



RIGA TECHNICAL
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Rodions Saltanovs

INCREASED EFFICIENCY OF WIRELESS ENERGY TRANSFER TO VEHICLE SYSTEM

Summary of the Doctoral Thesis



RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering
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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Rodions Saltanovs (signature)

Date:

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 5 Chapters; Conclusions; 108 figures; 9 tables; 3 appendices; the total number of pages is 165, including appendices. The Bibliography contains 43 titles.

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1. INTRODUCTION

1.1. Topicality

Every year, due to the increase in energy prices, there is a search for alternative energy sources, methods and mechanisms for converting and storing energy.

One of the most widespread and efficient types of energy is electrical [1]. Its advantages are relative cheapness, ease of transmission, storage and conversion into other types of energy.

As a result, vehicles with electric propulsion systems installed in tandem with internal combustion engines are becoming increasingly popular [2]. Various systems are also being implemented to save fuel and reduce exhaust gas emissions by turning off the internal combustion engine while parked at traffic lights or providing communication with the surrounding infrastructure (traffic lights, nearby cars) to calculate the optimal mode and speed [3]. Also, vehicles are being developed that have only an electric motor as the only means of propulsion [4].

The advantages of electric transport are the reduction in energy costs and engine repairs, general reduction in the level of pollution, as well as the pollution transfer to energy generation sites and the ability to use alternative sources of electrical energy.

With the current global policy governing the reduction of emissions of harmful gases into the atmosphere, one of the state-subsidized areas is the development of public vehicles using hybrid or all-electric power sources [5].

The main problem with such vehicles is the limited longevity of these energy sources. The lithium-ion battery has a lifespan of 500 to 2500 charge–discharge cycles.

According to a study by the German Institute for Power Electronics and Electric Drive (ISEA) [6], a city bus with a daily mileage of 300 km and operating more than 5000 hours per year, will have about 16 000 complete recharge cycles over 15 years.

Compared to a private car, with a daily mileage of 20 km to 80 km and operating 400 hours per year, only 2250 complete battery charging cycles will occur in 15 years. Based on this data the resource of the lithium-ion battery for a private passenger car will be enough for the estimated resource of the vehicle in 15 years; in turn, for the bus 7 sets of expensive batteries will have to be replaced within 15 years.

In turn, more frequent replacement of batteries will entail a need to increase the production of batteries, the consumption of expensive materials such as copper and lithium, and their disposal. As a result, the main advantages of electric transport – environmental friendliness and economy – will come down to the level of a conventional vehicles with internal combustion engines, if not worse.

One of the most acute problems of vehicles using electric batteries as a power source is the low mileage on a single charge – the average maximum distance is 130 km. The absolute leader in this situation is the Tesla Model S car with a maximum mileage of 360 km, which is also not a great distance for intercity trips [7]. As a result, a large number of European families who have already purchased electric vehicles are in no hurry to part with their

internal combustion cars. A possible solution to the problem of the short driving range is an increase in the size of batteries, which will affect the energy consumption per kilometre, as well as the cost of the vehicle and its maintenance. A logical decision to create “filling stations” at which, for a certain fee, a quick-detachable battery pack could be replaced is difficult to implement – there are many manufacturers with many proprietary standards for cell blocks.

Perhaps the most user-friendly solution would be to develop an “electric road” infrastructure to provide power to vehicles moving along them. This solution would reduce the required size of power elements and increase the maximum distance that an electric vehicle could travel [1], [2]. The purpose of this work is to find solutions to create a workable prototype of the electrified mains.

According to the author, the most promising method of wireless energy transmission for vehicles in motion is inductive-resonant energy transmission [1], [2]. The most common designs of the receiving and transmitting modules of the inductive-resonant wireless power transmission system are ferrite cores with coils wound around them. In this work, the author sets himself the task of researching the features of the wireless power transmission using these coils in order to answer the question about the possibility and features of the use of the inductive-resonant method of energy transmission for building the infrastructure of electric roads.

Since the coils of an inductive-resonant wireless power transmission system are a pair of inductively coupled oscillatory circuits, the author suggests that hardware tuning of the parameters of the oscillatory circuits will allow tracking the point of the optimal operating mode.

The author also sets himself the task of testing in practice the proposed solutions by developing a prototype of an electrified road with wireless charging.

1.2. Main Hypotheses and Objectives

Hypotheses

The following hypotheses are put forward for defence.

1. The most optimal way to organize a system of electrified roads is inductive-resonant power transmission.
2. The characteristics of the inductive-resonant power transmission coils have extremes whose tracking allows improving the power transmission parameters.
3. For the functioning of the inductive-resonant energy transmission system, it is necessary to adjust its parameters.

Objectives

1. To justify the choice of inductive-resonant technology for wireless transmission of energy to create an infrastructure of electrified roads.
2. To conduct a practical study of the characteristics of inductive-resonant wireless power transmission using DD coils.

3. To prove the possibility and feasibility of regulating the operating parameters of the inductive-resonant wireless power transmission system.
4. To develop practical methods for regulating the operating parameters of the inductive-resonant wireless power transmission system.
5. To develop a prototype of a road with wireless power transmission to a vehicle in motion and related systems necessary for its functioning.

Means and methods of research

In order to achieve these goals, a detailed analysis of existing solutions for wireless power transmission was carried out.

For a detailed study of the characteristics of DD coils, a setup was assembled with parameters close to the wireless charging systems used for cars. The installation allows the use of various types of resonant coils, as well as to adjust the electrical parameters and the spatial arrangement of the coils in static mode. The installation was used to study the dependence of the frequency characteristics on the relative position of the DD coils, the efficiency and density of energy transfer, various excitation methods, as well as a number of tests on the ability to stabilize the energy transfer parameters.

An original method of tuning the resonant frequency by switching capacitors was developed and tested based on the data obtained. A method was also developed for adjusting the parameters by changing the load on the secondary circuit. The joint operation of both systems was tested on a small-scale prototype.

In the course of the work, a communication network was developed based on a transceiver built on a CC2650 chip. The network was tested for baud rate and noise immunity.

The final part of the work was to combine all the data obtained in order to create a segment of a 4.5 m electrified road, which allows charging electric vehicles in motion. The prototype has been tested with and without a working parameter tuning system.

Scientific novelties

1. A complete study of the characteristics of DD coils when operating in an inductive-resonant system of wireless power transmission has been carried out. The extrema of characteristics were revealed, which allowed to obtain optimal operational parameters.
2. A new method of tuning the resonant frequency of an oscillatory circuit in an inductive-resonant system of wireless power transmission using a store of connected capacities has been proposed. For this solution, the author was awarded patent No. WO2016181186A1.
3. A new method for matching oscillatory circuits in an inductive-resonant system of wireless power transmission using an adjustable load on the secondary circuit has been proposed.
4. A study of the operation of the system for adjusting the parameters of the inductive-resonant method of wireless power transmission has been carried out on the example of a small-scale prototype.

5. A study of the operation of a prototype of a wireless road based on an inductive-resonant method of wireless energy transmission was carried out using the example of a prototype track of 12 modules with a total length of 4.5 m.

Practical novelties

1. The method of tuning the resonant frequency of the circuit of an inductive-resonant wireless power transmission system by connecting a container store using a semiconductor switch has not been previously used in practice.
2. Adjustment of the load on the secondary circuit of the inductive-resonant wireless power transmission system in order to find the maximum power point has not been previously used in practice.
3. A communication network with the transmission of packets in a common information environment has not previously been used to organize feedback circuits in energy converters.
4. The method of complex adjustment of the parameters of the inductive-resonant wireless power transmission system has not been used previously in practice.

Practical application of research results

Based on the data obtained during the research, it is possible to create adaptive systems for wireless power transmission based on inductive-resonant technology. The system for adjusting the parameters of inductive-resonant power transmission can work in charging systems for electric vehicles and in other applications, for example, for charging mobile devices. The research also resulted in a working prototype of a wireless charging system for a car in motion. In practice, the main units necessary for its functioning were worked out. In the future, this will allow the design and implementation of electrified lines.

1.3. Dissemination of Research Results

The author has 10 publications on the topic of the work and received 1 patent.

1. Saltanovs, R., Krainyukov, A. Employment of SIC MOSFETS and GaN-transistors for wireless power transmission systems (2019) Lecture Notes in Networks and Systems, 68, pp. 293–301.
2. Saltanovs, R., Rubenis, A., Krainyukov, A. Influence of constructive materials of road cover on magnetic field dispersion of wireless power transmission systems (2019) Lecture Notes in Networks and Systems, 68, pp. 214–223.
3. Saltanovs, R. The system of dynamic wireless charging for transport using transmitter and receiver parameters adjustment (2018) 31st International Electric Vehicle Symposium and Exhibition, EVS 2018 and International Electric Vehicle Technology Conference 2018, EVTeC 2018, art. no. 20189343.

4. Krivchenkov, A., Krainyukov, A., Saltanovs, R. Effective wireless communications for V2G applications and objects in motion (2018) *Lecture Notes in Networks and Systems*, 36, pp. 360–370.
5. Saltanovs, R., Krivchenkov, A., Krainyukov, A. Analysis of effective wireless communications for V2G applications and mobile objects (2017) 58th Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTU CON 2017, Proceedings, November 2017, pp. 1–5.
6. Saltanovs, R., Galkin, I. Method of adjustment and stabilization of parameters for wireless energy transfer system (2017) 2017 19th European Conference on Power Electronics and Applications, EPE 2017 ECCE Europe, January 2017, art. no. 8099254.
7. Krainyukov, A., Krivchenkov, A., Saltanovs, R. Performance Analysis of Wireless Communications for V2G Applications Using WPT Technology in Energy Transfer (2017) *Procedia Engineering*, 178, pp. 172–181.
8. Krivchenkov, A., Saltanovs, R. Analysis of wireless communications for V2G applications using WPT technology in energy transfer to mobile objects (2015) 2015 56th International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTU CON 2015, art. no. 7343134.
9. Krainyukov, A., Lyaksa, I., Saltanovs, R. Research of the efficiency of the wireless power transfer with the employment of DD inductance coils (2015) *Transport and Telecommunication*, 16 (4), pp. 341–352.
10. Saltanovs, R. Multi-capacitor circuit application for the wireless energy transmission system coils resonant frequency adjustment (2015) 2015 IEEE Wireless Power Transfer Conference, WPTC 2015, art. no. 7140142.
11. WO2016181186A1 A resonator for a wireless transfer system. 2015.

2. PRINCIPLES OF CONSTRUCTION OF ENERGY TRANSMISSION SYSTEM TO VEHICLE

2.1. Introduction

The essence of the resonant induction method is to use two circuits tuned to one resonant frequency. Classically, it was accepted to consider two closely spaced circuits as a single resonant transformer [8]. However, the coils of the circuits can also be considered as loop antennas, and the entire power transmission system as the interaction of two antennas located in the near-field radiation zone [9], [10]. In this case, the combination of antennas on the receiving and transmitting side can be tried to be considered as a phased array antenna (PAA). At the moment, the interaction of two antennas in the near-field radiation zone is poorly studied; however, experiments and theoretical works suggest the possibility of concentrating the energy of the near-field using a PAA [11], [12]. The use of PAA may reduce or completely eliminate the dissipation of energy in surrounding objects and side radiation into the environment characteristic to the induction method of energy transfer.

This method has the following advantages:

- lack of electrical contact between the receiver and transmitter of electrical energy;
- instant readiness to operate;
- ability to operate with short stops;
- ability to operate while the vehicle is moving.

The system includes the following disadvantages:

- short working distance;
- low efficiency in comparison with contact systems due to the non-directionality of the emitters;
- high level of generated interference;
- the complexity of the design.

