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CONSTRUCTION OF A RADIOFREQUENCY WIRELESS SYSTEM FOR ELECTRIC ENERGY TRANSMISSION

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Abstract: *THE PURPOSE. The objective of this study is to investigate the possibilities of longer distance resonant energy transmission applying Wireless Power Transfer (WPT) in the MHz frequency range. The planned final purpose is the energy to be transferred to all types (aerial and terrestrial) of electric vehicles (EV), mainly for the battery charging at a larger distance, compared to the normal dis-tances of WPT in use at this moment. The key to this type of High Frequency (HF) WPT system is the strong resonant inductive coupling. METHODS. This project is based on the HF power oscillations generating equipment, which original function is to generate several kW of power at MHz frequency for welding of acrylic or other plastic details. RESULTS. As a first step, the equipment was modified to supply HF power for the WPT transmitter coil, instead of supplying power to the soldering plates. The operation frequency is defined by the factory, and it is made now regulable between 8 and 14 MHz by introducing a vacuum variable capacitor. The internal powerful oscillator is based on the electronic vacuum tube ITL 5-1, a military type, capable to deliver up to 3.5 kW active power at the output. The original output had a coaxial form for supplying finally the capacitive load of the dielectric welder. This had to be reworked and a resonant loop, i.e., a capacitively compensated transmitting coil, is now connected. The intended application of this HF system is to charge the batteries of a public transport EV, possibly during its periodic stops, while the passengers will enter and leave. CONCLUSION. The applied frequency is relatively high and the distances are larger, this system still uses the magnetic field as the energy transporter, i.e., it is a near field transmission, a non-radiating system, and is expected not to produce adverse effects on the human being's health, or to achieve a safe protection from the field.*

Keywords: *Wireless Power Transfer; Aerial and Terrestrial Electric Vehicles; Longer Distance Resonant Energy Transmission; Batteries Charging; Magnetic Coupled Resonator.*

СОЗДАНИЕ РАДИОЧАСТОТНОЙ БЕСПРОВОДНОЙ СИСТЕМЫ ПЕРЕДАЧИ ЭЛЕКТРОЭНЕРГИИ

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Резюме: *Целью данного исследования является изучение возможностей резонансной передачи энергии на большие расстояния с применением беспроводной передачи энергии (WPT) в диапазоне частот МГц. Планируемая конечная цель - передача энергии всем типам (воздушным и наземным) электромобилей (EV), в основном для зарядки аккумуляторов на большем расстоянии по сравнению с обычными расстояниями БПЭ, используемыми в данный момент. Ключом к этому типу высокочастотной (ВЧ) системы БПЭ является сильная резонансная индуктивная связь. МЕТОДЫ. В основе этого проекта лежит оборудование для генерации высокочастотных колебаний мощности, первоначальная функция которого - генерировать несколько киловатт мощности на частоте МГц для сварки акриловых или других пластмассовых деталей. ПОЛУЧЕННЫЕ РЕЗУЛЬТАТЫ. В качестве первого шага оборудование было модифицировано для подачи ВЧ мощности для катушки передатчика БПЭ вместо подачи питания на паяльные пластины. Рабочая частота определяется заводом-изготовителем, и теперь она регулируется в пределах от 8 до 14 МГц за счет использования вакуумного переменного конденсатора. Внутренний мощный генератор построен на базе электронной вакуумной лампы ИТЛ 5-1 военного типа, способной выдавать на выходе активную мощность до 3,5 кВт. Исходный выход имел коаксиальную форму для питания емкостной нагрузки диэлектрического сварочного аппарата. Это пришлось переделать, и теперь подключен резонансный контур, то есть передающая катушка с емкостной компенсацией. Предполагаемое применение этой ВЧ-системы - зарядка аккумуляторов электромобиля общественного транспорта, возможно, во время его периодических остановок, когда пассажиры будут входить и выходить. ЗАКЛЮЧЕНИЕ. Применяемая частота относительно высока, а расстояния больше, эта система по-прежнему использует магнитное поле в качестве переносчика энергии, то есть это система передачи ближнего поля, не излучающая, и ожидается, что она не окажет неблагоприятного воздействия на человека. здоровья существа, или добиться надежной защиты от поля.*

Ключевые слова*: беспроводная передача энергии; воздушные и наземные электромобили; передача резонансной энергии на большие расстояния; зарядка аккумуляторов; магнитно-связанный резонатор.*

Introduction

The desire to make possible the energy supply to remote consumers, led Nikola Tesla to invent and start experimenting a system that allows a transmission of electrical energy over long distances, without using cables. The history will always remember this inventor with his remarkable 235 patents [1]. The concept of the power transmission without any physical support has more than a century. Pioneering this concept, Tesla built an experimental system in Colorado in 1899. With that system he transmitted electric energy by high frequency at a considerable distance [1, 2].

