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PRINCIPLES OF CONSTRUCTION AND APPLICATION OF MICROWAVE SYSTEMS FOR WIRELESS ENERGY TRANSMISSION OF GROUND AND SPACE BASING

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Abstract: The results of the investigations, carried out in Kharkiv National University of Radio Electronics, into the principles of construction of modern microwave systems for wireless energy transmission (WET) on the basis of a multipositional system of radiators (MSR) with focusing of single-stage discrete V-shaped multi-frequency signals and a circular polarization rectenna, are presented.

Two versions of such systems are considered: one system is intended for power supply of ground-based remote regions, the second system is intended for energy supply of low-orbit small-size (LS) space vehicles (SV).

Key words: wireless energy transmission, rectenna, multipositional system of radiators, electromagnetic radiation focusing, remote object, low-orbit space vehicle.

1. Introduction

According to modern opinions, the creation of the WET systems is considered to be one of the potential directions of alternative energy sources development. Fig.1 shows the WET system structure.

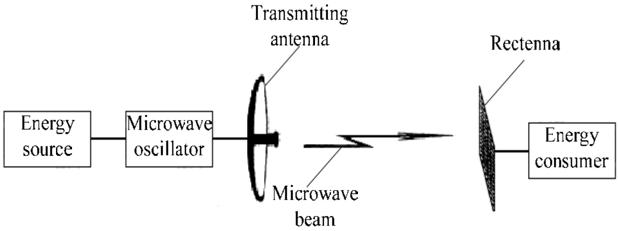

Fig. 1. WET system block diagram

In the general case a WET system consists of a transmitting subsystem, where the energy of an initial source is transformed into a directional radiation, using a microwave generator and a transmitting antenna; afterwards the energy transmission is realized by a microwave beam. A receiving subsystem in the form of an antenna-rectifier (rectenna) is located at a certain distance in the Fresnel zone, it is intended to derive energy from space and convert it into the direct current delivered to a customer.

At the stage of the electrical engineering formation N. Tesla offered WET, having received the USA patent for “WET (Tesla effect)” in 1891, which he realized in 1893 in the system of lighting of the World Exhibition in Chicago in 1893. In the 60s of the XX century interest in WET was rekindled owing to creation of powerful super-high-frequency oscillators. Numerous experiments have shown the expediency of the WET systems creation and their application. Thus, for example, a medium-sized experiment of 30 kW microwave power transmission for a distance of 1,6 km was performed by the scientists of the USA in 1975. The rectenna contained about 5 thousand receiving-rectifying elements; each of them converted 6W of microwave power. The rectenna efficiency was 82% at the frequency of 2388 MHz. Since the turn of the XX century the possibility to create rectennas with dimensions up to 10×13 km and powerful solar space electric power stations with the ranges of microwave power reception and transmission up to 4000 km has been considered. To create such WET systems it is still necessary to perform large–scale experiments on reception of the solar energy and its conversion into microwave energy radiation for its further conversion into direct current in such rectennas; by the experts estimates this will require tens of years and hundred billion dollars. Fig.2 demonstrates possible versions of using such WET system as an energy complex. The energy complex consists of the solar space electric power stations in the geosynchronous (1) and low (5) orbits, transporting energy to the space (2,3,4) and the ground-based (9) customers, and of the ground-based WET system (8) which serves for energy supply from the Earth to space vehicles with electrical jet engines and to pilotless aircrafts (6,7).

Thus, the WET systems offered for realization in the 60s of the XX century were built on the basis of the transmitters with one-positional phased antenna arrays (PAA) or mirror antennas and traditional spatial-phase (SP) focusing of the microwave beam (with the aim to receive a high efficiency) through the rectenna location in the Fresnel zone. The results of such systems study up to 2006, carried out in Kharkiv National University of Radio Electronics, were generalized in [1].

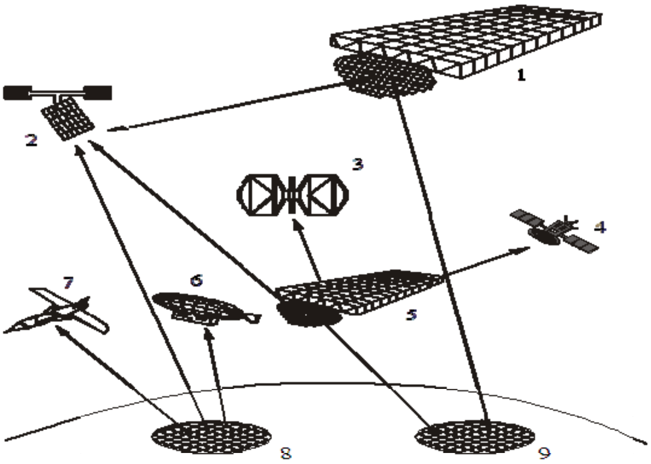

Fig. 2. Power supply complex of WET systems

In the course of further investigations aimed at constructing modern WET systems the authors have put forward the electromagnetic radiation (EMR) focusing based on the interconsistent space-phase-frequency (SPF) control over the MSR signals parameters.