2.2. The Main Elements of a Resonant Wireless Power Transmission System

The components of a resonant wireless power transmission system are shown in Fig 2.1. They include:

- configuration and control interface;
- power inverter and controller;
- coupling coils;
- rectifier, filters and regulator;
- communication system between the vehicle and the controller on the roadside (communications link).

The algorithm of the resonant charging system works as follows: the vehicle is placed above the charging platform; after completing the identification process, the power inverter converts the incoming current into a high frequency current that drives the resonant coils. The energy received on the side of the receiver, after passing through rectifiers or filters, goes to the battery or to the power plant. To implement feedback, information about the charging parameters is transmitted wirelessly to the controller of the power inverter and vice versa.

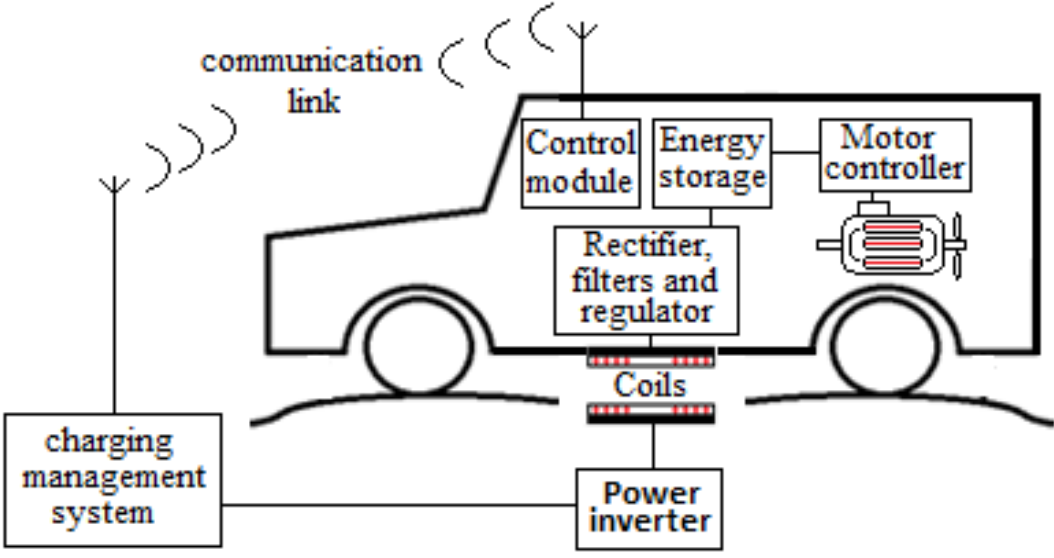


Fig. 2.1. Diagram showing the main elements of a wireless power transmission system.

The design of a ring resonant coil used to receive and transmit power

The design of a ring resonant coil used for receiving and transmitting energy is shown in Fig. 2.2 [13].

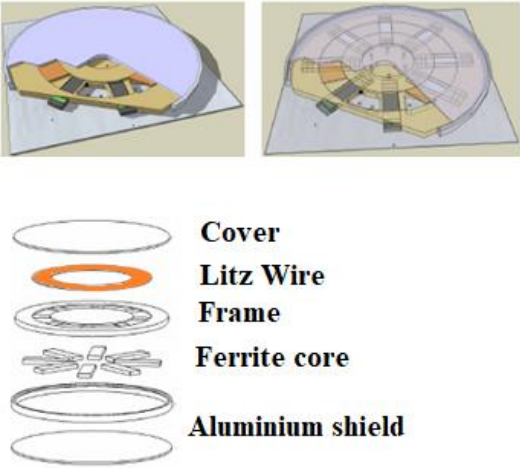


Fig. 2.2. Ring resonant coil design.

The advantage of this design is that when working at a certain tuned resonant frequency, the system has an insignificant effect on the surrounding objects. The disadvantage is that when the receiving coil is displaced relative to the transmitting one, there is a sharp drop in efficiency.

2.3. Analysis of the Mathematical Model for Wireless Power Transfer Using Magnetic Resonance Method

The effective operation distance of the circular coils of the wireless power transmission system is in the range from $0.25D$ to $0.75D$, where D is the diameter of the used coil. The ground clearance of the overwhelming majority of passenger cars is in the range of 0.1 m to 0.3 m. In addition, the depth of placement of the coils under the road surface layer can be up to 0.05 m; based on this, minimum distance h_{\min} between the coils can be assumed equal to 0.15 m.

When the vehicle is moving, the receiving coil will move above the sequentially installed transmitting coils shown in Fig. 2.3, the maximum distance between the coils can be found as the distance between the centres of the receiving coil at a point equal to the distance from two adjacent transmitting coils at the height of the maximum vehicle clearance according to the formula:

$$h_{\max} = \sqrt{\left(\frac{h_{\max}}{2D_e}\right)^2 + (h_{\text{car}} + h_{\text{RS}})^2}, \quad (2.1)$$

where h_{\max} – maximum distance between the centres of coils, the required value;

h_{\max} – maximum height of the vehicle's ground clearance, in our example assumed 0.3 m;

h_{RS} – thickness of the road surface, in our example assumed 0.05 m;

D_e – the ratio of the effective maximum transmission distance to the coil diameter, in our example 0.75.

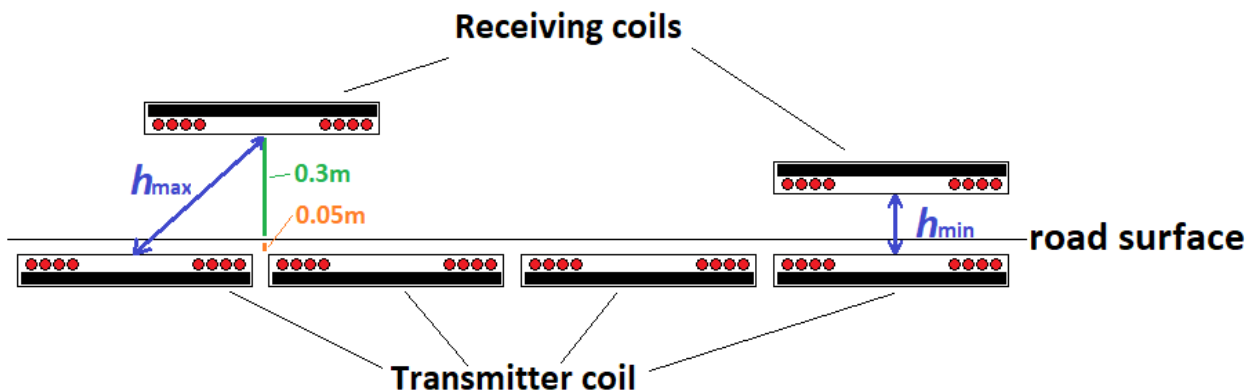


Fig. 2.3. Maximum and minimum distance between coils.

By calculating this equation, one can establish that the maximum distance between the centres of coils will be 0.47 m, from which it is not difficult to determine that the effective diameter of the coil for this distance is equal to 0.63 m.

To assess the required speed of tuning the parameters of the dynamic power transmission system, it was assumed that at a vehicle speed of 90 km/h the system must complete at least 10 tuning cycles. The duration of one cycle can be found as follows:

$$t_{\text{round}} = 0,1 \frac{D}{0,278V}, \quad (2.2)$$

where D – the diameter of the coil, in our example 0.63 m;

V – the vehicle speed, in our example 90 km/h;

t_{round} – duration of one round of system tuning.

From Expression (2.2), it can be established that the speed of the system tuning should not exceed 2.5 ms.

Also, when forming the requirements for the adjustment system, it is necessary to take into account the natural vibrations of the vehicle body during movement. According to some studies, when a vehicle is moving at a speed of 50–90 km/h, the vibration of the car body will not exceed a frequency of 14 Hz, which corresponds to a period of 71 ms. Since the previously formed requirements for the speed of the restructuring of the system were 2.5 ms, then during one period of oscillation, 28 restructuring cycles will occur, and a vehicle moving at a speed of 90 km/h will have time to pass almost 3 transmitting coils, which is illustrated in Fig. 2.4.

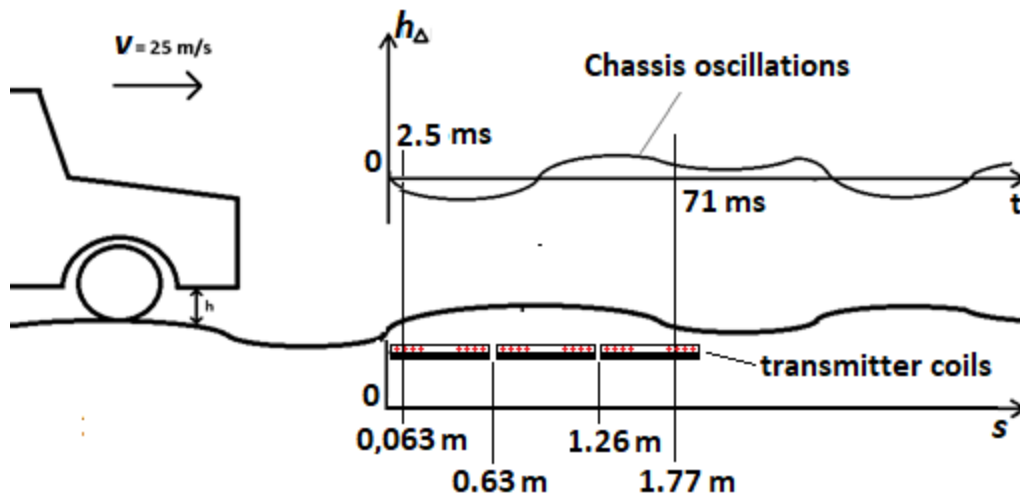


Fig. 2.4. Assessment of the influence of body vibration.

From this it can be concluded that the power transmission system has at least two times the speed margin for tuning parameters when operating at a frequency of 85 kHz.

3. RESEARCH ON PARAMETERS OF WIRELESS POWER TRANSFER USING INDUCTIVE RESONANCE

In this chapter, a comprehensive study of the main component of the induction-resonant method of transferring energy is carried out, namely, two coupled oscillatory circuits that form a resonant transformer. Its characteristics are experimentally obtained when operating in various modes. The dependences of the influence of distance, position, methods of excitation on the frequency response, the transmitted power and the efficiency are found.

The experimental setup contains a transmitting circuit consisting of capacitor C_1 and inductor L_1 and a receiving circuit consisting of inductor L_2 and capacitor C_2 . Serial excitation of the transmission circuit is carried out by using an excitation transformer formed by primary winding L_3 and secondary winding L_4 . The block diagram of the experimental setup is shown in Fig. 3.1.