With the advance of the semiconductor technologies Tesla's dream has now become reality [2, 3]. The wireless nature of this process makes it useful in environments where implementation of physical (galvanic) connection can be inconvenient, hazardous, or impossible. Particularly in the electric vehicles (EV) battery charging, the WPT shows to be very convenient [3]. The different types of the wireless power transfer are shown in Figure 1.

The different technologies used in the branches of Figure 1, are associated with the working distance and the power to be transferred between transmitter and receiver.

Nowadays, the WET has different applications in a large spectrum of human activity. For example, in order to reduce the risk of post-operative infection and patient discomfort, a Transcutaneous Energy Transfer is widely applied to wireless powering of implantable biomedical devices [4, 5]. Examples may be some left ventricular assist devices, artificial retinas and wireless neurostimulators [5]. The technology used in these applications are the inductive coupling and the magnetic resonance coupling [6].

In the applications concerning EV batteries charging, both Stationary (in a garage) or In Movement (online), the technology used is the magnetic resonance coupling, because of a lot improved efficiency [7, 8]. To exercise a long-range energy transfer, the developed technology is the Electromagnetic Waves Power Transfer (EWPT), which is still not enough mature for a practical implementation. This technology is based on the very high-frequency energy beam, possibly transmitted from a geostationary orbital Solar Power Satellite System (SPSS) [9]. The concept was introduced by Peter Glaser in 1968, who suggested the receiver to be mounted on the Earth surface of several km^2. The microwaves beam was experimented by Glaser for supplying a small flying helicopter at 200 m distance. Another idea is suggesting a Laser beam sent to the Earth a rectenna (rectifier plus antenna) system [9].

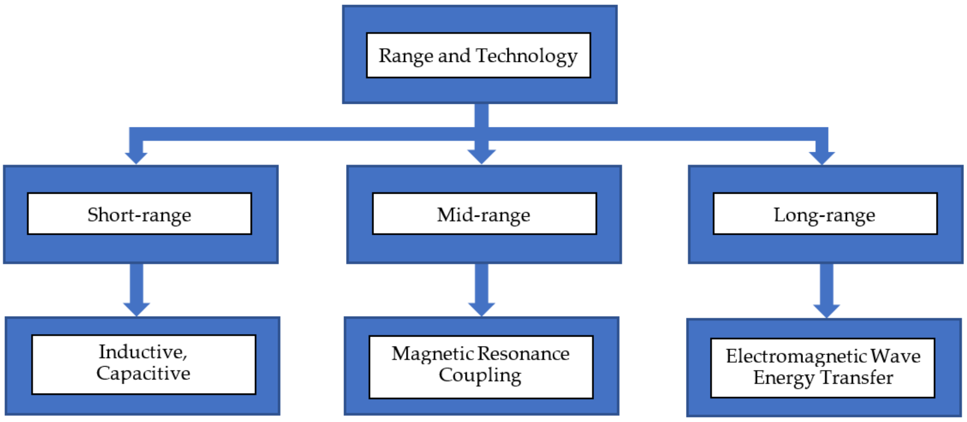

Fig. 1. Types of the Wireless Power Transfe *Рис. 1. Типы беспроводной передачи энергии.*

Methods. Wireless Power System Formulation. Triode operation

The electronic tubes are constructively formed by a casing of glass, ceramic and metal, containing therein a gas (special cases) or vacuum (normally). In the first case they are called gas valves, the second type are just the normally used electronic valves. To conduct an electric current the electronic tube has at least two electrodes. The first electrode is emitting electrons [10-12]. This is the cathode (k_T). The target electrode that attracts and receives the electrons, is called a plate (p) or anode (a).

To produce free electrons the cathode (k_T) must be heated and this is done directly or indirectly. In the first case, the cathode (k_T) is heated by an electric current that passes through it. In the second case there is a heating resistance (filament), inside the cathode (k_T), which stays isolated from that filament [11, 12].

For an electron to leave the surface of the cathode (k_T), it is necessary to obtain the extraction energy level, represented by W_0. If the charge of the electron is represented by q_0, then the extraction potential is given by:

$$V_0 = \frac{W_0}{q_0} \tag{1}$$

The V_0 represents the extraction potential that is used as the fundamental value for the formula given by Owen Richardson:

$$I_p = KT^2 \cdot e^{(-11666 v_o \cdot T)} \tag{2}$$

Where I_P is the anode current, here named the plate current, K is a constant that depends on the material and T is the absolute temperature in Kelvin.

The coefficient K is known mostly as Richardson coefficient A_G and its approximated value is: 1.2×10^6 [Am^{-2}K^{-2}], i.e., it is a current density per absolute temperature squared.

Once the cathode (k_T) is heated, a cloud of electrons is formed, as a space charge, around the cathode (k_T). The effect is known as Edison effect [12, 13]. It is concluded that the electric current depends on three factors:

The voltage applied between the cathode (k_T) and the plate;

The temperature of the cathode (k_T);

The distance between the cathode (k_T) and the plate $(anode)$.

