieved in a prototype system, equipped with magnetic field shielding, which significantly impairs the parameters of efficiency and transmitted power. In many research papers the parameters of efficiency and transmitted power are given without regard to the shielding factor.

To increase the output power of the system it is required to replace a step-up DC-DC converter with an alternative device with suitable parameters. In addition, suitable transistors and other passive components have to be selected. To increase the system power, alternative transmitting and receiving circuits have to be calculated and applied. Nevertheless, the structure and principal circuit solutions proposed in this paper remain the same.

9 Conclusion

This paper presents structure and principal circuit solution of a bidirectional WETS based on the self-oscillator with a parallel resonant circuit. The operational principle of the developed system in receiving and transmitting mode is described. The coil parameters are calculated, and optimal turn number values are chosen for fixed capacitance of the resonant circuit, according to the criterion of maximum transmitted power with respect to limited permissible current in the conductor of the coil.

Experimental test of operational robustness of the proposed system is performed with the resonant circuit coils, of 19 turns each, and oscillography records for voltage forms on receiving and transmitting coils are obtained. The voltage form on both coils follows a sinusoidal pattern with minor distortions. Graphical dependencies are established for system efficiency and transmitted power from the distance between the receiving and transmitting parts of the system. Maximum efficiency of system performance is achieved by transmitted power of 10.09 W and makes up 59,91%. The transmitted power at distance of 5 mm was 14.01 W by efficiency of 56.68%. The maximum value of transmitted power (15.4 W) is achieved when the transmitting and receiving parts of the system are in close proximity to each other. By increase of distance between the parts of the system the transmitted power decreases; at distance of 25 mm, it equals to 2.5 W.

The advantage of the presented bidirectional WETS is that it enables to obtain the voltage value at the output of the receiving part equal or greater than the voltage power supply of the transmitting part. The developed solution can be employed for energy resource redistribution among the autonomous agents in robotic systems, supplied from the accumulator batteries with equal or different operational voltage. Also, it can be applied as a power supply for autonomous sensors in cyber-physical systems [38, 39].

Further research will be aimed to development of algorithms of positioning for robotic systems equipped with the bidirectional WETS considering the constraints of the developed system.

10 References

[1] N. Pavliuk, A. Saveliev, E. Cherskikh, D. Pykhov: Formation of Modular Structures with Mobile Autonomous Reconfigurable System, Proceedings of the 14th International Conference on Electromechanics and Robotics “Zavalishin's Readings”, Kursk, Russia, April 2019, pp. 383 – 395.

[2] V. Kh. Pshikhopov, M. Yu. Medvedev: Group Control of Autonomous Robots Motion in Uncertain Environment via Unstable Modes, Informatics and Automation (SPIIRAS Proceedings), Vol. 5, No. 60, October 2018, pp. 39 – 63.

[3] I. Bychkov, M. Kenzin, N. Maksimkin: Two-Level Evolutionary Approach to Persistent Surveillance for Multiple Underwater Vehicles with Energy Constraints, Informatics and Automation (SPIIRAS Proceedings), Vol. 18, No. 2, April 2019, pp. 267 – 301.

[4] Z.N. Low, R.A. Chinga, R. Tseng, J. Lin: Design and Test of a High-Power High-Efficiency Loosely Coupled Planar Wireless Power Transfer System, IEEE Transactions on Industrial Electronics, Vol. 56, No. 5, May 2009, pp. 1801 – 1812.

[5] N. Hasan, I. Cocar, T. Amely, H. Wang, R. Zane, Z. Pantic, C. Bodine: A Practical Implementation of Wireless Power Transfer Systems for Socially Interactive Robots,

Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, September 2015, pp. 4935 – 4942.

[6] J.- I. Itoh, K. Noguchi, K. Orikawa: System Design of Electric Assisted Bicycle Using EDLCs and Wireless Charger, Proceedings of the International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA), Hiroshima, Japan, May 2014, pp. 2277 – 2284.

[7] K. Noguchi, K. Orikawa, J.- I. Itoh: System Design of Electric Assisted Bicycle Using the EDLCs as Power Source, Proceedings of the Japan-Korea Joint Technical Workshop on Semiconductor Power Converter, Nagoya, Japan, October 2013, pp. 1 – 2.

[8] S. Samanta, A.K. Rathore, D.J. Thrimawithana: Bidirectional Current-Fed Half-Bridge (C) (LC)–(LC) Configuration for Inductive Wireless Power Transfer System, IEEE Transactions on Industry Applications, Vol. 53, No. 4, July 2017, pp. 4053 – 4062.