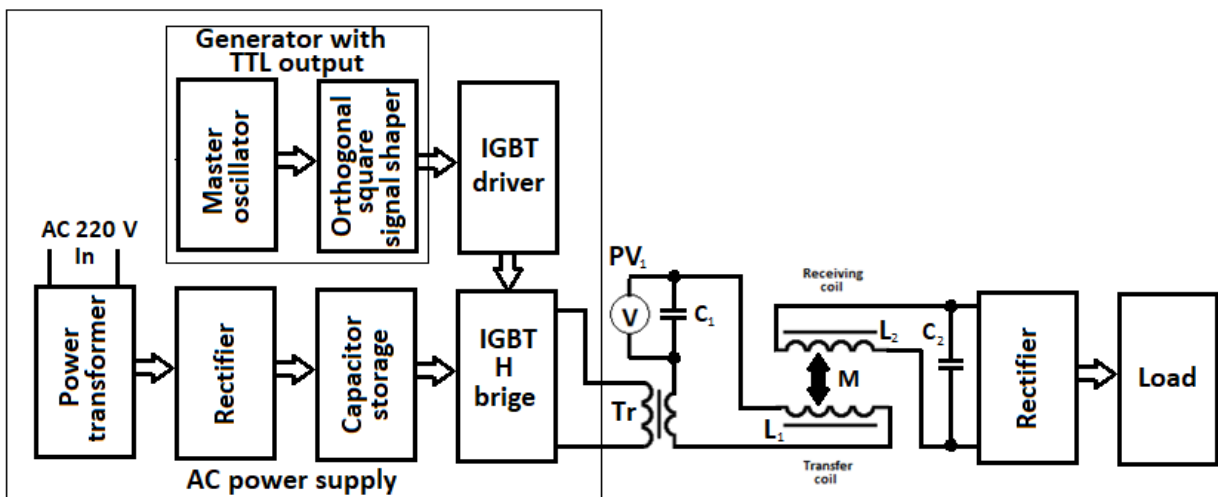


Fig. 3.1. Block diagram of the experimental setup for wireless power transmission.

The experimental setup (Fig. 3.2) includes:

- autotransformer;
- bridge rectifying circuit of the mains voltage and two storage capacitors;
- generator of orthogonal meander signal;
- IGBT driver board – transistors;
- H bridge of IGBT-transistors (IGBT switches), mounted on a metal plate of a radiator;
- transmitting and receiving circuits formed by inductors and capacitor banks;
- receiving coil load – rectifier bridge circuit with resistive load.

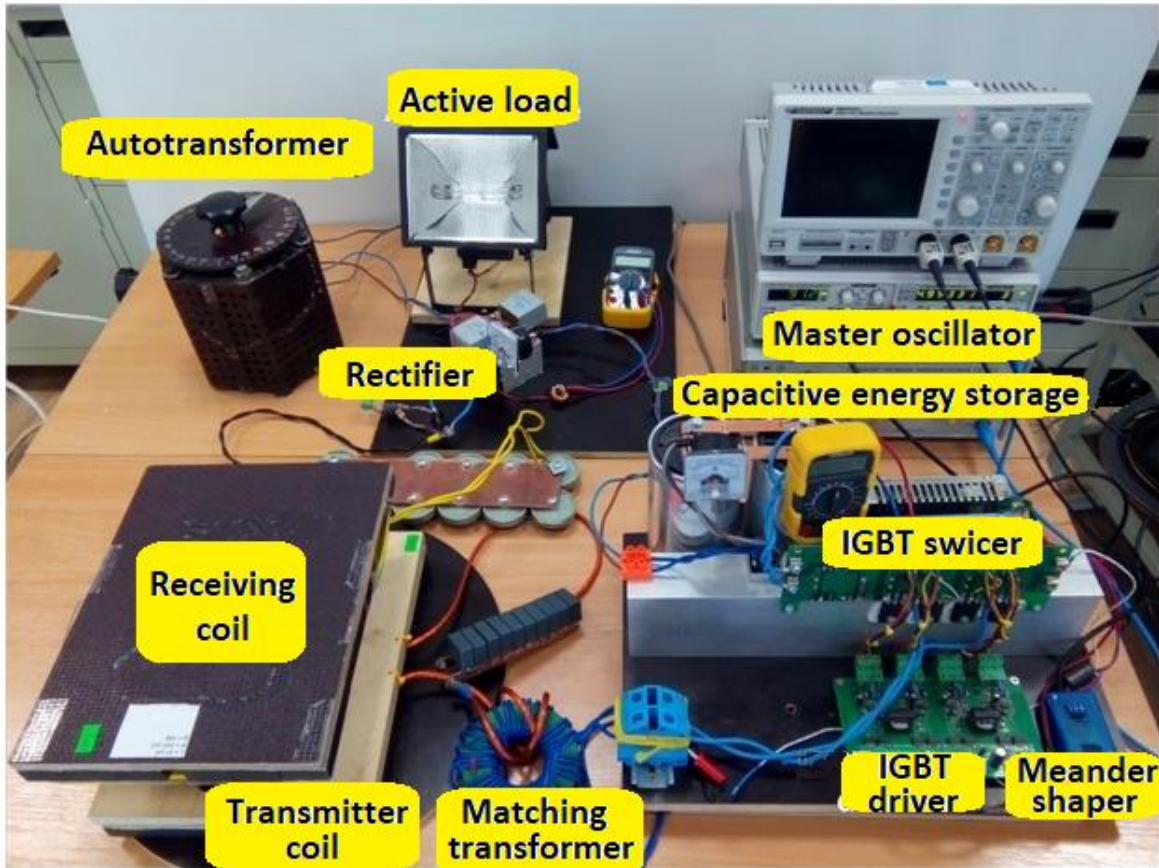


Fig. 3.2. Experimental setup for wireless power transmission.

The design of flat square DD inductors is shown in Fig. 3.3. Figure 3.3 a shows the transmitting coil, and Fig. 3.3 b the receiving coil from the side of the turns of coils. Figure 3.3 c shows the transmitting coil from the reverse side – from the side of the ferrite shield, and Fig. 3.3 d – the receiving coil from the side.

Each spiral winding of the transmitting DD coil contains 8 turns of a litz wire with a diameter of 4.5 mm. Each spiral winding of the receiving DD coil contains 10 turns of W-520 × 0.2–2L wire. The ferrite screen was made in the form of a plate of ferrite magnetic bars with permeability $\mu = 2000$ and geometric dimensions of 74 mm × 35 mm × 15 mm. The areas of the transmitting and receiving DD coils were the same: 290 mm × 230 mm.

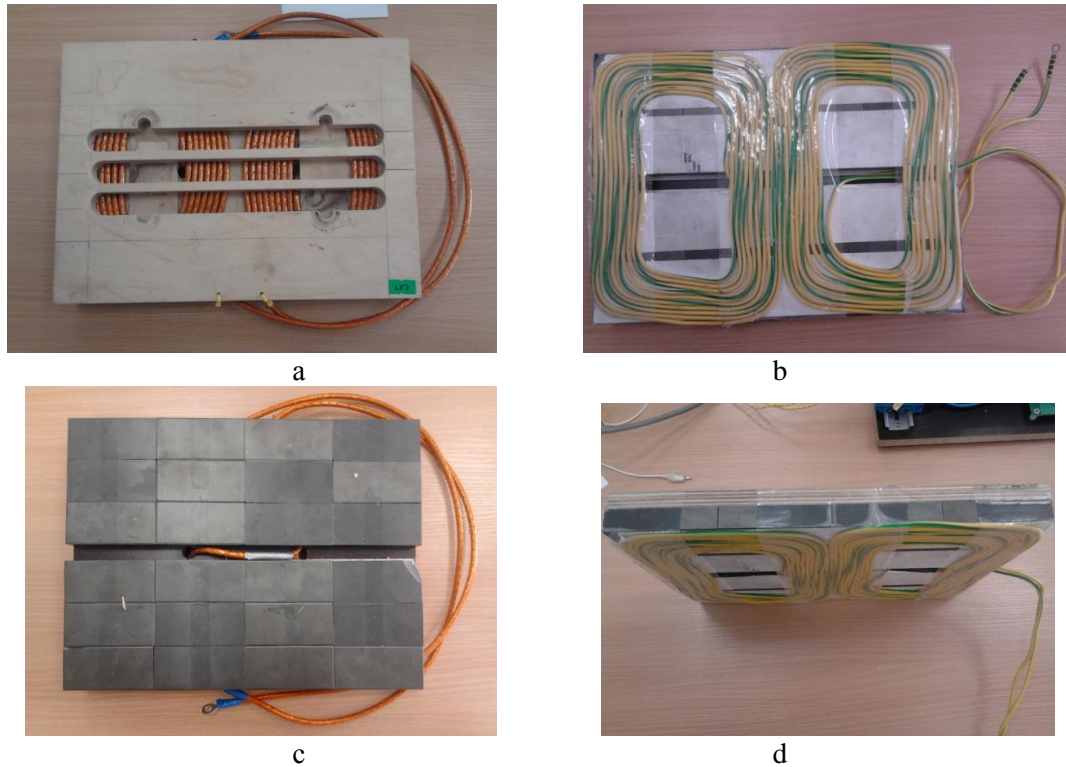


Fig. 3.3. Square DD inductors (a and c – transmitter coil; b and d – receiver coil).

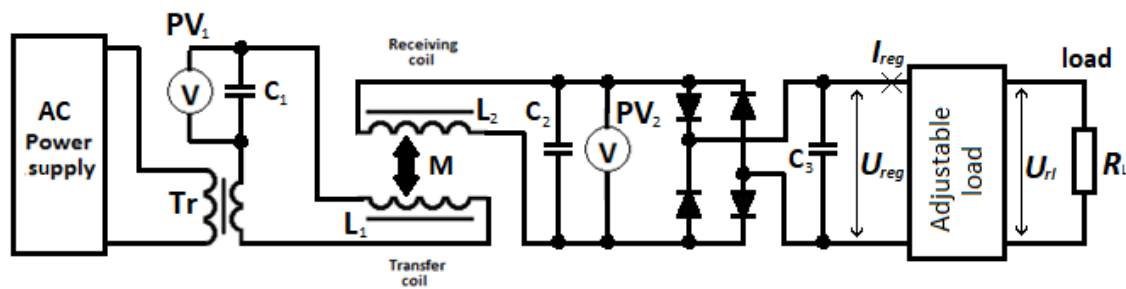
To study the possibility of tuning the resonant inductive energy transfer by adjusting the load on the secondary circuit for different characteristics of the resonant transformer system, the measurement scheme shown in Fig. 3.4 was used. This circuit used a series-parallel resonant transformer topology. The transmitting circuit is a series circuit formed by inductance L_1 and capacitance C_1 . The receiving circuit is a parallel circuit formed by inductance L_2 and capacitance C_2 .

The “Controlled Load” is a block that provides the ability to set a predetermined voltage limitation (U_{reg}) or current (I_{reg}) at the input of the regulated load. In the case of voltage stabilization, when the voltage set from the control panel is reached, the current in the load will increase. In the case of current stabilization, on the contrary, if the current will reach the predetermined level, the load resistance will drop and the voltage will increase.