Briefly, the electric current rises when the anode *(a)* is growing more positive in relation to the cathode (k_T) and the current goes higher also with the rising temperature and with the reduced distance between the anode (a) and the cathode (k_T). The function current/voltage known as “two thirds”, is further developed in (3). This operation, conducting at positive voltage of the plate and not conducting at negative plate voltage, is used in the simplest electron tube diode Rectifiers. Being the flux of electrons very limited, the vacuum tube diodes are far from ideal, presenting quite a high voltage drop [13, 14]. This particularity of the electron tubes obliges to use always a relatively high voltage supplied to the electronic tube circuits when the power electronics equipment is constructed.

Lee De Forest conceived the idea of introducing a third electrode in the vacuum tube. This additional element, the grid, controls the current flowing between the cathode (k_T) and the plate (*p*). Fig. 2 shows the triode (three terminals tube) symbol with its elements.

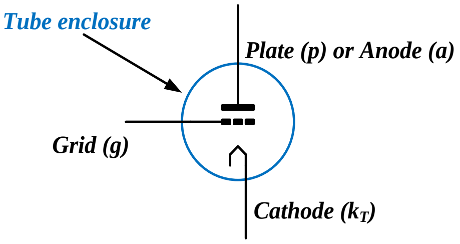

Fig. 2. Triode symbol *Рис. 2. Обозначение триода.*

The grid is more negative than the cathode when the valve operates as an amplifier or as a linear regulator of the electron flux. Then the grid repels some electrons. This negative grid voltage is used as a bias voltage, i.e., a fixed voltage between the grid and the cathode, when the tube is a linear regulator. The most negative grid-to-cathode voltage value that blocks completely the plate current is the cut-off voltage. Its value depends on the plate voltage [14, 15]. The plate (*p*) current is a function of the grid voltage, and the plate *(p)* voltage is given by:

$$I_p = K\left(E_g + \frac{E_p}{\mu}\right)^{3/2} \tag{3}$$

In (3) constant *K* depends on the size of the valve. According to (3) the anode (a) current is only possible plate (*p*) when:

$$\left(E_g + \frac{E_p}{\mu}\right) > 0 \tag{4}$$

The factor μ represents the most important parameter of the valve, the "voltage amplification", and is a constant, independent of any voltage. It depends only on the geometry of the valve [15, 16]. The maximum current could be reached if the grid would be made positive, but this is made very carefully as the grid is only capable to accept limited values of grid current. There are three static characteristics, which are essential, and characterize the valve. In the case of the tube ITL 5-1 it is declared by the producer:

Amplification factor (μ)–20 (approx.)

Grid resistance $\left(R_g\right)$–1250 Ω

Transconductance $\left(g_m\right)$–23 mA/V

These (differential) parameters are defined as:

$$\mu = \left(\frac{\Delta E_p}{\Delta E_g}\right) at\, I_P = constant$$

$$R_p = \left(\frac{\Delta E_p}{\Delta I_p}\right) at\, E_g = constant$$

$$g_m = \left(\frac{\Delta I_p}{\Delta E_g}\right) at\, E_p = constant$$

Relates the three parameters is given by:

$$g_m = \frac{\mu}{R_p} \tag{5}$$

Fig. 3 represents the physical model of a triode, where all the "small signal" important elements that constitute a triode are shown.

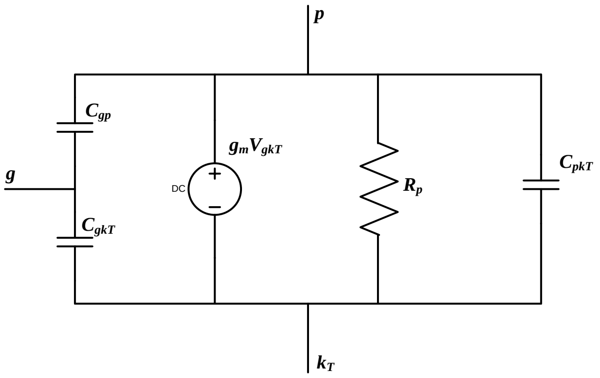

Fig. 3. Equivalent circuit of a triode as amplifier a "small signal" approximation

Рис. 3. Схема замещения триода в качестве усилителя в приближении "малого сигнала"

Oscillator operation

The requirement for negative grid voltage is not valid in the case of an oscillator circuit. In this case the "amplifier" has a positive feedback.

By the positive feedback the oscillator will transform the DC supply voltage into an AC voltage output, i.e. producing oscillations. The basic principle of an oscillator is shown in Fig. 4.

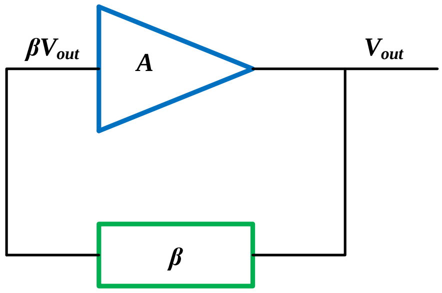

Fig. 4. Basic principle of an oscillato

Рис. 4. Основной принцип работы осциллятора.

