ONE OF THE NEW FEATURES OF THE SPACE POWER STATIONS

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Abstract- The limited density of an energy flow (DFE) in the Wireless Power Transmission (WPT) systems of the Space Power Stations (SPS) creates a set of difficulties including the huge antenna sizes especially of the receiving ones. It happened so not only by reason to reach the Fresnel area but by reason to transmit enormous power needed for Earth feeding. These circumstances require sometimes dividing the whole antenna square by separate parts. It is a new feature of the WPT of the SPS. This paper is devoted to the problem of a decrease of radiating antenna sizes. Methods and algorithms for finding optimum phase and amplitude distributions in the WPT radiating antenna systems are developed. Numerical methods of the phase synthesis of antennas for a field in the Fresnel area are elaborated. The example of the synthesis field is shown

1. INTRODUCTION AND REVIEW

Interest in the focused electromagnetic field in a Fresnel area for the Wireless Power Transmission (WPT) systems has appeared long ago. United States[1,2], Japan[3] and France[4] have started to develop the projects for the Wireless Power Transmission (WPT) systems. In the European Union[5] the works in a microwave range were started to heat plasma for various economic tasks, including the nuclear researches. In the WPT systems the practical interest represents not a peak - phase field distribution in the area of the observer but the relation of an energy flow which is taking place through a reception platform, to all energy radiating by transmitted antenna[6,7]. There is an opportunity of improving WPT systems not only by change of the field distribution on the radiating aperture, but also of its shape. This form can be discontinuous (discrete antenna). One of the mainost difficulty for the power WPT stations is the limited density of an energy flow (DFE). This circumstance requires huge sizes of antennas. This paper is devoted to the problem of decreasing the size of the radiating antenna.

The scientific researches on application of a microwave energy range through free space, without the transfer devices such as coaxial lines and wave-guides have begun since the appearance of the papers[1,8,9]. And though till now these researches are not completed, the benefits from use of the WPT systems are assumed to be so appreciable, that the works in this direction are the priority. Systematically conducted International conferences show it as a fact. The novelty of these problems has attracted the attention of a number of scientists from the different countries. During International antennas conferences in Moscow in 1998 and in Davos in 2000 special sessions on wireless transfer of energy were organized. The problem was discussed on the International and Commonwealth of Independent States (CIS) meetings[10,17] and also in May, 2001 at the 3-rd International conference (WPT'01) in France (Reunion Island).

For WPT systems there are many useful applications, but the majority of them do not justify the huge expenditures, which are required for their realization. The expensive experimental researches in this area can be justified only, when the necessity of creation of Space Power System, (SPS) stations will be accepted as a sole measure of power maintenance of the Earth[2,18-20] .

Therefore the works carry only theoretical and model character. In spite of the fact that the technology of creation SPS is known, cost of its creation is so great, that the mankind is not ready yet to do this. Therefore any offers for the SPS cost decrease are urgent. Below an attempt is made to lower down the SPS creation cost reduction of an radiating antenna active part by special field distribution on it.
WPT can be used to transfer power from solar space project to the consumers in space[21] . They can also transmit energy from a surface of the Earth to flying devices, which have no pilot[22] . The WPT on the Earth is necessary, when the wire transfer causes difficulties or it is impossible (transfer of energy in mountainous districts, from continent to an island, transfer of energy for plasma heating[5] etc.).

30 years of scientific researches in this area gave the significant experience of development. It is summed up in the reviews[23-24] . It is possible to consider many questions of WPT construction as essentially solved. The fragmental models of the WPT experimental units were created in the different countries. Most interesting of them are:

1. Experimental units in USA provide 30 KW of power on one mile[25]. For a line of transmit the power klystron generator (length of a wave 0.125 m, capacity of 450 KW), radiating mirror by a diameter of 85 ft and reception antenna (rectenna), specially developed for this purpose was used. A basic element, which was created anew, was 4-watt diode Schottky, which parameters are not exceeded now. The experiment was carried out in Goldstone (California) in 1975.
2. Creation and demonstration in October, 1995 in Êîbå (Japan) of a dirigible balloon and model of the helicopter, which received energy transmitted from Earth with the help WPT[26,27].
3. WPT Project (extent 700 ì) on an Reunion Island (France)[4] .
4. Project WPT-2000, presented by the Institute of space researches of Japan with the participation of the Moscow State University[3].