During last two decades the methods for EMR focusing with the combined methods of control over the signals of radiators along the MSR apertures were published. WET to remote objects should offer efficiency, realization simplicity along with high power characteristics. The locations and central operating frequencies of the transmitting and receiving subsystems of the WET's should be known beforehand as well. The compromise and the most effective solution of these requirements is possible when using single-stage discrete (SSD) V-shaped multifrequency (MF) radio pulses in the transmitting MSR subsystems with space-phase-frequency (SPF) focusing [2]. These MSR create a great spectral density in the EMR maximums without scanning when ensuring the required temporal parameters of the focused pulses bursts.

The principles of operation and concrete versions of the transmitting subsystem and rectenna construction for such WET systems have not been presented so far. The partial elimination of this gap is the aim of the given work.

2. WET system for energy supply to objects in remote regions

The distribution of the radiation sources initial frequencies in the MSR with the SSD V-shaped MF signals at a small number of the radiation sources N can be written in the simplified form [2]:

$$f_{0n} = f_0 + |n|\Delta F_n, \tag{1}$$

where f_0 is the initial frequency of the central radiation source in the MSR, f_{0n} is the initial frequency of the n-th radiation source in the MSR, $\Delta F_n = \Delta F_{\max}/n$ is the frequency setting discreteness between neighboring radiators in the MSR, $\Delta F_{\max}$ is the maximal separation of the radiators carrier frequencies over the MSR aperture, $n \in \left[-\frac{N-1}{2},\dots,0;\quad 0,\dots,\frac{N-1}{2}\right]$.

Under the same condition the radiators initial phases' distribution in the MSR for the coherent addition of the EMR at the focusing point P_F located on the axis OZ of the rectangular coordinate system can also be written in the simplified form [2]:

$$\varphi_{0n} = -2\pi f_{0n}\left(\frac{z_F}{c} - \frac{R_{Fn}}{c}\right), \tag{2}$$

where $R_{Fn}=[(x_F-x_n)^2+(y_F-y_n)^2+(z_F-z_n)^2]^{1/2}$ is the distance between the focusing point and the center of the n-th radiator with the coordinates $P_F(x_F,y_F,z_F)$ and (x_n,y_n,z_n), respectively, c is the light speed, z_F is the distance between the focusing point and the central radiator of the MSR along the axis OZ.

The spectral density of the EMR energy flux at the point of focusing is described with the following relation [2]:

$$S(x,y,z,t) = \left| \sum_{n=-\frac{N-1}{2}}^{\frac{N-1}{2}} \sqrt{\frac{P_n\ G_n}{4\pi\ R_n^2}}\ \mathrm{e}^{-j\left[2\pi\ f_{0n}\left(t-\frac{R_n}{c}\right)+\varphi_{0n}\right]} \right|, \tag{3}$$

where, respectively, $S(x,y,z,t)$ is the EMR energy flux spectral density at the instance t; P_n and G_n are the power and amplification factor of the n-th radiator in the MSR; $R_n=[(x-x_n)^2+(y-y_n)^2+(z-z_n)^2]^{1|2}$ is the distance between the observation point and the n–th radiator.

The spatial-temporal and energy characteristics were obtained as results of the mathematical simulation of the MSR with the SPF focusing of the SSD V-shaped MF signals for different distances to the focusing points and following given data: the number of radiators N=33 placed uniformly on the axis OY in the linear antenna array (the MSR aperture base) 500 m long, radiators power P_n=10 kWt, carrier frequency of the cenral radiator f_0=3 HGz, the maximal frequency separation over the MSR aperture $\Delta F_{\max}$ =100 MHz [2]. The coordinate system and the radiators' location in the MSR with the EMR focusing at the point $P_F(x_F,y_F,z_F)$ are shown in Fig.3, where L is the base of the MSR aperture along the axis OY. The distributions of the initial frequencies and phases over the MSR base for the case of the uniform allocation of its radiators along the axis OY calculated by the relations (1) and (2) are shown in Figs. 4 and 5.

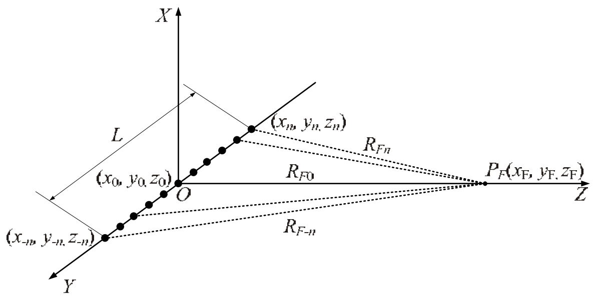

Fig. 3. Coordinate system and radiators' distribution in the MSR with EMR focusing at the point $P_F(x_F,y_F,z_F)$

