WIRELESS ENERGY TRANSMISSION IN LIMITED POWER SYSTEMS. PROBLEM ANALYSIS AND WAYS TO SOLUTION

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ABSTRACT

The development of wireless energy transfer technologies occurs in several directions, each of which is characterized by its own set of driving forces and factors motivating the development. These factors are different and must be explicitly taken into account in our analysis, because in the dynamically changing world of knowhow and high-tech innovative projects, there is a clear tendency to reduce the time distance between a technical idea and its commercially in demand implementation. The paper provides an analysis of existing approaches in wireless transmission of electrical energy (WPT). The choice of one of the promising directions in wireless energy transmission technologies is justified - energy transmission via microwave radio signals. The main problems in this area are formulated and the possibility of supplying energy to remote autonomous devices using low-power high-frequency signals is considered. The results of the analysis are aimed at developing working prototypes of wireless power transmission devices. The current level of development of the production of electronic components makes it possible to create devices with dimensions of several millimeters, while the dimensions of the final devices are determined by the dimensions of antennas and batteries.

KEYWORDS: *Wireless energy transfer, high-frequency radio emission, magnetic resonance method, remote charging, sensor networks, printed antennas, rectenna, reverse diodes.*

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1 Introduction

Wireless energy transmission technologies are increasingly making themselves known in the modern industrial world. At the same time, the development of such technologies occurs in several directions, each of which is characterized by its own set of driving forces and factors motivating the development. These factors are different and must be explicitly taken into account in our analysis, because in the dynamically changing world of knowhow and high-tech innovative projects, there is a clear tendency to reduce the time distance between a technical idea and its commercially in demand implementation. However, along this path, directions, methods and solutions that have great prospects from a general technical point of view may be deprived of the attention of researchers and venture investors at the current moment.

WPT technologies, actively being developed and partly already used today, can be classified into:

– the physical principles underlying them;
– power of transmitted energy flow;
– technical and design solutions for transmitting and receiving devices;
– areas of practical application and technological features of use.

According to physical principles, WPT technologies are divided into the following:

– technologies based on electrostatic induction;
– technologies based on magnetic induction coupling;
– technologies based on magnetic resonance induction;
– based on the use of radio channels of various frequencies for energy transmission;
– based on the use of electromagnetic radiation of various ranges, in addition to radio radiation.

The focus of this work will be on the consideration of the last two groups of technologies.

2 Review of existing technologies and their areas of application

Figure 1 shows the main modern technologies for wireless power transmission.

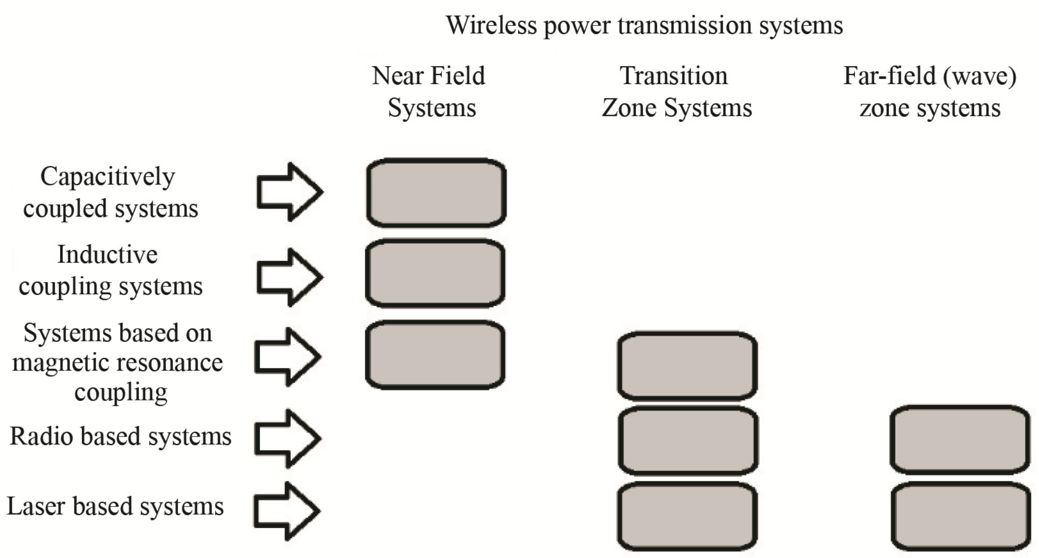

Figure 1. Basic technologies of wireless power transmission

Short-range systems for wireless power transfer are designed for remote charging of batteries of low- and medium-power autonomous devices from a mobile phone and tablet to an electric vehicle. Systems of this kind are on the verge of practical implementation to the extent that documents have already been issued that are prototypes of regulatory regulations and standards for the development and use of technologies of this kind [1, 2, 3]. From a physics point of view, such systems and devices use the principle of electrostatic induction [4], magnetic induction or magnetic induction-resonance interaction [5].