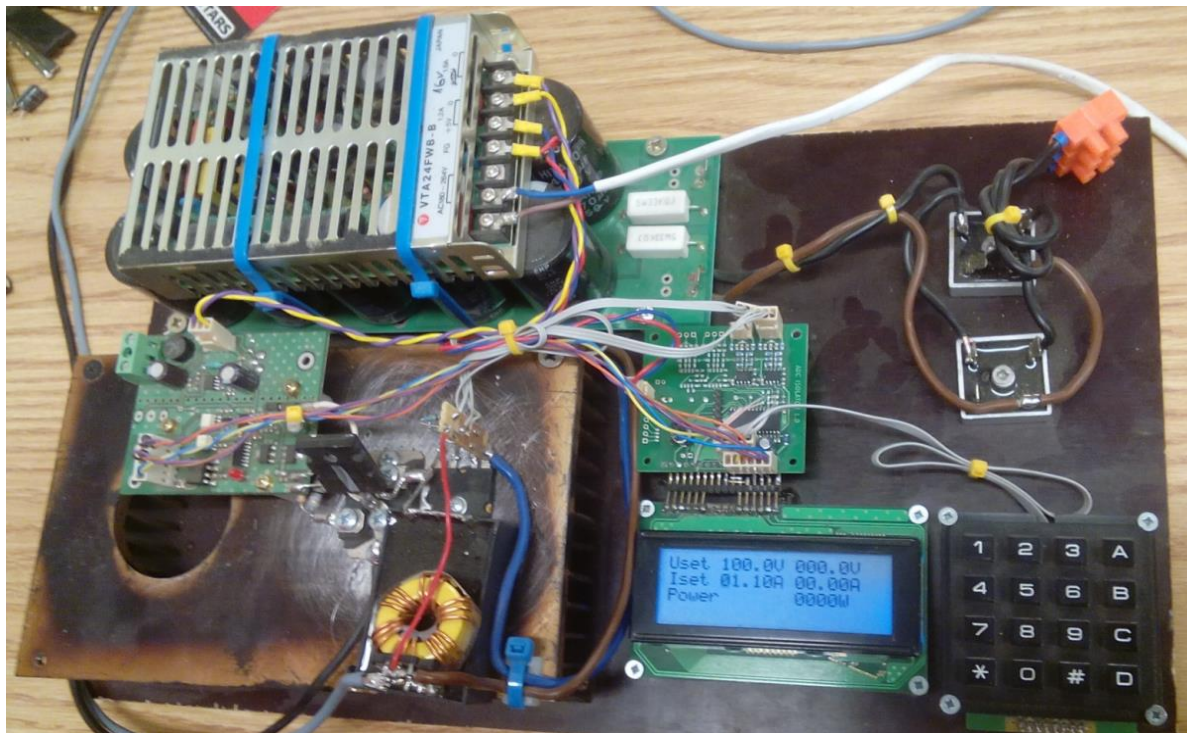
The “Controlled Load” block provides the following tasks:

- change in voltage U_{reg} and current I_{reg} , in order to ensure the equality of powers at load R_L and at the input of the device itself;
- input of limit values of voltage stabilization $U_{\text{reg max}}$ or current I_{reg} ;
- display of limit values of voltage $U_{\text{reg max}}$ and current $I_{\text{reg max}}$, current values of voltage U_{reg} and current I_{reg} , as well as the power dissipated in the regulated load itself.

The block “Controlled load” allows setting the value of $U_{\text{reg max}}$ in the range from 40 V to 400 V, and $I_{\text{reg max}}$ in the range from 1 A to 10 A.



a



b

Fig. 3.4. a – Diagram of the study of the method of stabilization of the maximum efficiency of wireless power transmission; b – external view of the “Controlled load” block.

Investigation of the method of stabilization of the maximum efficiency of the resonant induction method of energy transfer using DD coils

To perform this study, DD inductor $L_1 = 33.3 \mu\text{H}$ and $L_2 = 91.3 \mu\text{H}$ was used in the transmitting circuit. The capacitances of the capacitors in the oscillating circuits are $C_1 = 99.95 \text{ nF}$ and $C_2 = 37.3 \text{ nF}$. The calculated values of the resonant frequencies are: in transmitting circuit – 87.633 kHz, in receiving circuit – 86.244 kHz.

When studying the method of stabilizing the maximum efficiency of the resonant induction transmission method, the following parameters were varied:

- the distance between DD inductors d ;
- voltage across storage capacitors U_c ;
- limit voltage value $U_{\text{reg max}}$.

The limit value of control voltage $U_{\text{reg max}}$ varied in the range from 40 V to 250 V. The limit value of the controlled load current $I_{\text{reg max}}$ was always set equal to 10 A. The voltage across storage capacitors U_c was set equal to 50 V, 75 V or 100 V.

To determine the capabilities of the method for stabilizing the maximum efficiency of the resonant induction method of energy transfer, the following energy parameters of the resonant transformer were measured and calculated:

- current of the controlled load;
- input resistance of the controlled load;
- output power – the power supplied to the load;
- current of the transmitting circuit;
- input power – the power entering the transmission loop;
- power transfer coefficient characterizing the efficiency of a resonant transformer with a controlled load.

The energy parameters were measured when the frequency of the control signal by meander generator F_m and the resonant frequency of the resonant transformer with DD inductors were equal.

The results of this study are presented in Figs. 3.5 and 3.6. Figure 3.5 a shows the dependences of controlled load current I_{reg} on control voltage $U_{reg\ max}$ at three voltage values on storage capacitors U_c . These dependences are volt-ampere characteristics of the controlled load, which have a hyperbolic dependence on voltage $U_{reg\ max}$. Increasing of the storage capacitor voltage U_c increases the slope of these characteristics. The dependences of the input resistance of the controlled load on voltage $U_{reg\ max}$ and on U_c are shown in Fig. 3.5 b. The influence of these voltages on the input resistance of the controlled load is opposite.

Figure 3.5 c shows the dependences of the power supplied to the load on control voltage $U_{reg\ max}$ at three values of the voltage on storage capacitors U_c . These dependences have extremes, and the maximum power values are observed when voltage $U_{reg\ max}$ is equal to the voltage of storage capacitors U_c . That is, to obtain the maximum power supplied to the load, the voltage across storage capacitors U_c and control voltage $U_{reg\ max}$ must be equal.

An increase in control voltage $U_{reg\ max}$ leads to changes in the transmitting circuit current (Fig. 3.5 d). The input current changes in the same way as the controlled load current I_{reg} at the corresponding voltage U_c , but the input current is about twice as large. This is clearly seen in Fig. 3.6 a, which shows the dependences of the input current (the current of the transmitting coil of the resonant transformer) on the current of the controlled load I_{reg} for three fixed voltages of storage capacitors U_c .

Figure 3.6 b shows the dependence of the output power (power transferred to the load) on the input resistance of the controlled load. Each dependence has a maximum, which corresponds to the optimal value of the input resistance of the controlled load. The optimal values of the input resistances have near values at the indicated voltages of storage capacitors U_c : $54.9\ \Omega$ at $U_c = 50\ V$, $54.8\ \Omega$ at $U_c = 75\ V$ and $58\ \Omega$ at $U_c = 100\ V$. Between the dependencies of the output power on the input resistance of the controlled load (Fig. 3.6 b.) and from control voltage $U_{reg\ max}$ (Fig. 3.5 c) there is an unambiguous relationship.

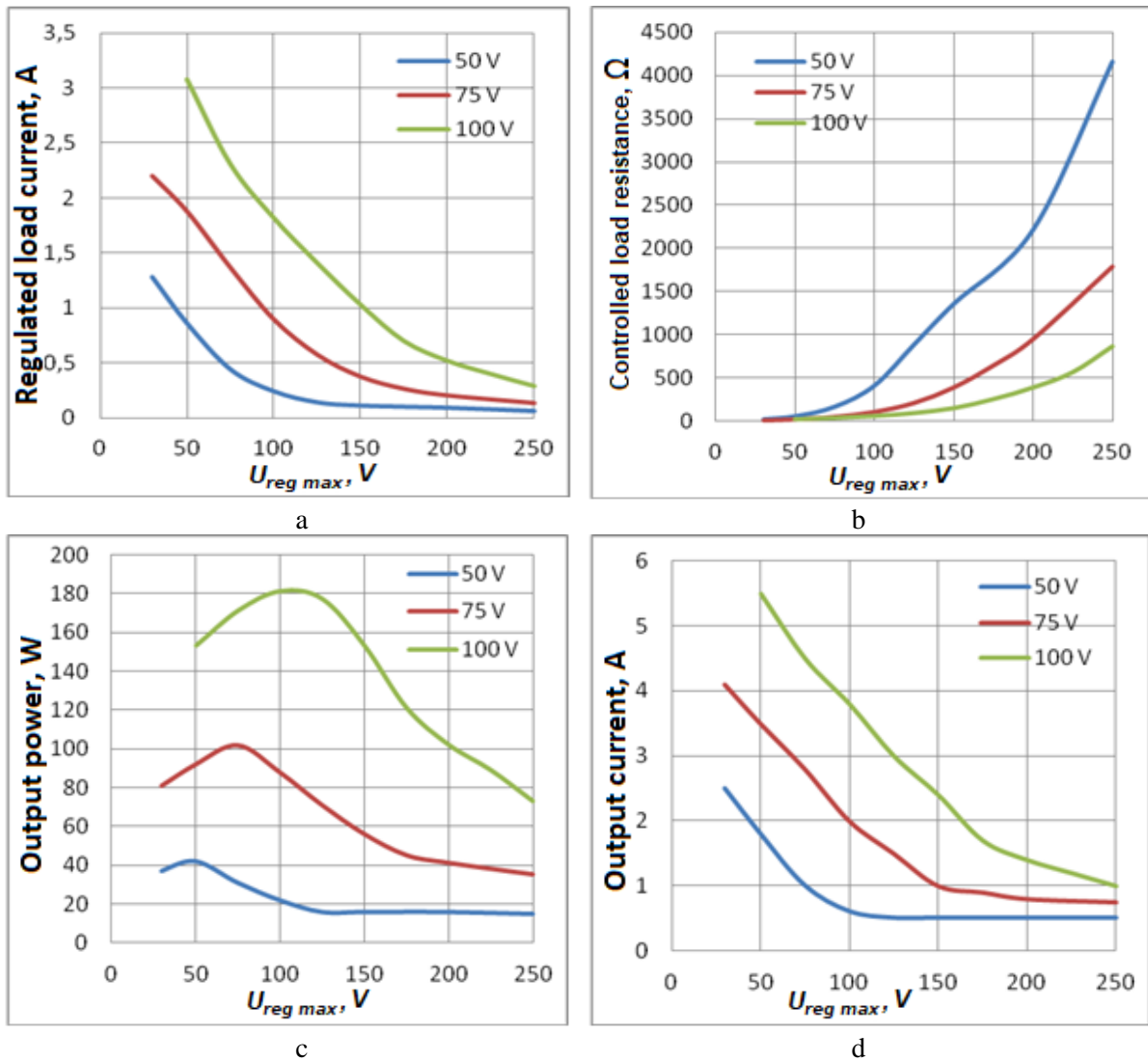


Fig. 3.5. Effect of voltage $U_{reg\ max}$ on the energy parameters of a resonant transformer with DD coils at $d = 13.5$ cm (a – dependence of adjustable load on current; b – dependence of adjustable load resistance on control voltage; c – dependence of output power on control voltage; d – dependence of input current on control voltage).

Unlike the dependencies shown in Fig. 3.6 b, there are no extremes for the input power dependency on the input resistance of the controlled load. The value of the input power decreases hyperbolically with an increase in the input resistance of the controlled load. The higher the voltage U_c , the faster is the decrease in the input power.

However, the use of optimal values of the input impedance of the controlled load does not allow obtaining the maximum values of the power transfer coefficient (maximum efficiency), which is clearly seen in Fig. 3.6 d. The maximum values of the power transfer coefficient can be obtained at higher values of the input resistance of the controlled load than those that are optimal for the dependencies in Fig. 3.6 d. This is explained by a decrease in both the output and the input power with an increase in the input resistances of the controlled load (Fig. 3.6 b and c). With a further increase in the input resistance of the controlled load, the values of the power transfer coefficients remain unchanged, which is clearly seen for the dependence obtained at $U_c = 50$ V.