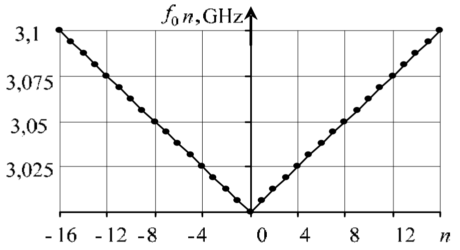

Fig. 4. Distribution of initial frequencies over the MSR aperture

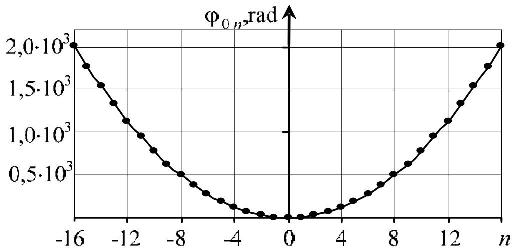

Fig. 5. Distribution of initial phases over the MSR aperture

Computation results of the energy flux density $S(x,y,z)$ at the focusing points $z_F^M=14$ and 24 by the formula (3) with the MSR parameters indicated above are shown in Fig. 6 (in calculations the given coordinates are introduced: $x^M= x/L$, $y^M=y/L$ and $z^M=z/L$, where $L= 500$ m – is the MSR base).

The distribution of the normalized values of the EMR energy flux density along the axis OZ (where $S_H =S/S_{\max}$) in the neighborhood of the points $z_F^M=4$, $z_F^M=14$ and $z_F^M=24$ are given in Fig. 7.

The analysis of the simulation results received in [2] shows that when choosing the focusing point at the distance $z_F^M \le 4$ and using the SPF focusing of the SSD V-shaped MF signals with the distribution of their frequencies and phases in the MSR in accordance wth (1), (2), only a single spatial-temporal impulse (STI) is formed.

When the distance to the focusing point increases, a STI sequence appears and the number of the focused STI grows in a periodic sequence with the increase in the distance to the focusing point z_F. In this case the duration and the STI repetition period in the periodic sequence are equal to $\tau_B \approx 1/\Delta F_{\max}$, $T_B=1/\Delta F_n$.

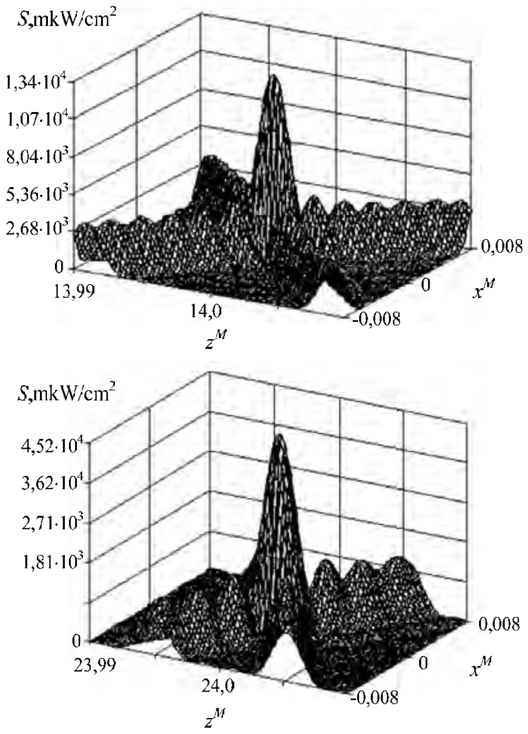

Fig. 6. Computational results of energy flux density at the focusing point z_F^M

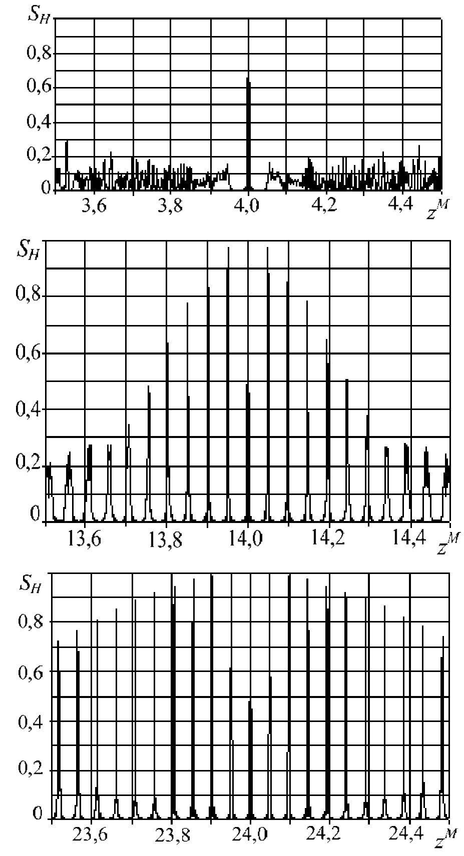

Fig. 7. Distributions of the normalized values of the energy flux density

Specificity of the WET systems access to the remote ground and mountainous objects determines peculiar requirements for the structure and parameters of the focused STI. Among these are:

- the need for the continuous operation within long intervals of time at the maximal spectral density of the STI energy flux of the WET transmitting subsystem;
- the elimination of the possible inoperating of the reception-rectification elements (RRE) of rectennas and of other semiconductor elements of radio electronic facilities (REF) in the object using the sequence of the focused STI of the WET transmitting subsystem.