These approaches are applicable for WPT at short distances and with relatively large dimensions of the energy source. However, these circumstances are not an obstacle to the commercial use of these technologies due to the advantages of using such types of WPTs as eliminating the need to use cables and connectors and reducing the time for auxiliary technological operations when charging batteries of various devices.

As for electrostatic induction, due to the complexity of controlling this process and the low speeds of energy transfer, today technologies based on this type of wireless energy transfer are of predominantly historical and, perhaps, scientific and methodological interest. However, systems based on electrostatic induction or slow remote recharging of micro-battery devices with long-wave electromagnetic radiation can be used for medical purposes to recharge implants with energy, since thermal energy dissipation during the induction-resonance method leads to heating of the implant and surrounding tissues of a living organism, which can have negative consequences [6-8].

Note that, although the use of electrostatic induction for wireless energy transfer is associated with the name of Tesla, a detailed analysis of the materials that have come down to us, including descriptions of experiments made by Tesla himself, shows that the remote ignition of lamps in Tesla's experiments was carried out by a rapidly alternating electric (microwave) field [9].

Further development of WPT technologies and the corresponding transition to greater power and range of such technologies, systems and devices is associated with the development and use of the Internet of Things (IoT), the concept of a smart home, etc. [10, 11]. It would seem that there should be no technical problems with recharging mobile devices included in the circuit of an electronic system located within an apartment, house or estate. However, the number of devices in a smart home may be such that recharging them by a human user may require a lot of time; in addition, the devices may be moved by the user from place to place. Since they must operate in a continuous mode, there is a need for automatic remote charging of such devices, which also puts forward new requirements for their functional electronic components and the batteries used in their composition.

Figure 2 shows a photograph of a device for magnetic inductive charging of batteries of an unmanned aerial vehicle [12].

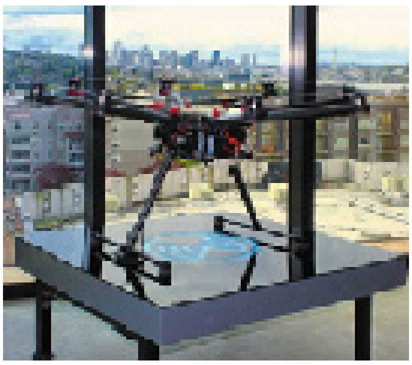

Figure 2. Wireless charging of unmanned aerial vehicle batteries using magnetic resonance method

Remote charging of electric vehicles is currently based on the same principles as remote charging of consumer electronic devices, with the difference that the power of the corresponding remote charging system must be significantly higher. Naturally, the remote charging system for electric vehicles is larger in size [1, 13]. The development of the remote charging system for electric vehicles is an attempt to create systems for recharging the batteries of a moving car. Thus, the Electreon company developed and piloted a system for remote charging of batteries of moving cars on the roads in Tel Aviv (Israel) and on the island of Gotland (Sweden) [14].

Thus, in the summer of 2020, during tests of the Electron system on a 1.9 km long section of the highway in Tel Aviv, a Renault Zoe electric passenger car with a power of 8.5 kW and a passenger bus were charged. The declared efficiency was 91%. In the winter of 2021, on a 1.65 km stretch of highway on the island of Gotland, Electreon installed the largest wireless charging system for cars in motion to date.