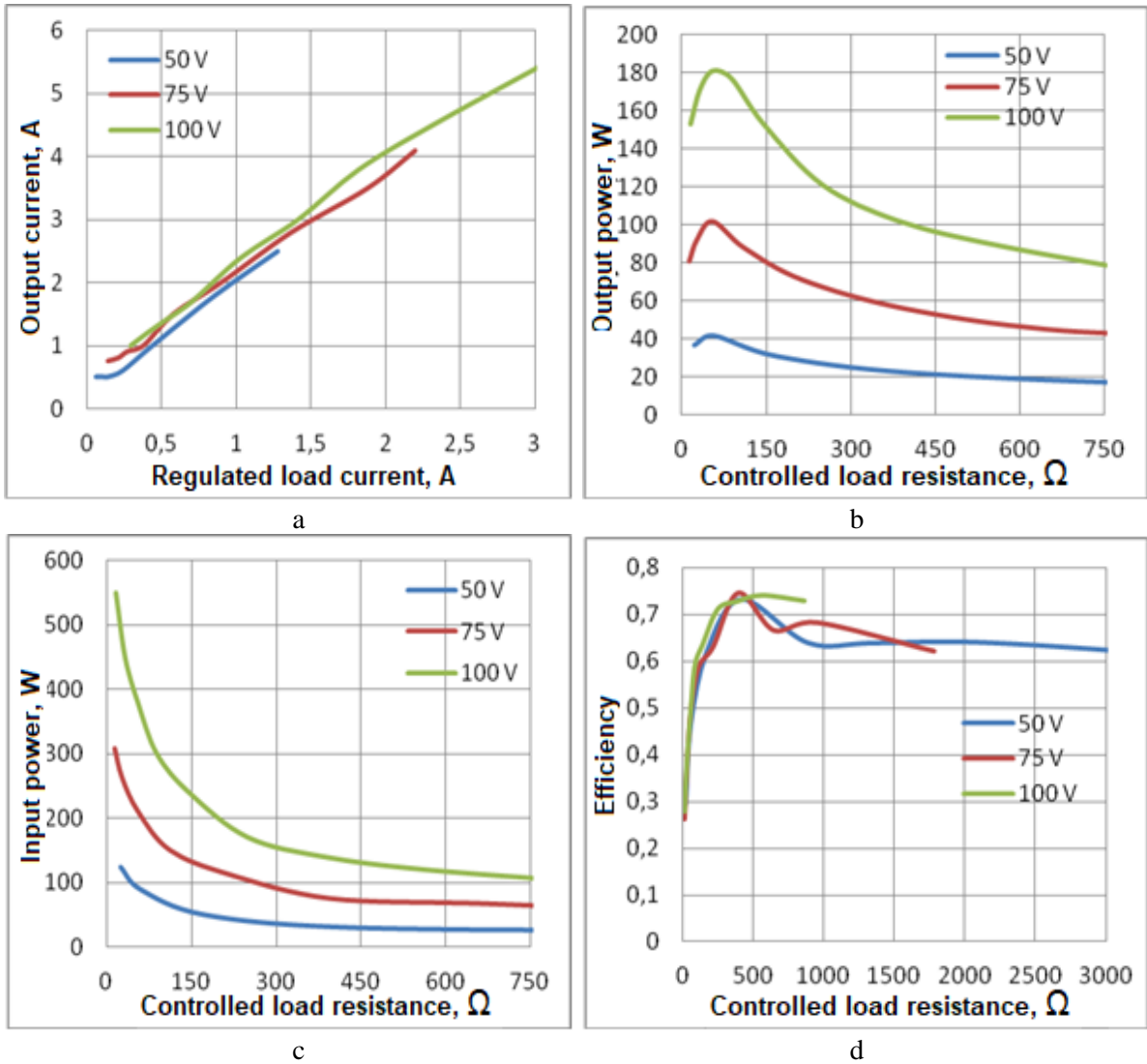


Fig. 3.6. Influence of a controlled load on the energy parameters of a resonant transformer with DD coils at $d = 13.5$ cm (a – dependence of input current on output power; b – dependence of output power on adjustable load resistance; c – input power dependence on adjustable load resistance; d – dependence of efficiency factor on adjustable load resistance).

4. DEVELOPMENT OF A SYSTEM FOR ADJUSTING OPTIMAL PARAMETERS FOR A DYNAMIC WIRELESS POWER TRANSMISSION SYSTEM IN MOTION

4.1. Introduction

As it was established in the previous section, in order to reach the point of maximum efficient operation of the wireless power transmission system, it is necessary to compensate for the change in the inductance of the coils, the change in the coupling parameters between them and the value of the load resistance, as well as the voltage of the excitation generator of the primary circuit. Changing the voltage of the exciting generator is not difficult. It is possible to compensate for the change in inductance and to adjust the frequency of the oscillating circuits by changing the capacitance included in the oscillating circuit. The load resistance can be changed using an electronic load. The block diagram of the control of parameters of the wireless power transmission system is shown in Fig. 4.1.

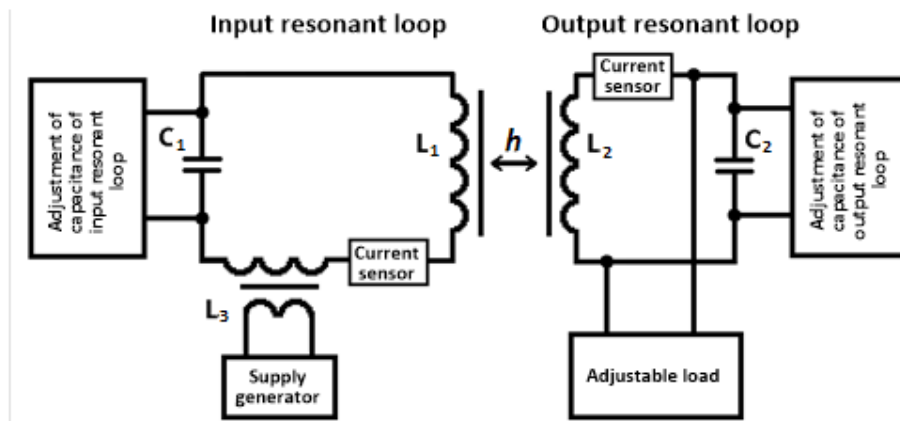


Fig. 4.1. System for adjusting the parameters of the wireless power transmission system.

During the operation, converter's input capacitors C_1 and C_2 will be charged up to the amplitude voltage across the capacitor of the resonant loop. The resistance of the DC-DC converter will be equivalent to a ratio of the voltage to the input current of the DC-DC converter [14], [15]. Therefore, since the output current of the converter with the constant load directly depends on its output voltage, controlling the voltage transfer ratio adjusts also the input current of DC-DC converter and its equivalent resistance, thus adjusting the quality factor (Q) of the resonant loop [16], [17].

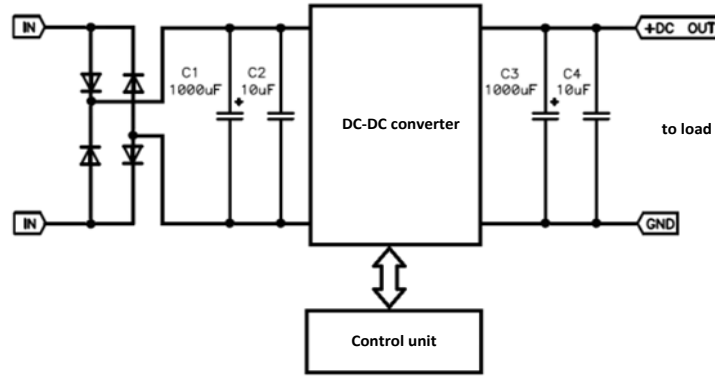


Fig. 4.2. Load with adjustable resistance.

4.2. Compensation for the Mutual Detuning of Oscillatory Circuits

One of the conditions for the operation of a wireless power transmission system in the maximum efficiency mode is full resonance [18], when the frequencies of the transmitting and receiving oscillatory circuits coincide. For this, it is necessary to compensate for the change in the inductance of coils. One of the options for compensating the change in the inductance of coils is the adjustment of the capacitance included in the circuit [12], [19], [21].

The author proposed a method for electronic switching of capacities. The essence of the method lies in the presence of a store of containers connected in parallel to the capacitance of the corrected oscillatory circuit. The experimental setup is shown in Fig. 4.3. A feature of the method is the use of a semiconductor switch shunted by a diode for switching the capacitance, which makes it possible to use one transistor to connect the capacitance. This inclusion allows to achieve minimum power losses, since the resistance of the open channel of a field-effect transistor connected in series with a capacitor does not exceed 0.1 Ω .

The mathematical model of electronic tuning of the frequency of the oscillatory circuit is reduced by solving the following equation:

$$C_{\text{new}} = f_{\text{old}} C_{\text{old}} \frac{1}{f_{\text{const}}}, \quad (4.1)$$

where C_{new} – the calculated value of the capacitance of capacitors for the next cycle of operation;

f_{old} – measured frequency of loop oscillations;

C_{old} – previous value of the oscillating circuit;

f_{const} – reference frequency to which the system aims;

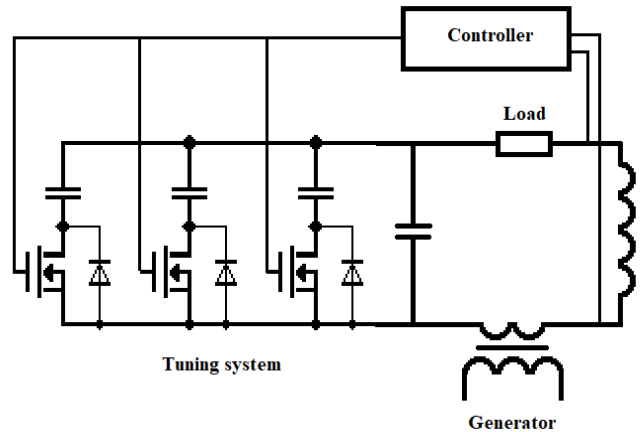


Fig. 4.3. Adjustment of capacitance of resonant loop by means of capacitors box.

In order to test the scalability principle, an experiment was carried out to adjust the resonant frequency in a circuit with a current of 100 A. For this purpose, the installation was assembled using a magnetic system with a diameter of 450 mm, the scheme and appearance of which is shown in Fig. 4.8. The multi-capacitor tuning circuit consists of main resonant system capacitance C_7 (175 nF) and the microcontroller operated block of six connectable capacitances C_1 – C_6 , which allows to add to the main capacitance additional capacity up to 102 nF with the step size 1.6 nF. Theoretical analysis of the circuit revealed that the tuning setup allows to compensate the drift of the transmitter coil inductance in the range between 13–20 μH , and, consequently, reduce the drift of resonance frequency with the step size 258–397 Hz. Oscillating circuit of the experimental setup is assembled according to the scheme of the parallel circuit. Excitation of the circuit was created using IGBT H-bridge connected to a square shape signal generator with output frequency of 60–100 kHz. Power to the system was supplied from DC voltage source, with output value set to 800V.

Control of the multi-capacitor circuit and wireless energy transfer between coils was performed by the micro-controller module assembled on dsPIC33FJ64GS610 processor. The receiving coil was connected to a resistive load, simulating the energy transfer to the charged batteries, at the same time lowering the quality factor of the resonant system. Oscilloscope DSO6032A was used to visualize the transmitted signal and to measure the frequency and amplitude of oscillations. LRC bridge HM8118 was used to measure the inductance. Set of spacers made from non-magnetic material with a 10 mm pitch was used to establish a precise distance between the transmitter and the receiver coil.