With regard to the above mentioned it has been offered to create the STI pulses package in the form of two parts which can be radiated *s* times in succession, should the need for a long action arise. The first part of the STI packages should ensure the maximum possible value of energy flux density transmitted from the WET transmitting subsystem to the WET receiving subsystem rectenna during the total time of action of the STI $\tau_{B\Sigma}$. In this case it is essential to choose energy and time parameters for this part of the STI packages structure to avoid the functional fail conditions or suppression of the REF being present on the object. The second part of the STI package structure should be in the form of the free interval of time (without the STI pulses filling) to ensure a reliable relaxation of heat processes in the REF semiconductor radio elements being on the object $\tau_{T.\max}$. It is essential to exclude the semiconductor radio elements degradation at the expense of thermal effects caused by the action of the first part of the STI packages structure. In [2] the requirements on the STI packages structure for the elimination of the semiconductor radio elements functional failure and functional suppression of various REF receiving paths were exemplified by the first part of the STI packages structure with its total action time $\tau_{\text{inpack}\Sigma}$ =100 ms without regard for the intervals between the pulses. In this case the STI duration in the package is τ_{inpack}=10 ns with the STI number in the package $N_{inpack}=10^7$ and the SRT repetition period T_{inpack}=20 ns. The STI duration was determined from the condition $\tau_{\text{pack}} \geq \tau_K$, where τ_K=10 ns is the response time of the best devices among the means of protection against microwave input of the real REF [2].The fulfillment of this condition is essential to exclude the possibility of the receiving devices blocking by the protection devices with high-level signals at the receiving devices input. Moreover, when choosing the above-mentioned STI duration the effect equivalent to the action of delta-function on the receiving device is ensured. The SRT repetition period is determined from the condition $T_{\text{pack}} < \tau_r$, where τ_r=22…76 ns is the time constant for establishment of natural oscillations of the majority of receivers of different REF [2]. Fulfillment of this condition is essential to ensure the support of the stable self-excitation conditions of the receiving devices being suppressed. The duration of the STI packages structure second part is chosen out under the condition that it should be less than $\tau_{T.\min}$=200 ns, it is the minimal value of the thermal processes relaxation time for the semiconductor radio elements. Based on the above data substantiated in [2] the corresponding parameters of the STI packages structure have been chosen for the WET systems to remote ground and mountainous objects, ensuring elimination of the functional damage of the rectenna radio elements and functional suppression of the REF receiving paths, being on the object. To exclude the service failure of rectenna radio elements and other REF on the object with a ten-fold store of energy, at the minimum, a number of pulses in the STI package should be $N_{\text{pack}} = (N_{\text{inpack}}/10) = 10^6$. The STI repetition period should be T_{pack} =80 ns (for the fulfillment of the condition $T_{\text{pack}} < \tau_r$). The STI duration τ_{pack}=20 ns (to meet the condition $\tau_{\text{pack}} \geq \tau_K$) and, respectively, the duration of the STI package without regard for the intervals between them equals to $\tau_{\text{pack}\Sigma} = 10^6 \tau_{\text{pack}}$=20 ms. The second part of the STI structure in the form of the free interval of time (without the STI pulses filling) equals to the maximum possible value of the time constant of the thermal processes relaxation for semiconductor radio elements $\tau_{m.\max}$=410 ns [2]. The total duration of such STI package structure is equal to

$$\tau_{\text{pack}\Sigma S} = s\,[N_{\text{pack}} \cdot T_{\text{pack}} + \tau_{T.\max}], \qquad (4)$$

where *s* is the necessary number of repetitions of both parts of the STI package structure during the required time of the WET receiving subsystem action on the rectenna for the required electrical power transmission.

It was offered to use the missile guidance stations (MGS) of the anti-aircraft missile complex (AAMC) of the “TOR-M1” type [3]. Their technical and design parameters can be taken as the initial ones for the transmitting subsystem of the offered WET system. They have square PAA fixed on the cabin of the following dimensions $L_X = L_Y$=1,7 m and their phase centers’ height is h_a=5 m. It is expedient to settle the maximal focusing distance, the PAA phase centers’ height in the MGS being h_a and that of the rectenna being h_r , no more than a distance of the direct radar visibility D_{DRV} calculated using a wide known simple formula:

$$z_F \leq D_{DRV} = 4{,}12[(h_a)^2 + (h_r)^2]^{1/2}, \qquad (5)$$

where D_{DRV} is measured in [km], h_a and h_r are measured in [m].