There are three essential conditions that an oscillator must have:

Ability to self-excitation;

Frequency Stability;

Amplitude stability.

The equation that the circuit must obey to oscillate and have a stable oscillation is the following:

$$\vec{\beta} \times \vec{A} = 1 \tag{6}$$

Here $\vec{\beta}$ is defined as a reaction, or the feedback factor, and is given by:

$$\vec{\beta} = \frac{\overrightarrow{V_r}}{\overrightarrow{V_p}} \tag{7}$$

The V_p is the rms value of the AC component of the plate *(p)* voltage and V_r is the rms feedback voltage. The amplification $\vec{A}$ is defined by the coefficient between the plate voltage V_p and the grid voltage V_g, given by the relation:

$$\vec{A} = \frac{\overrightarrow{V_p}}{\overrightarrow{V_g}} \tag{8}$$

The condition for which there is balance in terms of amplitude and frequency should be verified by the following equation:

$$\vec{\beta} = \frac{1}{\mu} + \frac{1}{gm\vec{Z}} \tag{9}$$

In this equation, the gain μ and the transconductance g_m do not depend on the frequency. Only $\vec{Z}$, the impedance, depends on it. To reach the maximum $\vec{Z}$ of the load, that includes inductance L and capacitance C, the oscillators use the resonant frequency, given by:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{10}$$

For the HF power generator, a tuned plate (*p*) oscillator is used as shown in the following Fig. 5.

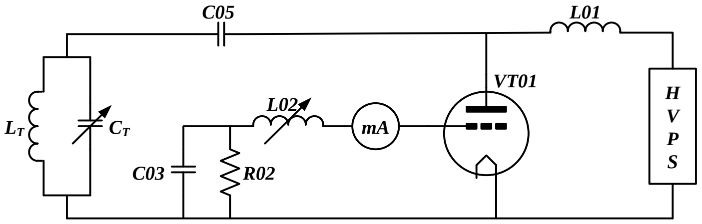

Fig. 5. Schematic of the oscillator used (plate (p) tuned)

Рис. 5. Схема используемого генератора (пластина (п) настроена)

The tuned circuit determining the frequency, comprises L_T and the regulable C_T. The capacitor C_{05} and the inductance L01 serve to isolate the DC power supply from the resonant tank circuit L_TC_T. The biasing of the grid is done by the leakage resistance R_{02} and the capacitor C_{03}. When the generator reaches its normal operation, only a low positive current shall be allowed, and for that reason the grid current is measured. The grid bias voltage is equal to the voltage drop at the R_{02} terminals. The measurement of the grid current is important for avoiding a highly positive grid current, which is known to be dangerous to the valve and its vacuum level.

Resonant circuits

The resonant processes and their parameters will be simplified in the further chapters text. The voltage source will be included with its internal impedance (resistance) into the resonant circuit. The generator voltage is presented further in series with the inductor L, as it is normally induced into the resonant inductance. In this generalized approach there are two important basic parameters that describe the resonance [17, 18].

- Resonance frequency ω_0;
- Intrinsic loss rate ξ (dumping factor).

The circuit of Fig. 6 represents the equivalent *RLC* series circuit.

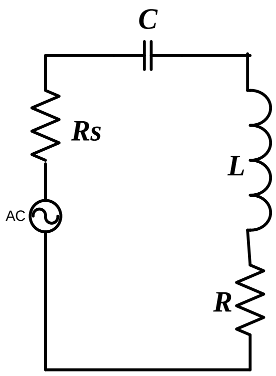

Fig. 6. RLC series circuit with an AC voltage source (generator)

Рис. 6. Последовательная схема RLC с источником (генератором) переменного напряжения

Here the R_S is internal resistance of the generator, and the resonant circuit parameters are as already defined.

Applying the Kirchhoff's Law to the circuit of Fig. 6 results in:

$$u_s.sin(\omega t) = u_L + u_R + u_C \tag{11}$$

$$i = \frac{dq_C}{dt} \tag{12}$$

$$u_s \sin(\omega t) = L\frac{d^2 q_C}{dt^2} + R\frac{dq_C}{dt} + \frac{q_C}{C} \tag{13}$$

Dividing (13) by L is given:

$$\frac{d^2 q_C}{dt^2} + \frac{R}{L}\frac{dq_C}{dt} + \frac{q_C}{L.C} = \frac{1}{L}u_s \sin(\omega t) \tag{14}$$

and:

$$\omega_0 = \frac{1}{\sqrt{L.C}} \tag{15}$$

then:

$$LC = \frac{1}{\omega_0^2} \tag{16}$$

Substituting the LC from (16) into (14) is obtained:

$$\frac{d^2 q_C}{dt^2} + \frac{R}{L}\frac{dq_C}{dt} + \omega_0^2 q_C = \frac{1}{L}u_s \sin(\omega t) \tag{17}$$