The basic fault of WPT system is that the essential part of the radiated energy does not reach the given area of space because of the wave beam diffraction expansion. With increase of length of the WPT this fault becomes more evident. The sizes of radiating and reception antennas should be chosen so that the area of reception would not extend far of a Fresnel area. The substantial construction of the WPT electromagnetic path is one of the basic problems in WPT area. Focusing of a field of the large aperture antenna having uniform or taper of the antenna field distribution with the purpose to transmit of energy was examined.

In investigation of the Moscow Power Energy Institute (MPEI (TU) the results for the equal phase field distribution and for focused wave spot[28] were published. The research of the focused field of the round aperture with peak distribution, falling down to edges, is shown by the function:

$$|u(x)| = \left(1 - \frac{x^2}{a^2}\right)^n , \quad (1)$$

where $n \geq 0$. It is shown, that for circularly symmetric phase field distribution in the antenna (uniform distribution) the efficiency of the main beam is equal 0.838. For $n = 1$ and $n = 2$ it is accordingly equal 0,983 and 0,997. The peak distribution of a field at $n = 1$ is close to $\cos\frac{px}{2a}$, and at $n = 2$ it is close to $\cos^2\frac{px}{2a}$ which similar on truncated Gauss field distribution.

A number of Moscow State University papers[29] discuss the synthesis of a field on the aperture of the transmitting WPT antennas. In these papers the opportunity to obtain on the reception antenna of a field close to uniform, and outside of the reception antenna of it's sharp reduction is examined. For this purpose as one of the methods the step function of distribution is used. Thus the field is synthesized inside the continuous radiating aperture.

The partially filled apertures were examined earlier to increase the efficiency of radio telescopes, where the sub aperture construction of antennas was used for the interferometer purposes, and the aperture synthesis have nothing in common with the WPT [30].

2. PROBLEM STATEMENT

It was noticed [10], that it is possible to achieve some increase of WPT efficiency by use of the partially filled (Discontinuous or Discrete) aperture.

The effectiveness of the WPT system depends on many parameters. Here is examined only a part of the system which includes both radiating and reception antennas and environment between them. To increase concentration of a field on the reception antenna, phase distribution on the radiating antenna, which is usually spherical has the center in a point of crossing of a reception plane and axis of radiation, and peak - falling to edges[7]. Such distribution allows to increase factor of WPT effectiveness and to reduce a field outside of the reception antennas. However, the continuous field, falling to edges results in poor use of a surface of the radiating antenna.

The way out of this contradiction is possible, if filling of the antenna is not complete. Let's better make field distribution on the radiating antenna falling down to edges not at the expense of creation of non-uniform distribution but let's create it by irregular accommodation of the sub apertures, as it is shown on fig.1

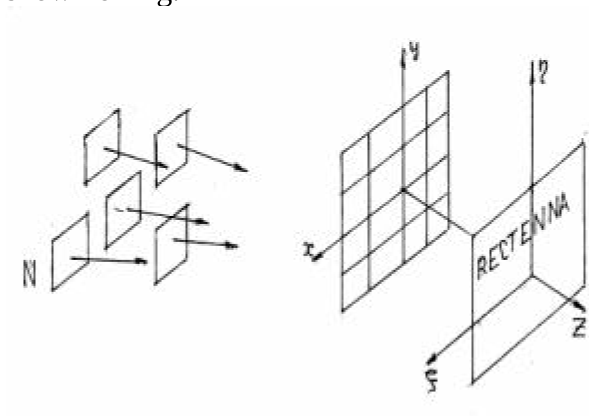

Fig. 1. Partially filled and continuous radiating

Each of them has a distribution of a field, uniform and equal on amplitude. It is supposed, that the quantity of these sub apertures is rather great to admit approximation of optimum distribution of a field, which is close by the form to Gauss curve, by means of step function. The locations of the sub apertures can be found by differentiation of this step function.