Location of the MGS with the PAA and that of the rectenna on the ground in the model cabins with h_a=h_p=5 m can be considered standard ones, and then the maximum distance of focusing is equal to:

$$z_F \le D_{DRV}=4{,}12[(h_a)^2+(h_r)^2]^{1/2}=4{,}12[(5)^2+(5)^2]^{1/2}\approx 29\text{ km}.$$

Fig.8 shows the plan of location of the elements (top view) appropriate for the system of the WET to remote ground objects.

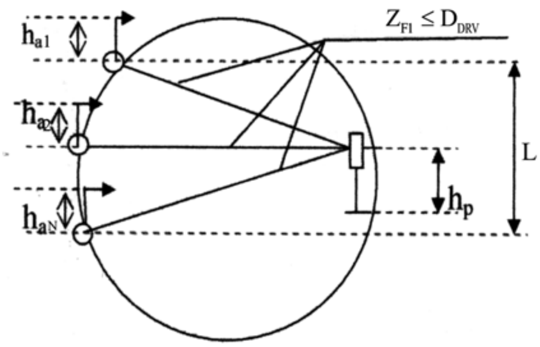

Fig. 8. Plan of the WET system (top view)

The following appropriate MSR parameters have been substantiated for the subsystem of the WET to remote ground objects based on the abovementioned:

1. The transmitting MSR consists of the MGS with the PAA located along the arch (Fig.8):

1.1 The base L=320 m, the quantity of MGS with PAA N=9, focusing distance $z_F \le D_{DRV}$=29 km for the WET to the ground objects.

The dimension of the MSR base L has been chosen for fulfillment of the condition $0{,}01z_D \le z_F \le 0{,}02z_D$, where $z_D=2L^2/\lambda_0$ is the distance to the origin of the MSR aperture far zone, λ_0 is a wavelength in the MSR central radiator. Fulfillment of this condition makes it possible to obtain a gain in the power flow density owing to the EMR focusing on the basis of the SPF control as compared to the case of an ordinary synphase radiation in the Fresnel zone at 37…27 dB, respectively [2]. Moreover, the MSR base dimension determines the focused STI duration over the axes OX and OY (cross-sectional linear dimensions ΔX and ΔY), which are defined by the approximate relation [2] $\Delta Y=(\lambda_0/L)\,z_F$; this duration should be coordinated with the linear dimension of the rectenna aperture of the WET receiving subsystem for losses minimization of the EMR energy when transmitting it to the MSR of the transmitting WET subsystem.

The quantity of the MGS with PAA N was chosen to ensure a compromise solution of the problem of receiving the maximal spectral density of the STI energy flux, elimination of the possible service failure of the semiconductor elements on the position of the WET receiving subsystem and diminution of safety zone for the population and operators serving the WET system [4].

1.2 The PAA contain n_{SA}=4 square subarrays, dimensions and radiators number being equal to $(L_{SA})^2$=(85×85) cm^2 and $n_{SP}=(n\times m)=(12)^2$=144, respectively.

1.3. Wavelength and intervals between radiators in the square subarrays, their sides dimensions and a number of radiators being equal to L_{SA}=0,85 m and $n=m$=12, respectively, are equal to $\lambda_0 \le (L_{SA}/n)=(0{,}85/12)\approx 0{,}07$ m and $d_{XSP}=d_{YSP}\approx 0{,}07$ м, respectively.

1.4. Gain coefficients of the PAA subarrays at operation with a narrow round beam $G_{SP}\approx 3750$.

2. Radiated signals of SSD V-shaped MF LFM coherent radio pulses bursts:

2.1. The initial signals frequencies in the N-th MGS are equal to $f_{0n}\approx(4{,}3\pm 0{,}1)$ GHz, the maximal frequency separation is equal to $\Delta F_{\max}$=50 MHz, and the frequency discreteness is equal to ΔF_n = 12,5 MHz.

3. The radio-wave pulses power for all radiators of each PAA subarrays is about P_{nm}=21,5 W, and the total power of the pulse radiation of each subarray is $P_{SP}=n_{SP}\times P_{nm}=144\times 21{,}5\approx 3{,}1$ kW.

The PAA subarrays of the MGS AAMS of the “TOR-M1” type represent the MSR radiators of the offered WET. In the given WET system their number is equal to $N_{EM}=(N\times n_{SA})=(9\times 4)=36$.

Since the amplitude distribution of radiators signals over the MSR apertures is the uniform one in the offered WET, the aperture radiators are similar and $z_F \le D_{DRV}$; the synphase fields composition is provided and the expression for calculation of the maximal density of the SSD V-shaped MF LFM coherent radio pulses power takes the form [2, 3]:

$$S_{\max} = N_{EM}^{\ 2}\, P_{SP}\, G_{SP} / (4\pi\, Z^2_F). \qquad (6)$$

Calculation results of the attainable $S_{\max}$ values at the distances z_F are shown in Fig. 9.