The intrinsic loss rate is defined by

$$\zeta = \frac{2L}{R} \tag{18}$$

or

$$\frac{R}{L} = \frac{2}{\zeta} \tag{19}$$

replacing (18) into (17):

$$\frac{d^2 q_C}{dt^2} + \frac{2}{\zeta}\frac{dq_C}{dt} + \omega_0^2 q_C = \frac{1}{L}u_s \sin(\omega t) \tag{20}$$

The stored energy is represented by the quality factor Q, which is defined by:

$$Q=\sqrt{\frac{L}{C}}\cdot\frac{1}{R}=\frac{\omega_0 L}{R} \tag{21}$$

Coupled resonators

Figure 7 represents a coupled resonator system:

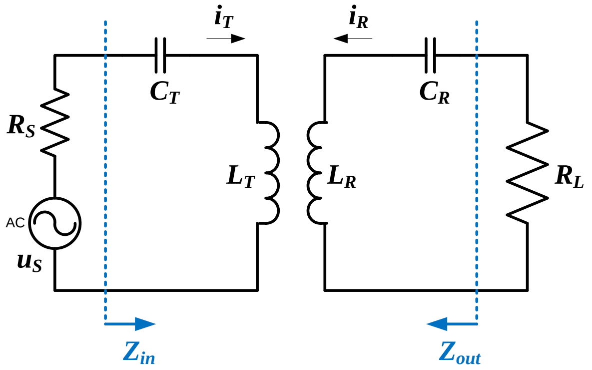

Fig. 7. Coupled resonators *Рис. 7. Связанные резонаторы*

There are two possibilities to reach the maximum transferred power. The first possibility is to use a constant AC current source, the second is to use a constant AC voltage source [17, 18].

Constant AC current source

The maximum power transferred reaches the maximum point when the current in the load is maximum and is defined by:

$$i_R=-\frac{\omega^2 M_{T,R}C_R}{j\omega C_R R_L+1-\omega^2 L_R C_R}\times i_T \tag{22}$$

The resonant frequency is given by:

$$\omega_0\left(I_R=\infty\right)=\frac{1}{2\sqrt{L_R C_R}} \tag{23}$$

Constant AC voltage source

In the second possibility, the maximum current is given by:

$$i_R=-\frac{j\omega^3 M_{T,R}C_T C_R}{\left(j\omega C_T R_L+1-\omega^2 L_T C_T\right)\left(j\omega C_R R_L+1-\omega^2 L_R C_R\right)-\omega^4 M_{T,R}^2 T C_R^2}\times u_s \tag{24}$$

The resonant frequency is given by:

$$\omega_0\left(I_R=\infty\right)=\frac{\sqrt{L_T C_T+L_R C_R-\sqrt{L_T^2 C_T^2+L_R^2 C_R^2-2\left(1-k^2\right)L_T C_T L_R C_R}}}{2\pi\sqrt{2\left(1-k^2\right)L_T C_T L_R C_R}} \tag{25}$$

Wireless resonant power transfer

The series resonance can be obtained in two modes [17, 18]:

- The influence of the receiver circuit on the transmitter circuit;
- The influence of the transmitter circuit on the receiver circuit.

The Figure 8 represents the secondary (receiver) impedance reflected as $R_{R,T}$ into the transmitter circuit.

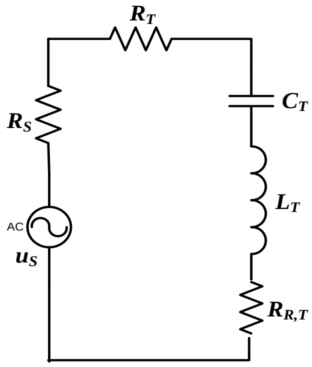

Fig. 8. The receiver impedance reflected into the transmitter circuit

Рис. 8. Импеданс приемника, отраженный в цепи передатчика

The reflected resistance of the receiver circuit into the transmitter circuit is represented by $R_{R,T}$, given by:

$$R_{R,T} = \frac{\omega^2 M_{T,R}^2}{Z_r} \tag{26}$$

In Figure 9 is represented the transmitter AC voltage source (generator) reflected on the receiver circuit.

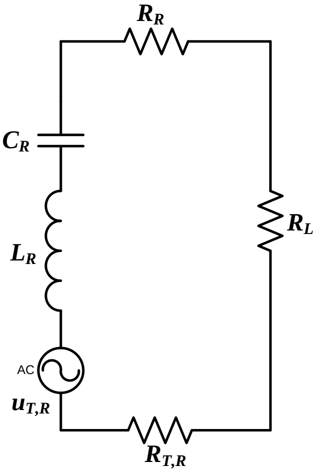

Fig. 9. The transmitter voltage source reflected into the receiver circuit

Рис. 9. Отражение источника напряжения передатчика в цепь приемника

The reflected resistance of the transmitter circuit into the receiver circuit is, represented by $R_{T,R}$, is given by:

$$R_{T,R} = \frac{\omega^2 M_{R,T}^2}{Z_t} \tag{27}$$

And the voltage $U_{T,R}$ is given by:

$$u_{T,R} = \frac{j\omega M_{R,T}}{Z_t} u_s \tag{28}$$

By modifying (26) is given by:

$$R_{R,T} = \frac{\omega^2 M_{R,T}^2}{R_r + R_L} \tag{29}$$

The transfer efficiency is given by:

$$\eta = \frac{\omega^2 M_{T,R}^2 R_L}{\left(R_r + R_L\right)\left[\omega^2 M_{T,R}^2 + \left(R_t + R_s\right)\left(R_r + R_L\right)\right]} \tag{30}$$

The mutual inductance is given by:

$$M = k\sqrt{L_T L_R} \tag{31}$$

Where k is the energy coupling rate between the two coils.