Discrete separate sub aperture accommodation represents non-equidistant antenna array[2,3] . Such accommodation can correspond and be an approximated optimum continuous field distribution. Thus the maximal error aspires to zero, when the quantity of elements aspires to infinity. The field in the location of the observer with a plenty of elements will be practically identical to step and monotonous distribution of a field on radiator. For discrete antenna with steps distributions of a field it means, that the clots of the sub apertures are concentrated at the center, that correspond to high density of an energy flow, and gradually disperse to edges (sub aperture amplitudes are constant but the distance between them are rarefied), where lower density of energy is necessary. All sub apertures are identical and have uniform distribution of a field with identical amplitude, which can reach maximum allowable size for a used type of the antenna. It allows to achieve a complete using of the antenna active area.

The increase of WPT system effectiveness with non-equidistant antenna array by the discrete radiating antenna was shown on mathematical model[2] and experimentally in an optical range of waves[3]. The results, which were received, have shown an increase of efficiency of WPT discrete (not completely filled) antenna in comparison with the continuous one. Factor of transfer of energy for a two-dimensional problem is expressed by the following functional:

$$\Lambda = \frac{\int_{-b}^{b} |E(x)|^2 dx}{\int_{-\infty}^{\infty} |E(x)|^2 dx}, \qquad (2)$$

where $2b$ is the linear size of the reception antenna.

Size of Λ is increased, if the amplitude of a radiating field falls down to edges[31], and Fresnel parameter

$$c = \frac{ka^2}{d} \qquad (3)$$

has the order 2 - 3. Here $2a$ is linear size of the radiating antenna, d is distance between radiating and receiving antennas and k is a wave number. At the given meaning of c and at optimum distribution of a field, which is close to truncated on to edges Gauss distribution; the size Λ^2 is close to unit.
For a three-dimensional task in case of shared aperture distributions, i.e. when factor of transfer of energy will be $A(x,y) = A(x)A(y)$ the factor of transfer of energy will be Λ^2.

In the majority of the known projects factor of transfer of energy is accepted rather high (more than 0,6-0,7). However, the efficiency of the WPT systems depends not only on size of Λ but it depends also on an active surface of the radiating antenna. The factor of antenna surface utilization for the square aperture is equal:

$$\boldsymbol{c} = \frac{\left\{ \int_{-a}^{a} |U(x)|^2 dx \right\}^2}{4a^2 |U_m(x)|^2}, \qquad (4)$$

Where $U_m(x)$- maximum allowable meaning of a field on the radiating antenna. It is usually located at the antenna center. These two factors $\boldsymbol{c}$ and Λ^2 are contradictory, as to increase Λ it is necessary to have a field which is falling down to edges, and, to increase $\boldsymbol{c}$, it is necessary to near distribution of a field to a uniform distribution. One from the purposes of the present work is the determination of conditions, when it becomes possible to receive a high factor of energy transfer, by saving the good operating active surface of an antenna. Or else, it is necessary to have to a high product $(\boldsymbol{c}\Lambda^2)$, which we shall name as a generalized criterion of energy transfer (GC).

We use for this purpose not completely filled antenna, in which all sub apertures have uniform and identical peak distributions of a field. High transfer of energy is reached by non-equidistant arrangement of rather a large number of such sub apertures.. Synthesis of a field in a radiator for want of mentioned above conditions (i.e. finding optimum arrangement of a plenty of the sub apertures) was possible. For good results a sub apertures concentration at the center and the dismemberment to edges is necessary. In this case it is possible to receive the distribution of a field on the receiving part close to a place, which would be created by a continuous antenna with optimum distribution of a field. The losses from partial use of an active surface of an antenna are small.

Usual parity between length of a wave l, length of a beam d, zone, not leaving for Fresnel limits, and width of a beam $2a$ (if radiating and receiving antennas have the same size) [14] should be:

$$d \approx \frac{a^2}{l} \qquad (5)$$

On the large distances the beam begins strongly to extend, and in a limit turns to a missing spherical wave, that is an unacceptable waste of energy.

Maximum factor of transfer Λ_{max} depends on the Fresnel parameter *c*. If $c << 1$, Λ_{max} becomes small (transfer to a Fraungofer zone. If $c \approx 1$ Λ_{max} can be close to unit (Fresnel zone).