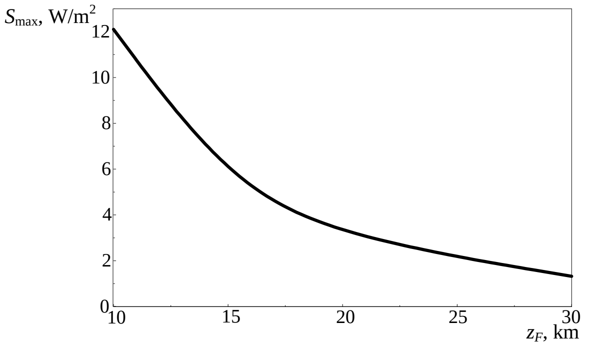

Fig. 9. Dependence of S max on the distance to the focusing point

The offered designs of the rectenna realization consist in the following. To decrease the aperture area the rectenna is made in the form of a two-layer microstrip structure (Fig.10) on the dielectric substrate at $\varepsilon_r = 3,5$. The radiating system is made in the form of a set of collinear tape microstrip conductors, Schottky diodes (in our case a bodyless diode 3A149A-3 has been chosen) are introduced into their gaps at regular intervals (Fig.10).

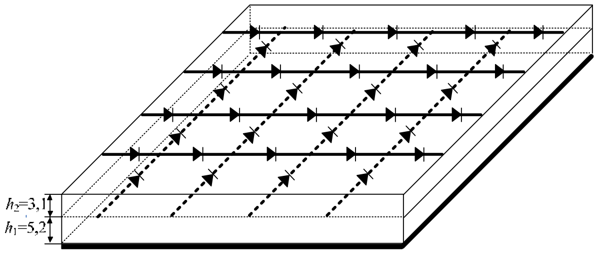

Fig. 10. Fragment of circular polarization rectenna

The utilization of such radiators is constructively beneficial for two reasons. First, the series-parallel circuit for direct current power collection is easy to realize. Some definite values of the rectenna EMF E_r and rectenna DC resistance R_r are needed to obtain the specified power in the rectenna load [1].

The required value of E_r is reached through the series connection of the RRE in the line and that of R_r – through the parallel connection of the lines (Fig.10). Second, the rectenna reliability increases since the rectenna maintains its serviceability at failure of a number of lines (this is urgent when transmitting high-level power).

T he RREs, operating at two orthogonal polarizations with respect to the planes of the upper and lower layers of the plate, were used to ensure that the rectenna would receive the circular polarization field (Fig. 10).

Calculation of the rectenna has been carried out according to the methods presented in [1]. When simulating, the rectenna has been considered as an infinite periodic array with Floquet's cells dimensions 13×13 mm^2 (Fig.11).

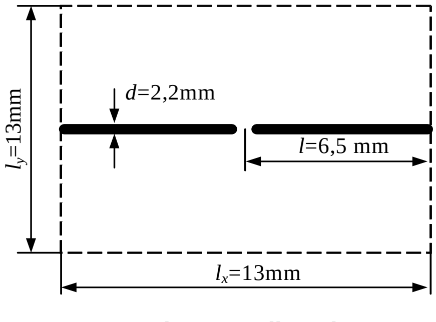

Fig. 11. Floquet's cell topology

Estimation of energetic characteristics of a separate RRE, being a part of the rectenna array, has been carried out with a simplified DC RRE model; it is equivalent to the idle EMF generator E_e with an internal resistance R_e [1]. Fig. 12 shows the DC joint circuit of the equivalent idle EMF E_e with the internal resistance R_e. The subscript indicates the number of the line and the superscript indicates the number of the equivalent generator in the line.

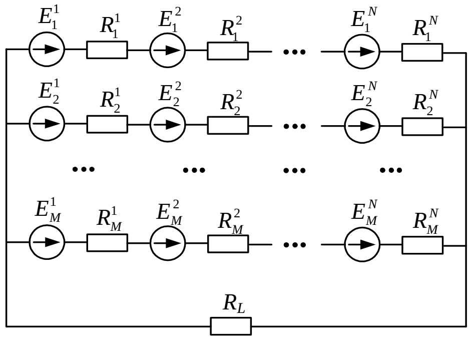

Fig. 12. Scheme of the RRE DC joint circuit

Fig. 13 demonstrates the dependencies of the rectenna rectification efficiency η_r (the rectenna aperture area A_r= 9 m^2) and of the voltage in its load on the distance to the focusing point.

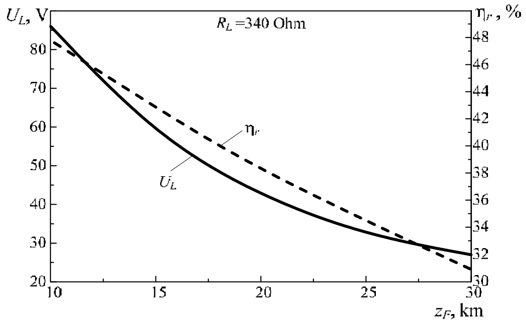

Fig. 13. Dependence of the rectification efficiency and voltage in the rectenna load on the focusing distance

The calculation of the total DC power transmitted to the rectenna load (to a customer) $P_{pack\Sigma S}$ for $\Delta t_{pack\Sigma S}$=2, 4, 8 and 16 hours of the WET system continuous operation have been carried out for the offered WET system. This power is being created by the STI packages series during the total time of their action without regard for the intervals between the STI in the packages and between the packages at *s* cycles of the MSR radiation (the transmitting WET subsystem) during the time of the WET system continuous operation.