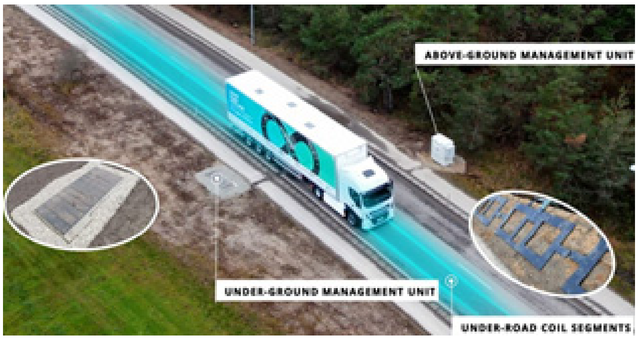

Figure 3. Charging system for electric vehicle batteries on the move

A photograph of the main components of such an assembled system is shown in Figure 3. During the tests, the batteries of an electric long-haul 40-ton truck equipped with five receivers of a wireless charging system with a power of 20 kW each were recharged. Charging was carried out from copper coils located under the road surface. The vehicle speed was up to 60 km/h. The coils were mounted in modules with a length of 200 m and a power of 70 kW each. Stabilization of the system operation was carried out using tracking algorithms implemented in the form of software for control controllers. The system allows remote monitoring of operation via the Internet. Tests have shown that the system operates effectively at sub-zero temperatures, while snow and ice on the road surface do not significantly affect the efficiency of the remote charging process. achieved stable operation with consistent results, and tests confirmed that snow and ice do not affect wireless charging capabilities.

At the “opposite end” of the WPT technology spectrum are industrial-scale wireless power transmission technologies over long distances. One of the first to give a theoretical justification for the fundamental possibility of such processes was S.I. Tetelbaum [15]. The first experiment of this kind was carried out in the USA in 1975 using a radio telescope [16]. In 1997, wireless transmission of electrical energy using radio emission was carried out from the mainland to Renyun Island over a distance of about 1 km [17]. In 2018, 1.6 kW of electrical energy was transmitted using radio emission with a frequency of 10 GHz over a distance of about a kilometer with an efficiency of 40% [18]. Due to low efficiency, technologies of this type have not yet found application on an industrial scale, but interest in them remains due to the project of transmitting energy using microwave radiation from orbiting satellites with large-area solar batteries [19].

A similar pilot experiment was carried out for laser radiation in the infrared range with a source power of 400 W and a process efficiency of about 60% [20]. The use of lasers for remote energy charging of autonomous network devices has the advantage of high energy concentration in the laser beam [21, 22], which, on the one hand, improves the efficiency of the WPT system as a whole.

However, it should be remembered that the efficiency of modern lasers themselves does not exceed 30% of the input primary electrical power. In addition, the use of a high energy density laser beam requires precise targeting of the radiation receiver, as well as additional precautions due to possible damage from laser radiation to people, animals and non-WPT equipment

In this work, as noted above, we will focus on WPT technologies using high-frequency radio waves and laser radiation for power-limited receivers. Such technologies will find wide application for remote recharging of devices integrated into certain information and telecommunication networks, while for a number of reasons direct access to such network devices can be difficult, which makes the use of WPT technologies very relevant for them. We are talking primarily about networks of sensor devices for monitoring the state of the environment in the interests of the Ministry of Emergency Situations, the meteorological service, for monitoring the environmental situation and measuring the level of water and air pollution, including near hazardous or hazardous industries. Sensor networks are also increasingly being used in urban areas. Moreover, many or almost all elements of such a network (sensors and sensors) may be located in places that make constant access to them difficult, so they must operate in an autonomous mode.

To ensure autonomous operation of this kind, recharging technologies based on the use of background electromagnetic radiation can be used. Thus, modules of solar batteries and photodiode arrays are already widely used to recharge autonomous lamps. They can also be used for autonomous power supply of networked sensor devices.

In the use of the background field of radio emission, the use of high-frequency radio waves used in mobile communication systems, for example 5G, can be considered promising [23]. The technical details of the proposed solution are of particular interest and will be discussed below.

The use of background radiation eliminates the question of the need to use a radiation source in the WPT circuit for remote charging of remote autonomous network devices. However, this approach is not without drawbacks. The power of background radiation is unstable and significantly depends on the geolocation of receivers (autonomous network devices). For example, radiation from mobile phone networks may be weak or absent in areas far from industrial centers. Solar radiation, which is a source of background energy in the optical range, may not provide sufficient energy in areas with frequent clouds or during periods of short daylight hours. For these reasons, the development of "complete" WPT circuits and technologies using both the receiving and transmitting sides (radiation sources) seems undoubtedly relevant.

3 Analysis of wireless energy transmission using high-frequency electromagnetic radiation

A general diagram of the WPT process using high-frequency radio waves is shown in Figure 4.