The maximum transferred power P_L can be achieved when the mutual inductance is fixed, and that P_L is given by:

$$P_L = \frac{\omega^2 M_{T,R}^2 U_s^2 R_L}{\left[\omega^2 M_{T,R}^2 + \left(R_t + R_s\right)\left(R_r + R_L\right)\right]^2} \tag{32}$$

Prototype Design. Proposed Wireless Power System

The Magnetic resonance coupling working in MHz frequency band is being widely considered a promising technology for mid-range transfer of a low up to a medium amount of power [19].

The results reported in this work, are based on a factory-made welding generator manufactured by APRONECS Ltd, Bulgaria. The active element of that generator is a vacuum tube (triode) ITL 5-1, working in class C, with the following basic data of the device.

Frequency up to 150 MHz
Continuous wave (CW) power, up to 13 kW
Plate (*p*) voltage up to 7.2 kV
Filament voltage 6.3 V
Filament current 65 A

A parallel resonance tank circuit is associated with the triode connected to its plate (*p*), and also named anode (*a*). The block diagram of the transmitter and receiver tanks is shown in Figure 10.

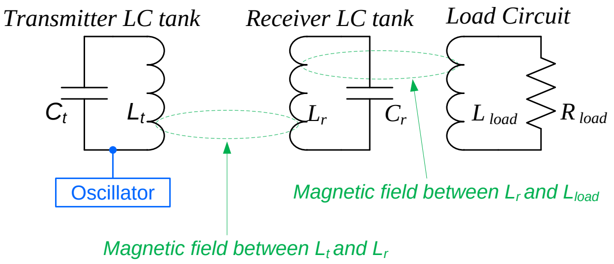

Fig. 10. Idealized diagram of the transmitter-receiver resonant circuits

Рис. 10. Идеализированная схема резонансных контуров передатчика-приемника

Transmitter coil value determination

The measured transmitter coil inductance value is:

$$L_T = 1{,}9\,\mu\text{H} \tag{33}$$

Medhurst's [20] formula was used to calculate the value of the distributed capacitance given by:

$$C = \left(11{,}26 \times l + 16r + 76{,}4 \times \sqrt{\frac{r^3}{l}}\right) \times 10^{-12} \tag{34}$$

$$C = \left(11{,}26 \times 0{,}11 + 16 \times 0{,}4 + 76{,}4 \times \sqrt{\frac{0{,}4^3}{0{,}11}}\right) \times 10^{-12} = 65{,}9\,\text{pF} \tag{35}$$

The available capacitor $\left(C_t\right)$, connected in parallel with the transmitter coil is a vacuum variable capacitor, with glass encapsulation and with an adjustable capacitance between 5 pF and

$100\,\mathrm{pF}$. Assuming that the variable capacitor is set to the middle of its total value, the resonance frequency value is given by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{1,9\times10^{-6}\times115,9\times10^{-12}}} = 10,73\,\mathrm{MHz} \tag{36}$$

Aiming a working frequency of $13,33\,MHz$, it was necessary to check the available variable capacitor, has enough capacitance C_{total} to tune to that frequency.

$$C_{total} = \frac{1}{4\pi^2 L_t f_0^2} \tag{37}$$

$$C_{total} = \frac{1}{4\pi^2\times1,9\times10^{-6}\left(13,33\times10^6\right)^2} = 75,03\,\mathrm{pF} \tag{38}$$

From this calculated value it is necessary to subtract the value of the distributed capacitance in (35), given by:

$$C_T = 75,03 - 65,9 = 9,13\,\mathrm{pF} \tag{39}$$

Thus, the calculated value is within the possible adjustment values.

Receiver coil inductance determination.

For maximum energy transfer, both resonant circuits must be tuned to the same frequency is given by:

$$f_T = f_R \tag{40}$$

Where:

$$L_T C_T = L_R C_R \tag{41}$$

The available capacitor for the receiver circuit is a similar vacuum capacitor, with a glass encapsulation and capacitance varying between $5\,\mathrm{pF}$ and $250\,\mathrm{pF}$. The assumed capacitance midpoint value is $125\,\mathrm{pF}$.

Replacing the values in (41) gives:

$$1,9\times10^{-6}\times75,03\times10^{-12} = L_R\times125\times10^{-12} \tag{42}$$

Then the calculated value is:

$L_R = 1,14\,\mu\mathrm{H}$ The measured value of the coil, built by the authors, was $1,2\,\mu\mathrm{H}$.