The total DC power $P_{pack\Sigma S}$, created by the STI packages series during the total time of their action without regard for the intervals between them and at *s* cycles of the MSR radiation is calculated by the following relation:

$$P_{pack\Sigma S} = S_{\max}\cdot A_r\cdot K_{ur}\cdot \eta_r \cdot \Delta t_{pack\Sigma S}/(\mathrm{N}_{\text{pack}}\cdot T_{\text{pack}} + \tau_{\text{т.max}}), \quad (7)$$

where K_{ur}=0,8 is the rectenna aperture utilization factor.

The results of these calculations are given in Table 1.

Table 1

The transmitted total DC power in the rectenna load ($P_{B\Sigma S}$) during continuous operation of the WET system $\Delta t_{B\Sigma S}$

Distance to $z_{F,\ \mathrm{km}}$	Total transmitted power $P_{pack\Sigma S}$, Mw			
	Time of the WET system continuous operation $\Delta t_{pack\Sigma S}$, hour			
	2 hours	4 hours	8 hours	16 hours
10	3,81	7,62	15,24	30,48
15	1,49	2,98	5,86	11,72
20	0,76	1,52	3,04	6,08
29	0,29	0,58	1,16	2,32

Thus, the above proposed design structures and algorithms as well as and the estimates of their realizability and efficiency serve as evidence for the possibility to create new effective transmitting subsystems of the WET to the remote objects, based on the MSR containing radars corporating the PAA and the SPF focusing of the SSD V-shaped MF coherent simple radio-wave pulses, as well as the transmitting subsystems with rectennas.

3. WET system for refining power supply of the low-orbit small-size space vehicles

In recent years the low-orbit small-size space vehicles (LS SV) are actively used at low orbits that are close to the circular solar-synchronous ones at the heights of 250…700 km. The subsystem of power supply (SSPS) for the space vehicles (SV) of this category consists, for the developed typical platform, of four solar batteries (SB) arrays, consisting of gallium arsenide (GaAs) solar cells (SC), of the skeleton type rigidly fixed with respect to the SV platform, and as an energy storage the chemical battery(CB) consisting of the hermetic nickel-cadmium cells with the CB final voltage is used, its variation range provides the required supply voltage of the SV on-board power supply equal to 24…34 V.

SB arrays have the limited overall dimensions determined by the LS SV platform design, thus, when using the SC of the definite type, the value of current, being given by the SB to the load, is a fixed one and depends only on the LS SV orientation to the Sun. But in new developments the power consumption of the required on-board equipment of the LS SV and the scientific devices, placed in it, exceed the available energy potential used by the SSPS SV for the standard platforms developed in Ukraine (“EgyptSat-1”, “MS-2-8” and “MicroSat”).

It is offered to use the WET system [4, 5] as one of the alternative methods for receiving an additional power for SSPS LS SV. The WET receiving subsystem rectenna can be placed on the back side of the SB arrays not used at present (Fig. 14). The total area of 4 solar arrays is equal to 1,6 m^2. Moreover, when using the given method of receiving the additional power for the SSPS SV of such class, it is possible (at emergency complete or partial absence of the CB SV charge from SB during a definite number of SV turns) to receive an additional electrical energy from the WET receiving subsystem for charging the CB to the minimal level required to realize the operation of the SV radio command link in case of an irregular emergency situation of the SV orientation system operation to provide a means for realization of the software correction of the SV control from the Earth.

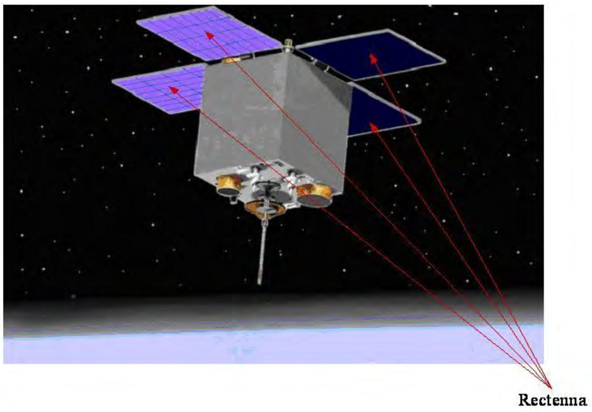

Fig. 14. The rectenna placement on the back sides of LS SV solar arrays

The ground WET SV transmitting subsystem should be placed at the site near the positional location of the SV REF control – National Center for Space Vehicles Tests Control (Eupatoria) or Center for Special Information Reception, Processing and Navigation Field Control (Vinnytsia Region, Dunayevtsi) because being in the observation zone of the mentioned control devices the SV is oriented by the back sides of its SB arrays to the Earth.