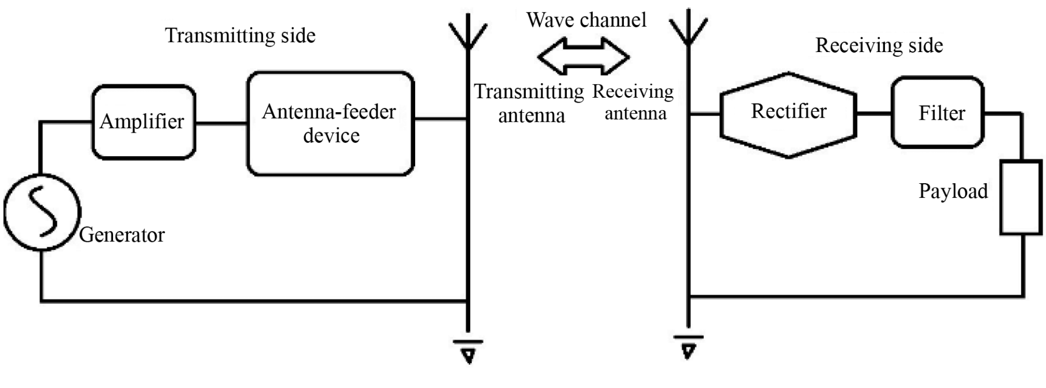

Figure 4. WPT process General diagram using high frequency radio waves

Technical problems arising when implementing this scheme can be grouped into the following categories (classes):

– generation of a high-frequency signal;
– coordination of the generator and transmitting antenna;
– ensuring the efficiency of the transmitting antenna;
– ensuring the efficiency of the receiving antenna;
– matching the receiving antenna with the current rectifier;
– charger control system.

As will be shown below, based on the results of the analysis, when implementing a specific WPT system using high-frequency radio emission, technical problems from all of the listed classes turn out to be interconnected. Consequently, achieving high efficiency values is only possible through an iterative step-by-step design procedure with clarification of solutions and parameters for all subsystems in order to harmonize them to the greatest possible extent.

Energy transfer using high-frequency radio waves can be directional or non-directional (with an isotropic or non-isotropic distribution of the emitter energy). Directional energy transfer allows the use of lower power transmitting devices, but it places higher demands on the design of transmitting devices, in particular on radiating antennas. Also, in the case of directional transmission, it is necessary to know the location of the energy receiver with varying accuracy, depending on the radiation pattern of the radiating antenna of the transmitting device. The use of omnidirectional WPT using radio waves is advisable for simultaneous recharging of several receiving (network) devices compactly located on an area with linear dimensions of the order of 100-300 m, for example, for perimeter control systems or monitoring technological processes within one room.

It is possible to use omnidirectional WPT using radio waves for remote charging of IoT devices in residential and other premises with the presence of people, but in this case, to avoid harm to health, it is necessary to conduct time-limited periodic charging sessions in the absence of people in the premises.

Despite the large number of technological and design problems associated with the development of transmitting devices for WPT, in this work we will focus our attention on the receiving side due to its autonomy, which increases the complexity of the development and operation of such devices. Let us note that, due to the reversibility of many radio engineering paths, certain technical solutions and development directions, such as flat printed antennas or antennas with matching circuits, can also be applied on the transmitting side [24-26]. Moreover, as a consequence of the indicated reversibility of the receiving and transmitting paths, there are specific requirements for the radiation pattern of the receiving antenna.

The use of quasi-optical elements such as Rothman lenses was justified in [27].

The foundations of the theory of energy transfer using high-frequency radio waves were laid down in [15] and were further developed in a number of works, for example [28-30]. One of the fundamental theses of this work is the statement that, while for systems transmitting information using radio waves, the accuracy of reproduction of the transmitted information comes first as an efficiency criterion, and energy efficiency is usually low, for WPT systems the value of transmission efficiency energy becomes key. The efficiency value can be defined as

$$\eta = \frac{P_T}{P_{RL}},$$

where P_T is the power supplied to the transmitting antenna and P_{RL} is the power dissipated into the payload at the receiving antenna side.

Let a signal source (EMF) $U(t) = U_0 \sin \omega t$ be connected to the transmitting antenna, and the receiving antenna is closed to the load resistance P_L.

The energy coming from the transmitting antenna to the receiving antenna is partially released on the payload R_L, and is also spent on ohmic losses, radiation resistance and is dissipated in space when passing through space in the form of radio waves.

For simplicity, the case of monochromatic radiation with frequency is considered. It should be taken into account that due to the radiation of the transmitting antenna, currents arise in the receiving antenna, which in turn induce additional “LCs” in the transmitting antenna. In linear mode, the sum of these “LCs is proportional to the total current induced in the receiving antenna.

This effect may not be taken into account at low efficiencies characteristic of systems and devices for transmitting information using radio waves, but for WPT systems and devices it must be taken into account when considered and analyzed explicitly.