[9] U.K. Madawala, D.J. Thrimawithana: A Bidirectional Inductive Power Interface for Electric Vehicles in V2G Systems, IEEE Transactions on Industrial Electronics, Vol. 58, No. 10, October 2011, pp. 4789 – 4796.

[10] L. Zhao, D. J. Thrimawithana, U.K. Madawala: Hybrid Bidirectional Wireless EV Charging System Tolerant to Pad Misalignment, IEEE Transactions on Industrial Electronics, Vol. 64, No. 9, September 2017, pp. 7079 – 7086.

[11] U.K. Madawala, M. Neath, D.J. Thrimawithana: A Power-Frequency Controller for Bidirectional Inductive Power Transfer Systems, IEEE Transactions on Industrial Electronics, Vol. 60, No. 1, January 2013, pp. 310 – 317.

[12] M.J. Neath, A.K. Swain, U.K. Madawala, D.J. Thrimawithana, D.M. Vilathgamuwa: Controller Synthesis of a Bidirectional Inductive Power Interface for Electric Vehicles, Proceedings of the 3rd IEEE International Conference on Sustainable Energy Technologies (ICSET), Kathmandu, Nepal, September 2012, pp. 60 – 65.

[13] D.J. Thrimawithana, U.K. Madawala: A Contactless Bi-directional Power Interface for Plug-In Hybrid Vehicles, Proceedings of the IEEE Vehicle Power and Propulsion Conference, Dearborn, MI, USA, September 2009, pp. 396 – 401.

[14] R. Miskiewicz, A. Moradewicz: Contactless Power Interface for Plug-In Electric Vehicles in V2G Systems, Bulletin of the Polish Academy of Sciences- Technical Sciences, Vol. 59, No. 4, December 2011, pp. 561 – 568.

[15] S. Miura, K. Nishijima, T. Nabeshima: Bi-directional Wireless Charging between Portable Devices, Proceedings of the International Conference on Renewable Energy Research and Applications (ICRERA), Madrid, Spain, October 2013, pp. 775 – 778.

[16] M. Huang, Y. Lu, R.P. Martins: A Reconfigurable Bidirectional Wireless Power Transceiver for Battery-to-Battery Wireless Charging, IEEE Transactions on Power Electronics, Vol. 34, No. 8, August 2019, pp. 7745 – 7753.

[17] H. Wu, B. Gu, X. Wang, V. Pickert, B. Ji: Design and Control of a Bidirectional Wireless Charging System Using GaN Devices, Proceedings of the IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, March 2019, pp. 864 – 869.

[18] P. Dubal: Rezence – Wireless Charging Standard based on Magnetic Resonance, International Journal of Advanced Research in Computer and Communication Engineering, Vol. 4, No. 12, December 2015, pp. 198 – 200.

[19] P.S. Riehl, A. Satyamoorthy, H. Akram, Y.- C. Yen, J.- C. Yang, B. Juan, C.- M. Lee, F.- C. Lin, V. Muratov, W. Plumb, P.F. Tustin: Wireless Power Systems for Mobile Devices Supporting Inductive and Resonant Operating Modes, IEEE Transactions on Microwave Theory and Techniques, Vol. 63, No. 3, March 2015, pp. 780 – 790.

[20] A. Berger, M. Agostinelli, S. Vesti, J.A. Oliver, J.A. Cobos, M. Huemer: A Wireless Charging System Applying Phase-Shift and Amplitude Control to Maximize Efficiency and Extractable Power, IEEE Transactions on Power Electronics, Vol. 30, No. 11, November 2015, pp. 6338−6348.

[21] Y. Lu, F. Mao, R.P. Martins: Bi-directional Battery-to-Battery Wireless Charging Enabled by Reconfigurable Wireless Power Transceivers, Proceedings of the IEEE International Conference on Electron Devices and Solid State Circuits (EDSSC), Shenzhen, China, June 2018, pp. 1−2.

[22] F. Mao, Y. Lu, U. Seng-Pan, R. P. Martins: A Reconfigurable Cross-Connected Wireless-Power Transceiver for Bidirectional Device-to-Device Charging with 78.1% Total Efficiency, Proceedings of the IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, USA, February 2018, pp. 140−142.