The duration of LS SV being within the observation zone of the ground REF SV control devices in the process of their orbital flight around the Earth depends on the orbit inclination. For example, the Ukrainian LS SV “MS-2-8” passes through the observation zone of the land REF control in Eupatoria from 4 till 6 turns per twenty-four hours. Depending on the azimuthal direction, when it enters into the observation zone of the land REF control, the LS SV “MS-2-8” stays in the zone from 7 to 13 minutes (the distance of the entry into the zone being equal from 2000 to 3000 km). Thus, it is possible to collect additional (to the energy from the SB) electrical energy during several turns using the offered on-board SV WET subsystem.

The radio telescope RT-70 (Eupatoria) can be used as a transmitting subsystem of the WET for realization of the additional power supply to the LS SV in case of the abovementioned irregular emergency situation [4]. As this takes place, when passing through the RT-70

(Fig. 15) radio conduction zone, it is possible to realize the emergency energy supply for a short–term operation of the radio command link only or it is possible, within several turns of the SV, to realize the CB charge up to the minimum necessary for the short-term radio command link and the LS SV control operation. The energy flux density created by the two-channel RT-70 transmitter (its radiation power in discontinuous mode constitutes 200 kWt) at the distance of $r = 600$ km where the rectenna aperature is located, with taking into account the losses of 1,3 dB (0,741) along the EMR route, is equal to $S_{\max}$=0,316 Wt/m^2 at the frequency of f_0=5,01 GHz [4].

The design of a multilayer rectenna was offered in [4]. This design provides the rectenna rectification efficiency equal to 37,9% (at the distance between the RT-70 and the LS SV being equal to 600 km), the CB charging current $I_L = 0{,}1$ A at the load voltage $U_L = 34$ V, when the rectenna is placed on the back sides of the SC arrays and of the LS SV heat screens with a total area of 3,2 square meters not used in the standard platform at present.

Fig. 15. The use of RT-70 radio telescope as transmitting WET subsystem

To realize the efficient additional energy supply for LS SV it is expedient to create a mobile powerful WET transmitting subsystem through the use of the MSR of the “Ohliad-3” (1RL141) type radar, being a part of the radio altimeter PRW-17 (radiation frequency – 2,625 GHz with a pulsed power of 2,5 Mwt, developed in the “Iskra” design department, Zaporizhzhia), with space-phase focusing of their EMR or with the SSD V-shaped signals (Fig.16) [5].

Table 2 demonstrates results of the calculation based on the relation (6) of the achievable values of the energy flux density $S_{\max}$ created by such WET transmitting subsystem depending on the quantity N of the radars in the MSR at the focusing distance of EMR z_F =800 km.

Fig. 16. The use of multipositional system of radiators of the “Ohliad-3” (1RL141) type radar, being a part of the radio altimeter PRW-17 as the WET transmitting subsystem

Table 2

Achievable values of the energy flux density $S_{\max}$ depending on the quantity N of 1RL141 radars in the MSR at the focusing distance of EMR z_F =800 km.

Maximal value of the created power flow density of the EMR depending on MSR, $S_{\max,}$, W/ m^2									
Number of 1RL141 radars in MSR of WET transmitting subsystem, N									
150	200	250	300	350	400	450	500	550	600
70	124	194	280	381	498	630	778	941	1120

4. Conclusion

It has been considered the possibility to create the WET efficient systems for the energy supply of the ground remote objects. The version of creation of the WET transmitting system on the MSR containing PAA of the available MGS of "TOR-M1" type with the SPF focusing of the SSD V-shaped microwave coherent radio pulses has been offered. Power and temporal parameters of the STI radiated packages have been substantiated. The principle of two-layer circular polarization rectenna construction has been considered. The fundamental possibility and versions of creation of the WET with a ground subsystem and on-board receiving subsystem for improvements in LS SV power supply have been investigated.

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ПРИНЦИПИ ПОБУДОВИ Й ЗАСТОСУВАННЯ МІКРОХВИЛЬОВИХ СИСТЕМ БЕЗПРОВОДОВОЇ ПЕРЕДАЧІ ЕНЕРГІЇ НАЗЕМНОГО Й КОСМІЧНОГО БАЗУВАННЯ

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Викладено результати досліджень у Харківському національному університеті радіоелектроніки принципів побудови сучасних мікрохвильових систем безпровідної передачі енергії (БПЕ) на основі багатопозиційної системи випромінювачів (БСВ) з фокусеуванням одноступінчастих дискретних V-подібних багаточастотних сигналів і двошарової мікросмугової ректени з круговою поляризацією.

Розглянуто два варіанти таких систем: для енергозабезпечення наземних об'єктів у важкодоступних районах і низькоорбітальних малогабаритних (НМ) космічних апаратів (КА).

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