Considering EMF, currents and resistance to be complex quantities, we can write Kirchhoff-type equations for transmitting and receiving circuits with wave coupling between them

$$\begin{cases} J_T Z_T + J_R Z_W = U(t) \\ J_T Z_w + J_R Z_R = 0 \end{cases}$$

Here J_T, J_R are the total currents in the transmitting and receiving antennas, and Z_T, Z_R are the corresponding resistances. The proportionality coefficient, which describes the above-mentioned effect of mutual influence of the receiving and transmitting antennas through the generation of secondary emf, also has the dimension of resistance. According to the author [15], this quantity can be called the “resistance of the wave channel” for transmitting energy by radio emission.

In turn, the resistances of the transmitting and receiving antenna circuits consist of ohmic resistances and radiation resistances. If the antennas are tuned to resonance at the operating frequency w, then

$$\begin{cases} Z_T + R_T + \Upsilon_T \\ Z_R = R_R + \Upsilon_R + R_L \end{cases}$$

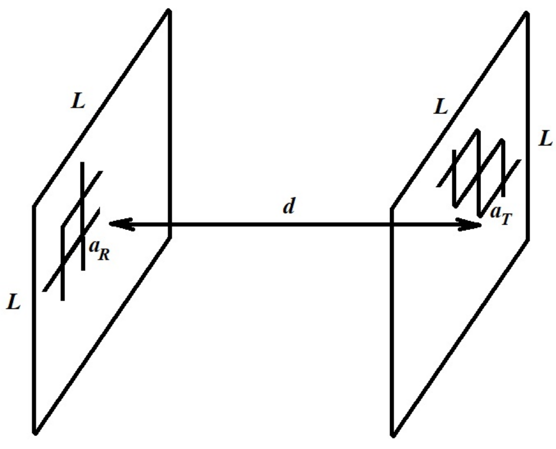

Figure 5. Optimal relative position of transmitting and receiving antennas

The wave channel resistance is a complex quantity that can be written in exponential form

$$Z_W = Z_0 e^{i\theta}$$

where Z_0 and θ are real quantities. For the idealized case of coaxial and parallel arrangement of transmitting and receiving in-phase antennas of the same geometric shape of a square with side *L* (Fig. 6), in [15] in the approximation that both transmitting and receiving antennas consist of a large number of identical square elementary vibrators with sides a_T and a_R, respectively, the following expressions were obtained for the modulus and phase of the complex resistance of the wave channel

$$Z_0 = \frac{60\pi}{\lambda d a_T a_R}\sqrt{A^3 + B^3}$$

$$\theta = atctg\frac{B\sin 2\pi\frac{d}{\lambda} - A\cos 2\pi\frac{d}{\lambda}}{B\cos 2\pi\frac{d}{\lambda} + A\sin 2\pi\frac{d}{\lambda}}$$

$$A = C_1(L,d) - C_2(L,d)$$

$$B = 2C_1(L,d) - C_2(L,d)$$

$$C_1(L,d) = L^2\left(\frac{\sqrt{2\pi}}{q}F_1(q) - \frac{\sin q^2}{q^2}\right)$$

$$C_2(L,d) = L^2\left(\frac{\sqrt{2\pi}}{q}F_2(q) - \frac{1-\cos q^2}{q^2}\right)$$

Here $F_1(q)$ and $F_2(q)$ – Fresnel integrals with parameter *q* equal to

$$q = L\sqrt{\frac{\pi}{\lambda d}}$$

d – distance between the planes of transmitting and receiving antennas, a $\lambda = 2\pi c/\omega$, wave length of radiation used.

$$F_1(q) = \frac{\sqrt{2}}{\pi}\int_0^q \cos x^2 dx$$

$$F_2(q) = \frac{\sqrt{2}}{\pi}\int_0^q \sin x^2 dx$$

For the idealized case under consideration, the relative position of the transmitting and receiving antennas, the radiation resistances will be proportional to the number of elementary vibrators in the antennas

$$\Upsilon_T = 60\pi \frac{L^2}{a_T^2}$$

$$\Upsilon_R = 60\pi \frac{L^2}{a_R^2}$$

If we introduce the directivity coefficients of the antennas D_T and D_R, then for the considered idealized relative position

$$D_T = D_R = 2\pi \frac{L^2}{\lambda^2}$$

then for the resistance modulus of wave channel we can write the approximate relation

$$Z_0 = \sqrt{\Upsilon_T \Upsilon_R} \frac{\lambda\sqrt{D_T D_R}}{2\pi d + \lambda\sqrt{D_T D_R}}$$

Magnitude

$$K = \frac{Z_0}{\sqrt{\Upsilon_T \Upsilon_R}} = \frac{Q}{1+Q}$$

is called the wave channel coupling coefficient
where

$$Q = \frac{\lambda\sqrt{D_T D_R}}{2\pi d}$$

wave channel quality factor.