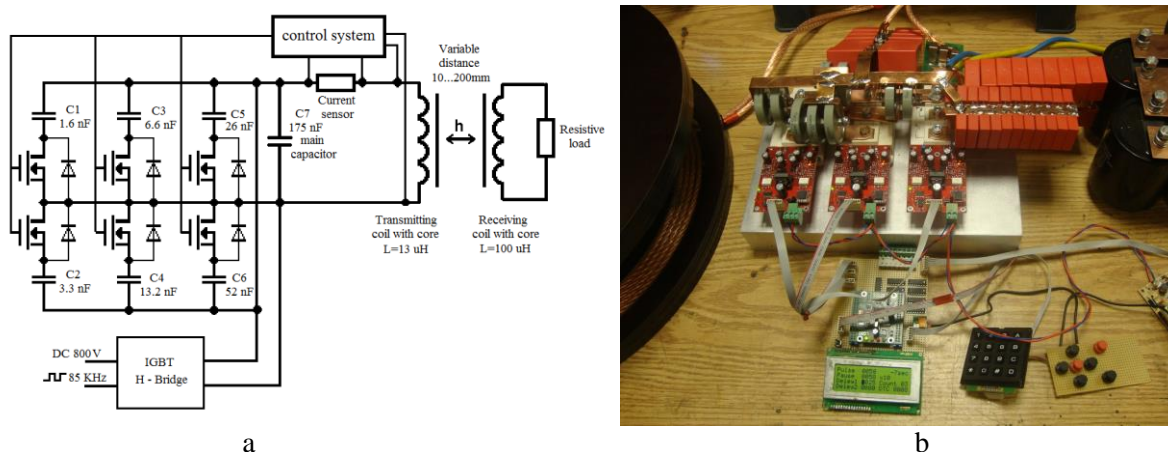


Fig. 4.4. Prototype of wireless energy transfer system with multi-capacitor circuit:
a – system design; b prototype.

Tests of current and voltage on the transmitting coil showed that they are at the stated level – current in the coil reached 100 A, and voltage 815 V.

The measurement results of the resonance frequency of the transmitter coil positioned in various distances from the receiving coil and using static and constant resonance circuit capacitor are presented in Fig. 4.5, line (A). With the capacitance of capacitor $C = 220$ nF the resonance frequency of the oscillating circuit was changing in line with the distance increase between the coils. The shape of the trend line was close to exponential, and with distance increase from 10 mm up to 190 mm the resonance frequency increased from 67 kHz to 93 kHz. If the stated working frequency of wireless energy transfer system and operational frequency of excitation generator is 85 kHz, the only distance, which lets the coil system to be in resonance, is $h = 70$ mm. Increase of the distance just by 20 mm (misalignment of coils because of improper positioning of the vehicle to be charged) will result in a shift up of the coil system resonance frequency.

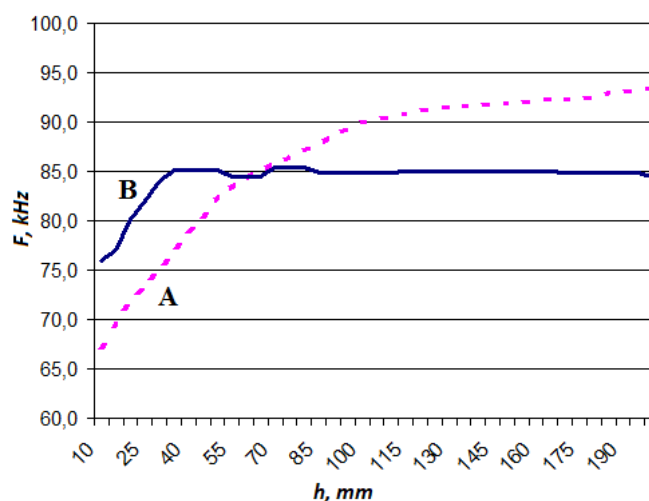


Fig. 4.5. Resonance frequency as a function of the distance between the coils: A – fixed capacitance capacitor; B – proposed fine tuning multi-capacitor circuit system.

Line B in Fig. 4.5 presents the results of measured resonance frequency of the transmitting system circuit using the proposed multi-capacitor system, which provides resonance frequency tuning. As it was predicted from theoretical analysis, the system was able to compensate for the inductance changes and to keep the resonance frequency equal to the generator oscillation frequency at stated value $f = 85$ kHz within the range of distances between the coils from 40 mm to 200 mm. Frequency deviation from the stated value was less than 800 Hz. At the same time, in close range between coils (10–40 mm) the control system of the transmitter resonance frequency was unable to compensate for the inductance changes. This could be done by setting a lower capacity of main capacitor $C7$, if the energy transfer system is used at such close distances.

A particular algorithm for the circuit resonant frequency measuring was developed during the field experiments with the coils. The main principle of this algorithm is based on the measurement of natural oscillations of the oscillating circuits. Disconnecting the excitation generator creates the transient processes in the coil system, lasting less than 3 full oscillation periods. This signal is being measured, and the resonance frequency is calculated. Measurement speed is high. For example, at oscillation frequency $f = 85$ kHz, the time required to measure the natural frequency of oscillating circuit was 35 μs , and subsequential fine tuning using the described system took one oscillation period or 12 μs .

4.3. Small-Scale Prototype

The proposed parameter optimization method has been experimentally studied with help of a small-scale prototype (Fig. 4.6). The block diagram of the prototype is shown in Fig. 4.7. The goal of this experiment was to determine the transferred power and energy efficiency of the converter as a function of equivalent load, as well as verification of the assumption that a maximal power and efficiency point can be found and achieved. The experimental setup consists of a transmitter and a receiver. Its rated transmit power is 60 W.

The structure of the transmitter includes a laboratory power supply with integrated current and voltage measurement function and a supply generator made as a controllable FET H-bridge, a transmitting coil wound on a ferrite core FERROXCUBE E71/33/32 with 20 turns of segmented wire of total cross section area 4 mm², the main loop capacitor 6.6 nF, a system of commutation of additional capacitors, a current sensor located in the transmitting resonant loop, as well as a microcontroller control module.

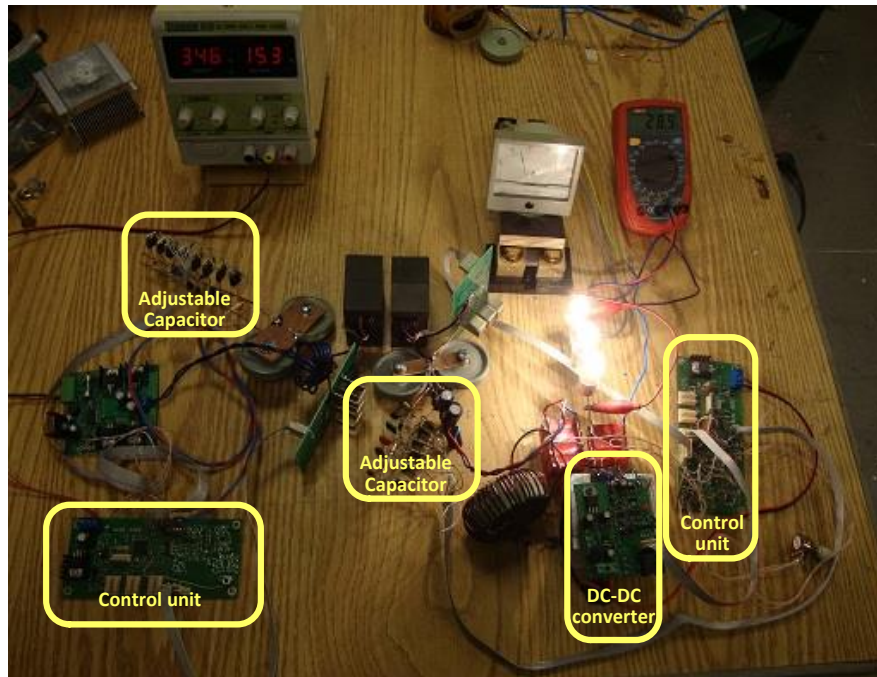


Fig. 4.6. Small scale laboratory prototype of wireless energy transfer system.

The structure of the receiver includes a coil, the main loop capacitor and additional capacitors with commutating switches, as well as a loop current sensor similar to those of the transmitter. Besides, it includes an adjustable load consisting of a bridge rectifier formed of 4 Schottky diodes, a controlled DC-DC converter and a constant load made of three incandescent lamps (12 V, 2 A) connected in series, as well as a microcontroller control module. The load circuit also includes a current indicator and a digital voltmeter, for determining the power transferred to the load.

The experimental setup is implemented using the previously described automatic resonance frequency tuning algorithm. The correction of the transmitter and receiver resonant loops is made with the help of adjustable 8-stage capacitor battery. The capacity of these elements ranges from 50 pF to 6.4 nF. This provides changes of the additional capacity in the range from 0 nF to 12.75 nF with increment of 50 pF. This, in turn, allows adjustment of the resonant frequency with a step of 500 Hz. At the main operation frequency of 85 kHz, and with the capacity of the main capacitor 1 nF, the mentioned battery of capacitors can compensate for the change of the inductance of the coil from 0.26 mH to 3.6 mH.

Besides, an electronic load enabling digitally selectable additional resistance has been implemented in the receiving resonant loop. In the conducted experiments, the load resistance has been selected manually from the range 2 Ω to 8 Ω with a step of 1 Ω .

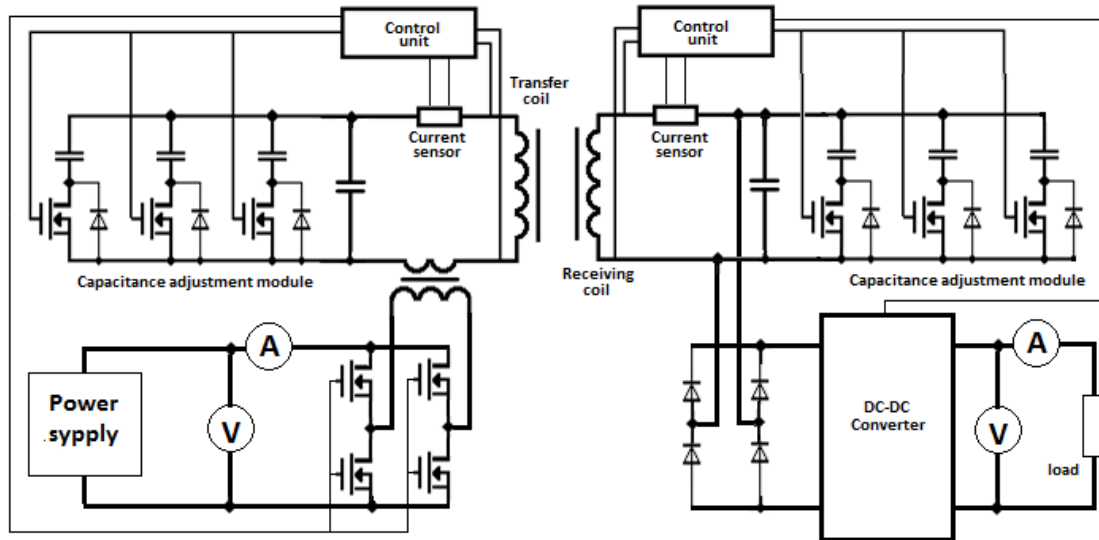


Fig. 4.7. Block diagram of a small-scale prototype.

The experiment has been repeated 4 times – with a 6 V, 9 V, 12 V, and 15 V input voltage of supply generator. Then, for each value of the voltage the experiment was made with different values of the additional load connected in series with the main one. For each measurement point the input current of the converter, as well as its load current and voltage were measured. Based on the measured data the output power of the converter, Fig. 4.8 a, and its energy efficiency, 4.8 b, were calculated. During these calculations the constant power of 3 W consumed by the microcontroller units, sensors and communications has been added to the total (input) power of the converter.