The distributed capacitance value of this coil is given by:

$$C = \left(11,26\times l + 16\times r + 76,4\times\sqrt{\frac{r^3}{j}}\right)\times10^{-12} \tag{43}$$

$$C_{Rd} = \left(11,26\times0,13 + 16\times0,15 + 76,4\times\sqrt{\frac{0,15^3}{0,13}}\right)\times10^{-12} = 16,2\,\mathrm{pF} \tag{44}$$

The total capacitance value results from the sum of the receiver coil distributed capacitance with the midpoint value capacitance from variable capacitor.

$$C_{Rt} = C_R + C_{Rd} = 125 + 16,2 = 141,2\,\mathrm{pF} \tag{45}$$

The resonance frequency value determination for these L and C values gives:

$$f_0 = \frac{1}{2\pi\sqrt{L.C}} = \frac{1}{2\pi\sqrt{1,2\times10^{-6}\times141,2\times10^{-12}}} = 12,23\,\text{MHz} \qquad (46)$$

The values of the transmitter and receiver frequencies can be adjusted via variable capacitors.

Mutual inductance value determination

The mutual inductance value is determined using the following equation.

$$M = k\sqrt{L_t L_r} \qquad (47)$$

Here, k is the coupling coefficient value, L_T is the inductance value of the transmitter coil, the L_R is the inductance value of the receiver coil and M is the mutual inductance.

The two circuits, the receiver, and the transmitter, are tuned to the same frequency f_0. Whenever k is greater than zero, the mathematical analysis shows that the two circuits, when magnetically connected, can admit two resonant frequencies f_1 and f_2, given by:

$$f_1 = \frac{f_0}{\sqrt{1-k}} \qquad (48)$$

and

$$f_2 = \frac{f_0}{\sqrt{1+k}} \qquad (49)$$

In the tests performed, the following values of f_1 and f_2 were measured:

$f_1 = 8,75$ MHz and $f_2 = 15,16$ MHz.

These values make it possible to determine the value of k equal to $0,5$.

Substituting the values in (47), the following mutual inductance value is given by:

$$M = 0,5.\sqrt{1,9\times10^{-6}\times1,2\times10^{-6}} = 755\,\text{nH} \qquad (50)$$

Prototype Implementation and Results

As mentioned previously, this work was based on an equipment, produced by the company APRONECS Ltd. Several modifications were made later to this equipment.

All the coils shown in this diagram are made of copper pipe with 12 mm outside diameter and 1mm thickness (internal diameter is 10 mm). The Figure 11 shows the real view of the transmitting coil. Figures 12 shows the transmitting coil and its adjustment bracket.

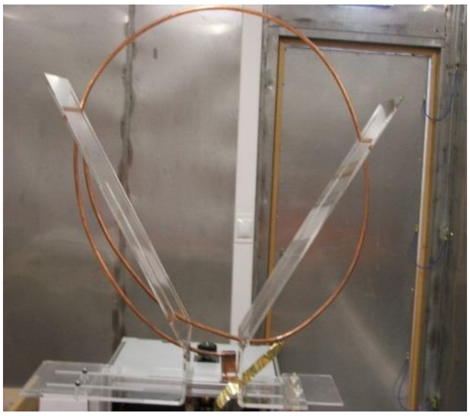

Fig. 11. Photograph of the transmitter coil *Рис. 11. Фотография катушки передатчика*

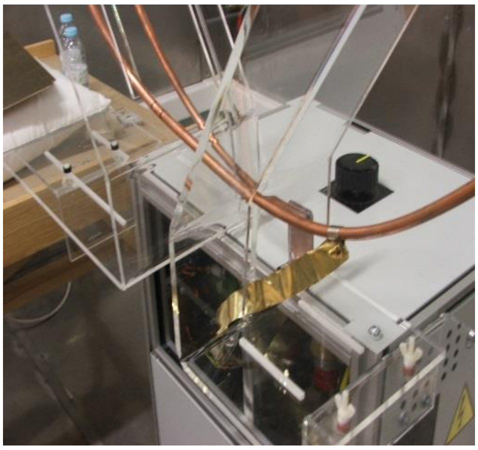

Fig. 12. Photograph of the connected adjustable transmitter coil

Рис. 12. Фотография подключенной регулируемой катушки передатчика

The Figure 13 shows the receiver unit.

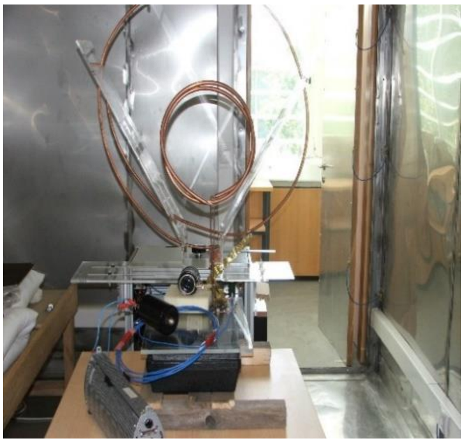

Fig.13. The receiver unit (in the center)

Рис.13. Приемный блок (в центре)

The Figure 14 shows the receiver unit with more details.