Gauss distribution of a field does not create side lobes. For real antennas all of them appear because of limitation of the radiator size, at which edges of the field are cut[32] . If the Fresnel parameter is $c = 3$[33], the level of a field on the reception party at edge of the reception antenna will be approximately the same. It would be at uniform distribution of a field (first side lobe is -13 db). It means, that from the point of view of reception of a small field out of the reception antenna, uniform and Gauss distribution of a field in the radiator differ a little from each other, though transmitted power at uniform distribution of a field will be much higher, since the antenna surface is better used (the meaning of c comes nearer to 1).

Gauss distribution of a field is expressed, as

$$U = U_{max} e^{-\frac{sr^2}{a^2}} \qquad (6)$$

where s is a factor, which determines the effective width of the Gauss curve.

Electrodynamics system for wireless power transmission differs from usual system (communication, TV, radar-location and so on). In the usual reception antenna the useful effect is the intensity of a field on an axis of radiation, and antenna is so small in comparison with width of the direction pattern, that density of energy flow on all receiving antennas obviously can be considered as uniform. In a WPT case a picture of a field is different. The reception antenna is in a Fresnel zone or near it and its area is commensurable with width of a wave beam. The ideal decision of the problem connected with finding of the best field distribution on radiator is the reception on the receiving antenna of a uniform field and absence of it outside of this antenna.

To approach to the ideal decision it is possible not only to vary the distribution of a field on radiator, but also to change the structure of the antenna construction[34]. Such problem was not put earlier. It opens some window in the theory of antennas poorly investigated earlier, but containing set of alternatives of the decision. Below not only this problem is discussed, but also some methods of its decision are offered and the decision as three examples is given.

If to compare not completely filled antenna, radiating a wave beam with uniform field distribution and with equal amplitudes in the sub apertures, to the continuous antenna, at which Gauss field distribution is present at the large meaning of factor s, then in both cases the efficiency can be close to 1. However active areas of these antennas will differ from each other not for only the benefit of the continuous antenna, which area will be used only in middle [35-36]. The quantity of transmitted energy at the continuous antenna will be less.

3. NON-EQUIDISTANT DISCONTINUOUS ANTENNA ARRAYS

The field on radiator, falling on amplitude to edges, is typical for WPT. For the non equidistant (discrete) in steps distributions of a field it means, that the clots of the sub apertures a concentrate at the center, that correspond to high density of a flow of energy, and gradually disperse to edges, where density of energy below is necessary, as it is shown on Fig. 2.

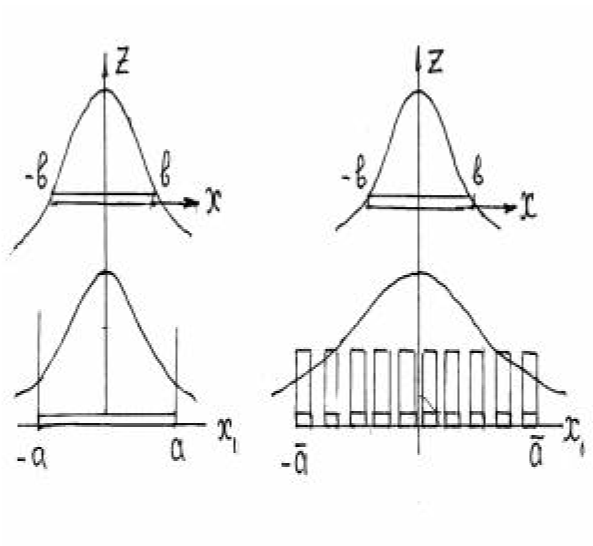

Fig.2. Peak distribution of a field on continuous (at the left) and on partially filled non-equidistant antenna to an array (on the right) for radiating (below) and reception (at the top of) antennas.

All sub apertures are identical and have uniform distribution of a field with identical amplitude, which can reach maximum allowable size.