The introduction of the coupling coefficient of the wave channel allows from a unified position, if the linear approximation for energy transfer is correct, i.e. for the dependences of induced EMF on currents in “opposite” antennas, consider the cases of capacitive, inductive and radio wave communication. For capacitive and inductive coupling λ~d, i.e. energy exchange occurs in the “near” zone of the transmitting device. In the case of radio wave communication $\lambda << d$, accordingly, the “phase” of the complex resistance of the wave channel θ can take on any values. In the general case, the coefficients K, D_T, T_D are functions not only of the distance between the antennas, but also of the angular coordinates that describe the relative position of the antennas in space. They can also be considered as empirically determined quantities.

The efficiency of WPT using high-frequency radio waves can be expressed in terms of the active resistance of the transmitting and receiving circuits, the radiation resistance of the antennas and the wave coupling coefficient. Without citing all the calculations of a sufficiently large volume, we point out that the general expression for the efficiency of WPT using high-frequency radio waves can be simplified for some optimal modes. First of all, it turns out that the maximum efficiency for arbitrary resistance values is achieved under the condition

$\cos 2\theta = 1$ или $\theta = \pi n$

where n is an integer.

Efficiency can then be maximized by appropriate selection of load resistance R_L

$$R_{L\max} = \frac{\Upsilon_R}{\eta_R}\sqrt{1-\eta_T\eta_R K^2}$$

Here the efficiency of isolated short-circuited transmitting and receiving antennas is equal

$$\eta_T = \frac{\Upsilon_T}{\Upsilon_T + R_T}$$

$$\eta_R = \frac{\Upsilon_R}{\Upsilon_R + R_R}$$

The maximum value of the efficiency of the system as a whole, subject to the optimal choice of load resistance and the "phase" of the complex resistance of the wave channel, is equal to

$$\eta_{\max} = \frac{\eta_T\eta_R K^2}{(1+\sqrt{1-\eta_T\eta_R K^2})^2}$$

From the above expression it can be seen that the efficiency of a WPT system using high-frequency radio waves significantly depends on the perfection of the transmitting and receiving antennas. So, even at $\eta_T = \eta_R = 0.9$, the efficiency of the system as a whole cannot exceed 51%. A conventional radio channel for transmitting information, for which K<<1 corresponds to the expression

$$\eta_{\max} \approx \frac{\lambda^2 D_T D_R}{16\pi^2 d^2}\eta_T\eta_R$$

This ratio is known from radio engineering. This is true provided

$$Q = \frac{\lambda\sqrt{D_T D_R}}{2\pi d} << 1$$

If ohmic losses in the circuits of the transmitting and receiving antennas can be neglected, then $\eta_T = \eta_R \approx 1$. The efficiency of the system as a whole can be expressed through the quality factor of the wave channel

$$\eta_{\max} = \left(\frac{Q}{1+Q+\sqrt{1+2Q}}\right)$$

In [31], a similar expression was obtained for the maximum possible efficiency of a magnetic resonance WPT system. The conclusions made in this work indicate that already with the magnetic resonance method, when the transmitting and receiving coils are separated, the energy transfer begins to take on a wave character at frequencies close to the resonant frequency of the transmitting and receiving oscillatory circuits.

This is also supported by the fact that the efficiency of energy transmission decreases more slowly with increasing distance between the coils if the area of the transmitting coil is an order of magnitude greater than the area of the receiving coil. All this suggests that not only at distances characteristic of the wave zone, but also for the transition zone, it is advisable to remotely recharge the energy of autonomous devices (for example, indoor IoT devices) using high-frequency radio waves. Satisfying the requirements of electromagnetic compatibility and sanitary safety of people can be achieved by limiting the power of the transmitting device and/or recharging autonomous devices with energy according to a certain agreed schedule.

The presented theoretical approach makes it possible to apply the methods of the theory of phased array antennas and was developed in a number of further works, for example [29, 30]. The appearance of these works is largely related to the ideas of WPT from orbital space modules of solar panels to Earth. These works examine the important issue of the influence of the number of elementary vibrators per m^2 of the receiving antenna array on the efficiency value. Although for frequencies of the order of 25-35 GHz the optimal value of this value, which delivers maximum efficiency, is estimated at 200 vibrators per m^2, it is possible to reduce this value to 80 vibrators per m^2 with a decrease in efficiency by no more than 5%.