[23] A. Abdolkhani, A.P. Hu, J. Tian: Autonomous Polyphase Current-Fed Push-Pull Resonant Converter based on Ring Coupled Oscillators, Journal of Emerging and Selected Topics in Power Electronics, Vol. 3, No. 2, June 2015, pp. 568−576.

[24] A. Abdolkhani, A.P. Hu: Improved Autonomous Current-Fed Push-Pull Resonant Inverter, IET Power Electronics, Vol. 7, No. 8, August 2014, pp. 2103−2110.

[25] A.P. Hu, P. Si: A Low Cost Portable Car Heater based on a Novel Current-Fed Push-Pull Inverter, Proceedings of the Australasian Universities Power Engineering Conference (AUPEC 2004), Brisbane, Australia, September 2004, pp. 1−5.

[26] K.D. Krestovnikov, E.O. Cherskikh, A. Ronzhin: Mathematical Model of a Swarm Robotic System with Wireless Bi-directional Energy Transfer, Edited by A.G. Kravets, Robotics: Industry 4.0 Issues & New Intelligent Control Paradigms, Studies in Systems, Decision and Control, Springer, Cham, 2020, pp. 13−23.

[27] K.D. Krestovnikov, E.O. Cherskikh, P. Smirnov: Wireless Power Transmission System Based on Coreless Coils for Resource Reallocation within Robot Group, Proceedings of the International Conference on Interactive Collaborative Robotics, Istanbul, Turkey, August 2019, pp. 193−203.

[28] K.D. Krestovnikov, E.O. Cherskikh, A.R. Shabanova: Circuit Designs and Engineering Solutions based on Synchronous Rectifier for Wireless Energy Transfer System, Modeling, Optimization and Information Technology, Vol. 7, No. 4, 2019, pp.11−12.

[29] K. Krestovnikov, E. Cherskikh, N. Pavliuk: Concept of a Synchronous Rectifier for Wireless Power Transfer System, Proceedings of the 18th International Conference on Smart Technologies (EUROCON 2019), Novi Sad, Serbia, July 2019, pp. 1−5.

[30] K. Krestovnikov, A. Saveliev, A. Shabanova, I. Vatamaniuk: Comparative Study of Synchronous and Non-Synchronous Rectifiers for Use in the Receiving Part of a Wireless Charging System, Proceedings of the 14th International Conference on Electromechanics and Robotics "Zavalishin's Readings", Kursk, Russia, April 2019, pp. 675−685.

[31] H. Meinke, F.W. Gundlach: Taschenbuch der Hochfrequenztechnik, Edited by K. Lange, K.- H. Löcherer, Springer, Berlin, 1986.

[32] H.A. Wheeler: Formulas for the Skin Effect, Proceedings of the IRE, Vol. 30, No. 9, September 1942, pp. 412−424.

[33] A.C.M. de Queiroz: Mutual Inductance and Inductance Calculations by Maxwell's Method, Home page of Dr. Antonio Carlos M. de Queiroz, March 2003, pp. 1−6.

[34] H.A. Wheeler: Simple Inductance Formulas for Radio Coils, Proceedings of the Institute of Radio Engineers, Vol. 16, No. 10, October 1928, pp. 1398−1400.

[35] Krestovnikov K., Shabanova A., Kovalev A. A mathematical model of a swarm robotic system with wireless two-way energy transfer // «Trudy NIIR» magazine. 2019. (In Russian)

[36] J.T. Hwang, D.S. Lee, J.H. Lee, S.M. Park, K.W. Jin, M.J. Ko, H.I. Shin, S.O. Jeon, D.H. Kim, J. Rhee: 21.8 An All-in-One (Qi, PMA and A4WP) 2.5W Fully Integrated Wireless Battery Charger IC for Wearable Applications, Proceedings of the IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, USA, January 2016, pp. 378 – 380.

[37] K. Krestovnikov, A. Bykov, A. Erashov: Structure and Circuit Solution of a Wireless Power Transfer System for Application in Mobile ARV, Robotics and Technical Cybernetics, 2021, In press.

[38] I.V. Vatamaniuk, R.N. Yakovlev: Algorithmic Model of a Distributed Corporate Notification System in Context of a Corporate Cyber-Physical System, Modeling, Optimization and Information Technology, Vol. 7, No. 4, 2019, pp. 32 – 33.

[39] I.V. Vatamaniuk, R.N. Yakovlev: Generalized Theoretical Models of Cyberphysical Systems, Proceedings of the Southwest State University, Vol. 23, No. 6, 2019, pp. 161 – 175.