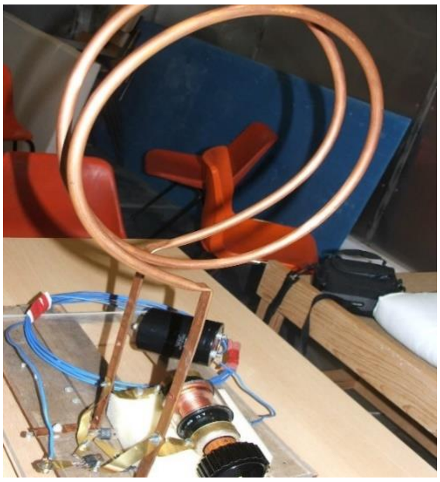

Fig. 14. The detailed image of the receiving unit

Рис. 14. Детальное изображение приемного устройств

Figure 15 shows an image taken during the final tests. It shows a 40 W lamp lit with the energy transmitted through the WPT system. The distance between the transmitting coil and the receiving coil is 1,5 m. The working frequency that allowed the system to be optimized was 8,461 MHz on the transmitting circuit and 8,426 MHz on the receiving circuit.

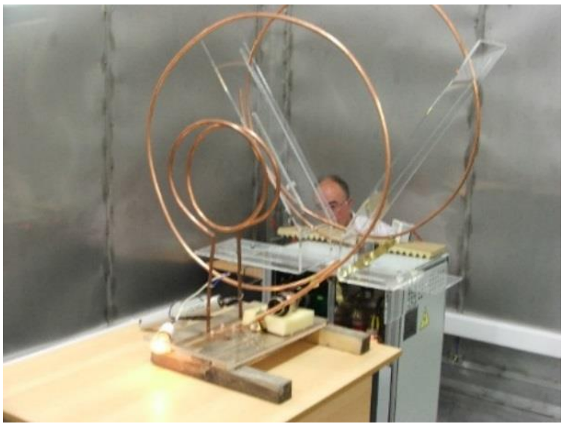

Fig. 15. An image obtained in the final tests, 40W lamp (author's photo)

Рис. 15. Изображение, полученное в финальных тестах, лампа 40Вт (фото автора)

Results

Figure 16 shows the voltage waveforms at the transmitting tank circuit (at the inductor). The scale voltage is 2.0 kV, so the peak is 8 kV.

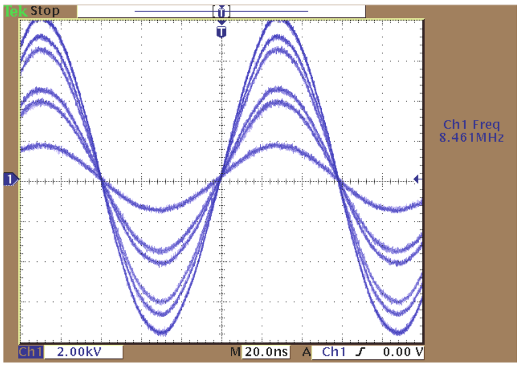

Fig.16. Voltage waveforms of the transmitting tank circuit (the inductor terminals)

Рис.16. Осциллограммы напряжения цепи передающего бака (клеммы индуктора)

Figure 17 shows the voltage signal to the receiving tank circuit terminals. The peak voltage is 200 V.

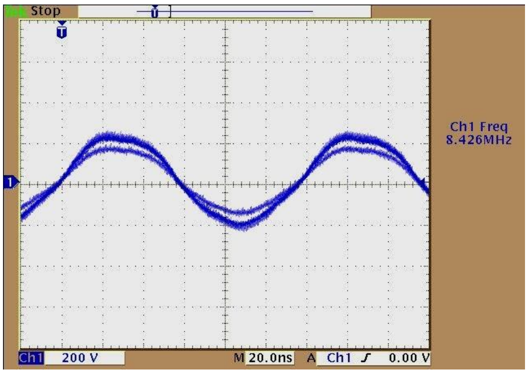

Fig. 17. The voltage waveform at the receiving tank circuit (the inductor terminals)

Рис. 17. Осциллограмма напряжения в цепи приемного бака (выводы индуктора).

Conclusions

The wireless power system presented was built based on a high-power high-frequency electronic tube oscillator. This oscillator has a triode valve as its central element. At a distance of 1,5 m it was possible to light a 40 W lamp. The main difference to the currently constructed systems is that it presents a transmitter based on vacuum tube oscillator. A necessary rectifier for battery charging was also experimented, implemented on silicon carbide (SiC) Schottky diodes. In [21], authored by George I. Babat, some more details could be found from his experiments during 1940s in Moscow, mainly in the metro lines. In the publications in Russian language during 1942 and after 1942, he claims more than 60% of efficiency by electronic valve generators for propulsion of electric vehicles online (during their movement).

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