This is achieved by optimizing the radiation pattern of the receiving array by suppressing the side diffraction lobes, through which the secondary radiation of the receiving antenna goes into space and turns into losses.

Increasing the efficiency of the WPT system under consideration is theoretically possible by using intermediate short-circuited antenna repeaters. However, in this embodiment, it is necessary to locate such antennas with high accuracy at specified distances from the transmitting and receiving antennas, which will cause additional technical difficulties in practical application.

The analysis shows that experimental high-power WPT at present can only be of a demonstration nature, or serve to clarify the parameters of the models. While remote recharging of autonomous network devices of limited power can already be used in practice today after some refinement of WPT technology using high-frequency radio waves. One of the directions for further research is experimental measurement of the efficiency of WPT in the case of vibrators as receiving and transmitting antennas.

Below are the results of remotely powering a system of LEDs connected in series. The AC signal received by the antenna is rectified using a Schottky diode. The signal frequency is 150 MHz.

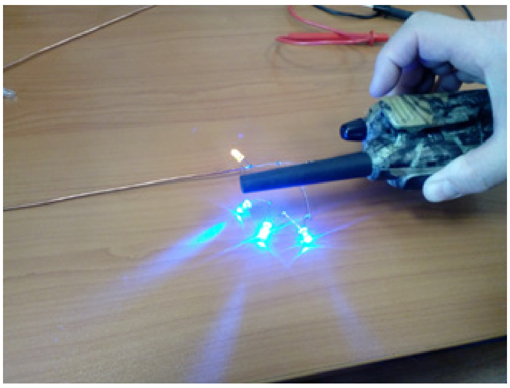

Figure 6. Remote power supply of LEDs at an angle between the plane of radiation polarization and the direction of the dipole antenna of 0 degrees. Radio frequency 150 MHz

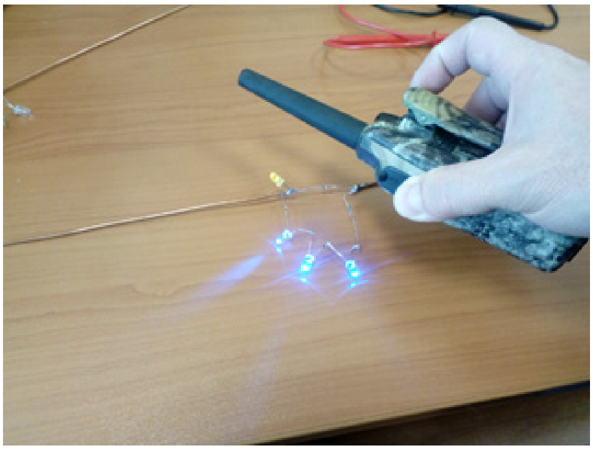

Figure 7. Remote power supply of LEDs at an angle of 60 degrees between the plane of radiation polarization and the direction of the dipole antenna. Radio frequency 150 MHz

Figure 8. Remote power supply of LEDs at an angle between the plane of radiation polarization and the direction of the dipole antenna of 75 degrees. Radio frequency 150 MHz

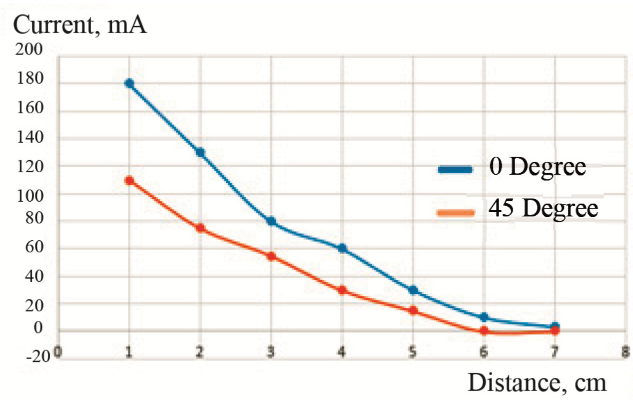

Figure 9. Dependence of direct current through the LED system on the distance between the receiving and transmitting antennas for mutual angles of 0 and 45 degrees