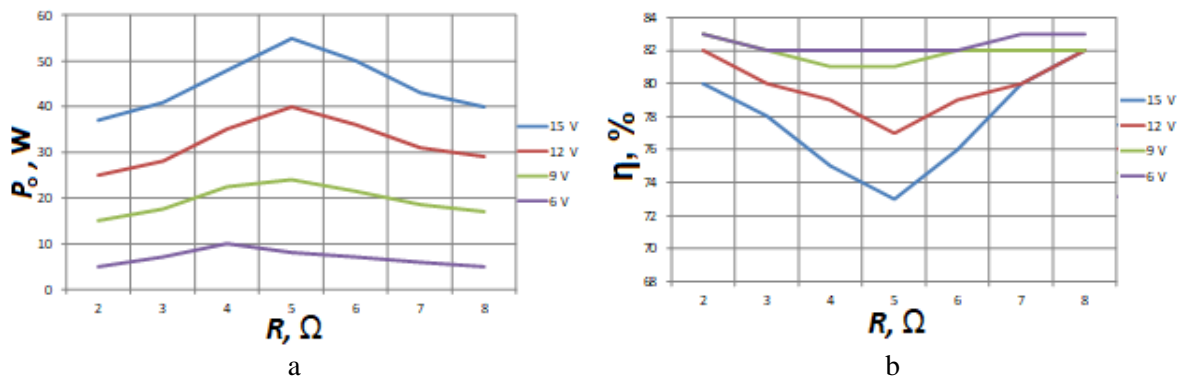


Fig. 4.8. Calculated output power (a) and efficiency (b) of the converter.

The experimental results show that there exist extreme points in the functions of output power and efficiency. In the case of the output power, Fig. 4.8 a, it is the point of maximal transmission power. In this point, with the help of electronic load it becomes possible to reduce quality factor Q of the resonant loop, so that it is numerically equal to the reversed magnetic coupling coefficient $1/k$. In the graph, the area to the left of extrema corresponds to the overloaded resonance loop, but the amplitude of oscillations is not sufficient to transmit significant power to the load. In the right area of the chart, on the contrary, the contour is

underused and the oscillation amplitude is excessive causing high losses in the resonant loops and their misalignment.

In the case of the efficiency, the extreme point is its minimum. Contrary to expectations, increase of the output power leads to a lower value of the efficiency. This effect can be explained by the quality of experimental setup, which is not perfect, but the losses in its elements are higher than expected.

4.4. Prototype of a Dynamic Energy Transmission System for a Vehicle in Motion

This section describes a prototype system for wireless transmission of energy to a vehicle in motion. The design and test results of a prototype system of 12 segments are presented.

Electric road construction

One of the possible designs of an electric road is presented in Fig. 4.9, which includes transmitting and receiving modules, a system of synchronization and data transfer. A transmitting part of the system consists of DD coil modules, positioned one after another and mounted onto road surface. A receiving part can consist of one or several modules of DD coils and can be placed under the vehicle. Synchronization system consists of magnetic sensors placed on a vehicle and sensors mounted in road covering. This distinguishes this design from other existing systems [22], [23].

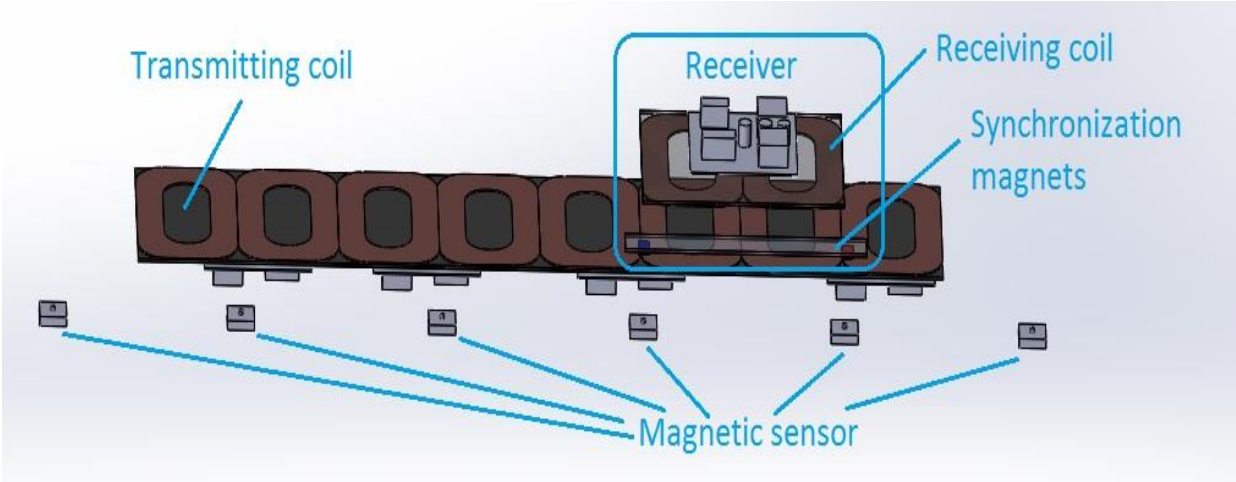


Fig. 4.9. Structural scheme of electric road.

During the system operation a receiver moves along transmitting modules. A synchronization system allows to spot the location of a receiver and to switch on a transmitting module, which at that point is aligned under the receiving coil. This procedure eliminates ambient electromagnetic radiation and enhances the efficiency of the whole system, as only that part of the transmitter operates over which the receiver is located.

Prototype

The measurements of the transmitting part of the electric road prototype are $0.25\text{ m} \times 4.5\text{ m}$. The transmitter consists of 12 DD coil modules arranged in series with measurements $250\text{ mm} \times 400\text{ mm}$. The design of the transmitting module with controlling electronics is presented in Fig. 4.10. Each module contains a scheme of resonant frequency adjustment, a power source, a control unit and communication and synchronization systems. Each module can operate independently of other modules. Operating frequency of the prototype is 85 kHz. A receiving module (Fig. 4.11.) contains DD coils with measurements $250\text{ mm} \times 350\text{ mm}$, a resonant frequency adjustment scheme, adjustment of load, a control unit and a communication module.

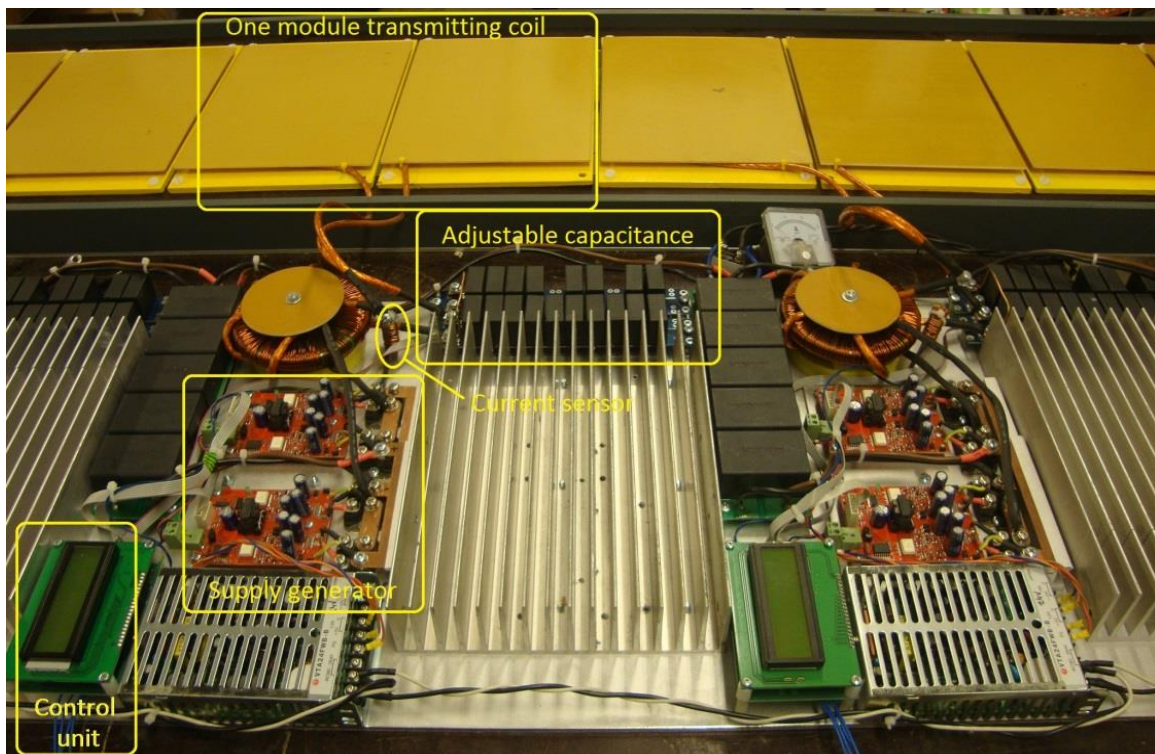


Fig. 4.10. Transmitting Module.

Magnetic sensors are used to synchronize the switching segments. In the receiver two constant magnets are installed – one with a south pole, the other-with a north one. In the transmitter near each couple of coils there is a magnetic sensor, which is screened from the variable magnetic field by a copper screen. Each magnetic sensor has a hall micro-scheme, an amplifier, a comparator and digital logics. The sensor has a digital output of the polarity of a magnetic field [24]. Each sensor is connected to the two adjacent segments. When a magnetic field of equal polarity arises on two vicinal sensors simultaneously, that is a signal for turning on the next segment and turning off the previous one. The design of the sensor is presented in Fig. 4.12. Additional sensors are installed on the margins of the road, securing the switch of the first couple of coils and turning off the last one. Synchronization system is aligned in parallel to the transmitting modules at a distance of 150 mm.

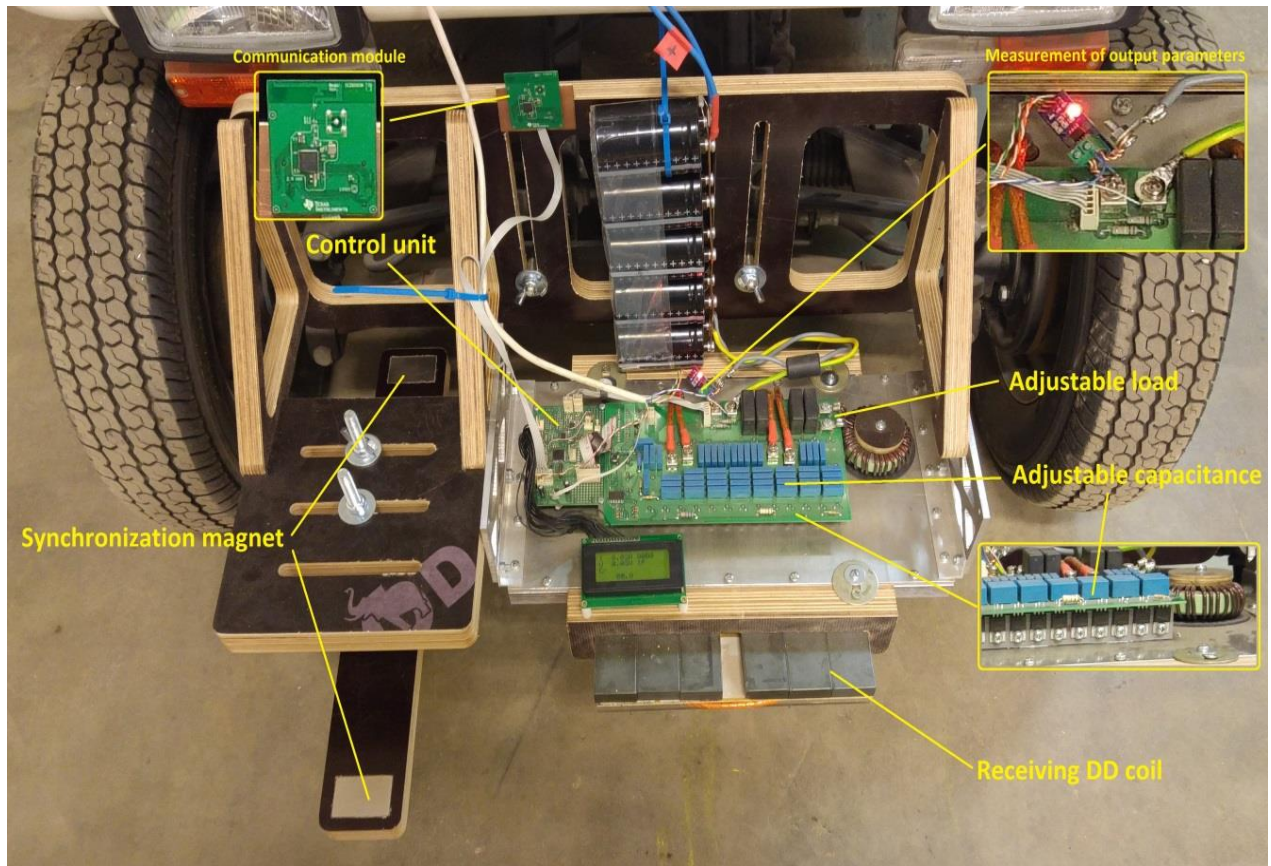


Fig. 4.11. Receiving module.