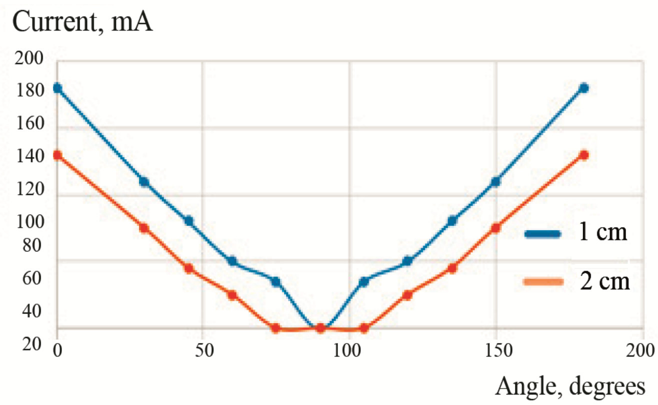

Figure 10. Dependence of direct current through the LED system on the mutual angle for distances between the receiving and transmitting antennas of 1 cm and 2 cm

For vibrators, the transition zone (between reactive and wave) corresponds to distances from the vibrator axis in the range

$$0,62=\sqrt{\frac{a^3}{\lambda}}\le l\le\frac{2a^2}{\lambda}.$$

For the parameter values of the transmitting antenna used in the experiments, at a given frequency, the range of distances between the antennas axes used in the experiments corresponds to wave zone. For the receiving antenna, the specified range covers the transition zone and the beginning of the wave zone.

Similar experiments were carried out for the 930 MHz and 2.4 GHz bands. Their results showed, in confirmation of the provisions put forward in [29, 30], that the rectifier module has a significant impact on the parameters of the receiving antenna circuit. For a more detailed analysis, it is necessary to use equivalent circuits of the rectifier module, for example, given in [30], and explicitly include the parameters and transfer characteristics of the devices included in it into the equations for currents.

Note that the use of printed antennas, quasi-optical lenses and heterostructures raises the question of the applicability of the elementary vibrator approximation, which was discussed above. So, if we turn to the photograph of a printed antenna with a Rothman lens for collecting 5G radiation energy [23] (Fig. 11), then it becomes obvious that it is possible to form high-frequency signal preprocessing devices in the form of heterostructures as part of the antenna array elements of the receiving antenna. The analysis of such systems will, in turn, require the use of new approaches to modeling, for example, based on the finite super element method.

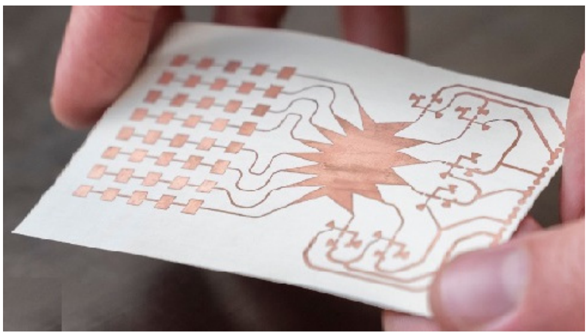

Figure 11. Antenna array with Rothman lens for collecting 5G radiation energy

In addition, separate additional studies are needed to clarify the frequency characteristics of Schottky diodes and the lower limit of the amplitudes of incoming high-frequency signals, below which the diodes do not exhibit rectifying properties. It is also possible to use reversed diodes to rectify high-frequency current [32].

3 Conclusion

Further development of electronic technologies in both the industrial and household sectors will require an even wider introduction and use of monitoring systems and collection of information about both the state of technical systems and the environment. This determines the prospects for developing systems for remote power supply and recharging batteries of autonomous network devices, for example, sensors for various purposes.

This technology sector is located on a conventional map of WPT technologies between short-range magnetic induction charging technologies for various devices, which are being intensively developed by the commercial sector, and technologies for full-scale wireless transmission of electrical energy over significant distances as a replacement for existing wired networks for transmitting electrical energy, which are currently only possible in pilot experimental version. It is in this sector that the next significant scientific, technical and technological step is possible.

The requirements for WPT systems in this sector are energy efficiency, and then economic efficiency, based on low cost of devices and systems and reliable performance.

The development of technologies for the production of micro- and nano-electronic element base, the use of complex multilayer hetero structural compositions and meta-materials makes it possible to satisfy these requirements, since it makes it possible to manufacture electronic components of sensors and transceiver circuits with dimensions of the order of several mm. However, before designing and developing devices of such classes, it is necessary to build and test mock-ups (samples) of transmitting and receiving devices on a traditional element base that operate reliably in various frequency ranges, as well as the development of adequate methods for mathematical modeling of the devices and systems considered.

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