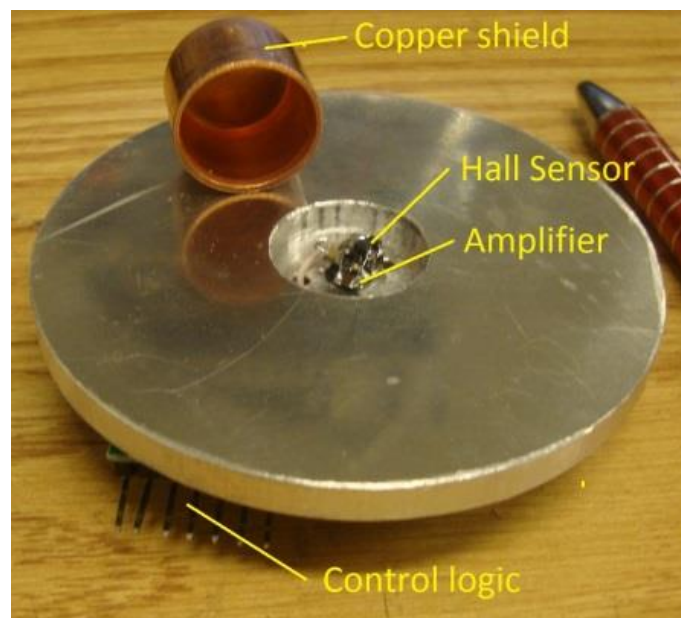


Fig. 4.12. Magnetic sensor of synchronization.

The communication system between transmitting and receiving modules is designed on the 802.15.1 technology based on a CC2650 chip. The coupling is initiated by a module aligned in the receiver of wireless power transmission. The receiver and the current transmitter exchange data consisting of both circuit currents, capacitors, the voltage of supplying generator and the load resistance. The point of optimal energy transfer for the

current value of the coupling coefficient receiving and transmitting circuit is calculated on the basis of this data. 20-byte data packets are used to exchange data between them.

Test results

During the experiment the operation of the system was tested in movement. The receiving module was mounted on a golf cart, which was driving over a segment of electric road with various speeds. The speed of the golf car was regulated by a controller and could be set constant from 0 km/h to 30 km/h. During the experiment, current and voltage were measured at the output of controlled electronic load, which was used to calculate the output power. The measurements were carried out by PICOSCOPL 5444A oscilloscope. Lead-acid batteries of a golf cart with voltage 48 V were used as a load. The transmitting part of the system was connected to the variable current mains using a rectifier. The general design of the experimental unit is presented in Fig. 4.13.



Fig. 4.13. General design of experimental unit.

The graph of the power transmitted as a load is presented in Fig. 4.14 a. The graph is scaled according to the distance. As the graph shows, at the speed of movement of 10 km/h and 20 km/h the operation of the system actually does not differ. At the peaks of power transmission there are oscillations emanating from the switching over of regulating systems. The difference in amplitude of transmitted power can be explained by the cross shift of receiving coil in relation to the electric road. At the speed of movement of 30 km/h the power lowers. The peak of power transmission moves to the right that indicates the delay of the algorithm of parameters adjustment. Figure 4.14 b presents the comparison of operation of the system with parameters automatic adjustment at the speed of 10 km/h with ideal characteristics and with a system without parameters adjustment.

The ideal characteristics were obtained by means of manually positioning the receiver in

relation to the transmitter at equal values of longitudinal shift and manually adjusting the parameters. On measuring the characteristic without the parameter adjustment, the circuits of an electric road and the receiver were separately tuned to frequency 85 kHz. The load of a secondary circuit was a resistor with a resistance of 10 Ω.

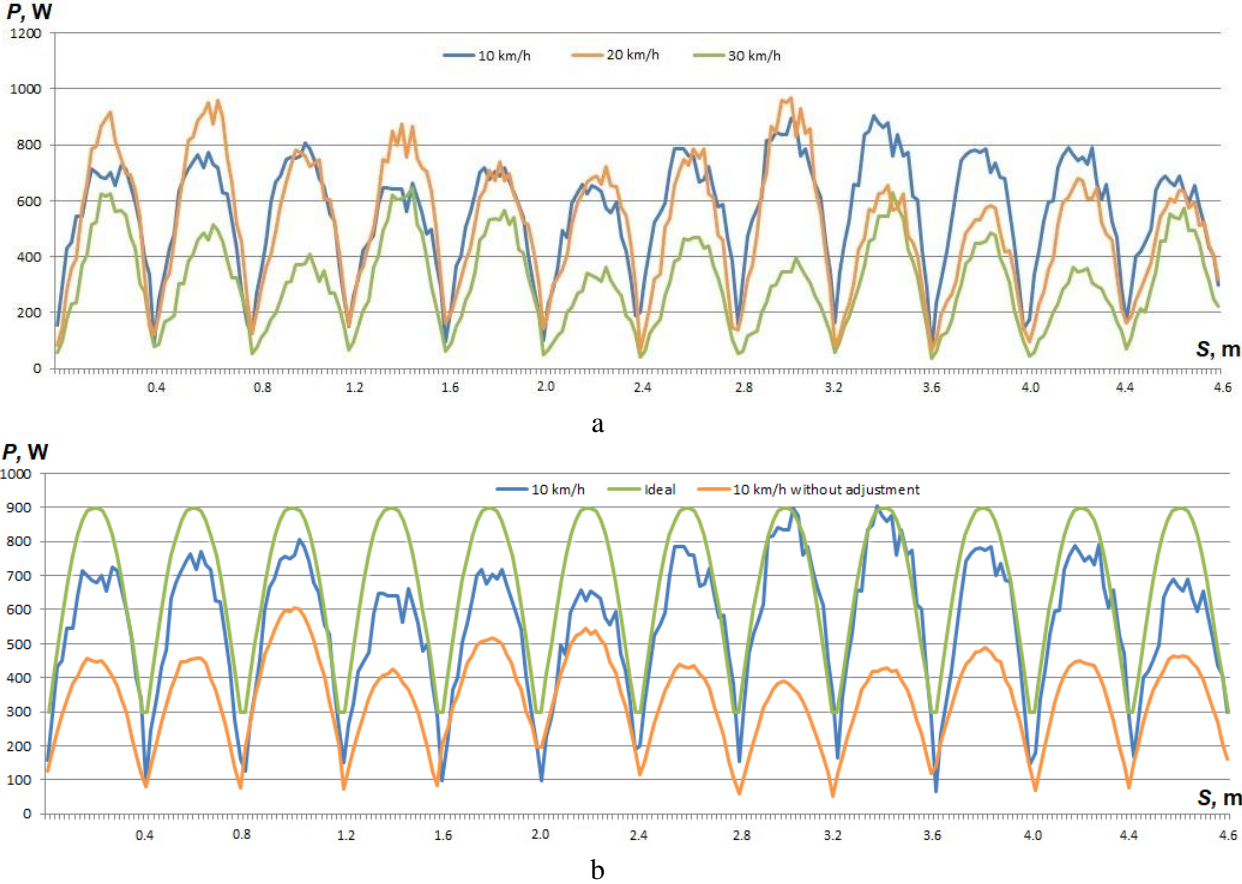


Fig. 4.14. Power in a load at different speeds (a); comparison of the operation with ideal characteristics and the system without parameters adjustment (b).

CONCLUSIONS

At the beginning of the work, the following hypotheses were formulated:

1. The most optimal way to organize a system of electrified roads is inductive-resonant power transmission.
2. The characteristics of the inductive-resonant power transmission coils have extremes tracking of which allows improving the power transmission parameters.
3. For the functioning of the inductive-resonant energy transmission system, it is necessary to adjust its parameters.

The following conclusions can be drawn from the research results:

1. During the research in Section 2, the most promising technologies for charging electric vehicles were considered. Most technologies available for stationary charging are not suitable for power transmission in motion. Of all the technologies the following may be suitable for this purpose: trolley systems with the electrical contact, transmission using microwave radiation and inductive-resonance method. Trolley systems have serious drawbacks in the form of mechanical contact and wear of exposed live parts, sensitivity to pollution and the problem of unification for different vehicles. Microwave energy transmission, at the moment, is only possible in theory due to the lack of receiving rectennas of the required power and dimensions. Therefore, at the moment, the only practical system for transferring energy to transport in motion is the inductive-resonant method. In this work, it has been proven in practice by implementing a road segment for wireless charging of vehicles in motion.
2. To confirm the second hypothesis, the study described in Section 3 was carried out, the hypothesis was fully confirmed. The characteristics of the coils of the inductive-resonant power transmission system were experimentally investigated, namely:
 - a) the influence of the distance between DD inductors on the parameters of the transmitting inductor;
 - b) the influence of the distance between the DD inductors on the frequency response of the resonant transformer;
 - c) the influence of the relative position of the inductors on the frequency response;
 - d) study of the efficiency of wireless power transmission using DD coils;
 - e) study of the influence of parallel excitation of the transmitting circuit on the parameters of the wireless power transmission system;
 - f) investigation of the effect of sequential excitation of the transmitting circuit on the parameters of the wireless power transmission system;
 - g) comparative estimates of the power transmitted from an area of a unit size of coils of different design (specific transmitted power);
 - h) investigation of a method for stabilizing the maximum efficiency of wireless power transfer by adjusting the output voltage.

With the help of an experimental setup the possibility of regulating the operating modes of the resonant transformer was confirmed by changing the voltage of the supply generator and the load parameters of the secondary circuit. Experiments on a

small prototype described in Section 4.3 clearly demonstrate the possibility of automatic adjustment of the parameters of wireless energy transfer.

3. The hypothesis was fully confirmed. From the experimental data, it can be concluded that the frequency drift to the side by 1 kHz makes the system inoperative. It was found that changing the distance between the coils by 20 mm leads to a shift in the resonant frequency by 3 kHz. This leads to a mismatch of the resonant transformer with the oscillation source and a drop in the transmitted power. It follows from this that it is necessary to adjust and track the resonant frequency of the circuits, otherwise the resonance effect will not appear and the system will work as an induction one. It can also be seen from the graph presented in Fig. 4.8 that the load resistance corresponding to the optimal point of operation varies depending on the distance between the coils. It follows, that to achieve the point of maximum power or maximum efficiency, it is necessary to adjust the load resistance. Looking at the test results of a dynamic power transmission system, presented in Fig. 4.14 b, it can be seen that the difference in transmitted power differs by two times when the system is operating with and without tuning parameters.

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