It is supposed, that the quantity of these sub apertures is rather great to admit the approximation of continuous function of optimum distribution of a field, which is close under the form of a Gauss step function curve. The locations of the sub apertures can be found by differentiation of this step function. Splitting of the continuous aperture on a part and dismemberment of them in space, when all apertures are equal and have uniform peak distribution of a field, improves the WPT system effectiveness, i.e. generalized factor of transfer of energy $\left(c\Lambda^2\right)$ is increased. The optimum form of distribution can be achieved only for enough large radiating apertures, where splitting the antenna into the large number of parts is possible. Such design allows to approach to unit of both factors Λ^2 and c. As a result the system effectiveness of the transfer of energy rises. Let's remind, that the factor characterizes a use of a surface only of active part of the antenna (it not a coefficient of utilization of antenna surface in the usual aerial of a terminology). If there is many sub apertures and the size of gaps between them is increased to the edge of the antenna, the wave beam has a field, falling down to edges. Certainly, the total area of the antenna will be large, but its active part remains without changes and product Λ^2 and c will be close to 1.

The meaning of the generalized criterion will be more, than at the continuous antenna with uniform distribution of a field, where $c = 1$, but Λ^2 is not great because of side lobes. It will be more also, then at the continuous antenna with a field, falling down to edges, as in this case Λ^2 is close to 1, and c <1. The advantages of the discrete antenna in comparison with the continuous one (in case of transfer of energy) and feature of synthesis of distribution of a field on it are executed with the help of algorithm described in detail in the papers[16,37,38].

So, we have replaced the continuous aperture with non-uniform optimum excitation by the discrete aperture of same active length made of the identical sub apertures with excitation, uniform and equal on amplitude. It allows at practically identical factor of transfer to receive the large transmitted power, if the allowable level of excitation is limited to its size at the center of the continuous antenna.

4. THE PHASE SYNTHESIS OF ON A FIELD IN FRESNEL AREA

Modern antenna systems consisting of the separate sub apertures, are expedient to be supplied with the systems of phase control and to be designed as the phased antenna arrays[41,42]. The elementary case of phase control – the creation of linear phase distribution on the flat transmitting aperture, that results in the deviation of a propagation direction of a wave beam from the normal to the plane of the aperture. It is expedient to use transmitting antennas with the uniform amplitude distribution, and to execute the optimization of the coefficient of energy transmission to a receiving antenna of a discrete size with the help of phase distribution control.

So, from the theoretical point of view the main feature is to produce the algorithms of the control of phase distribution. This work is devoted to the description of some effective algorithms of finding of necessary phase distributions (the algorithms of phase synthesis). The problems of phase synthesis and the methods of their solution have an exclusive practical relevance in antenna's theory. Engineering allow finding optimum (due to this or that yardstick) phase distribution of flow on the elements of the phased antenna arrays (in our case - on the separate sub apertures of discontinuous transmitting antenna) for the creation of the demanded direction diagrams (in our case – the creation of demanded distribution of an electrical field in Fresnel area). The antenna arrays are the basic perspective type of antennas in complex radar and communication systems and WPTS.

From the mathematical point of view, the problems of phase synthesis are complex non-linear approximating problems, that, as well as for any non-linear problems, handicaps the work-out of the methods of their solution and invokes the problems of existence and uniqueness of the solution (i.e. required phase distribution), and also of the indicating of a start-up approaching while constructing the iteration processes, if such are used.

The following algorithm appeared to be rather effective. The iterating process was used, on each step of which the linear sub problem was decided by using the method of least squares (with usage of the pseudo inverse of matrix[43]) for the linearized phase distribution (a set of values of the phases on each sub aperture): creating the best approximation to the demanded direction diagram or the field in Fresnel area (1). So to prevent the accidence of the allowed limits of linearization of flow phases, the principle of the trust region[44] was used. It's practically the variant of Tikhonov's method of regularization[45]. The regularization variable choice was executed automatically or in dialogue mode "person - computer".

The detailed description of the above mentioned method and the algorithm looks like the following. The problem of the phase synthesis for the linear discrete aperture with the phase control involves the definition of flow phases from the equation

$$\sum_{n=1}^{N} a_n e^{if_n} e^{i2pd_n u} = E(u)\,, \qquad (7)$$

where N – the number of modules (elements) of the aperture; a_n - given (fixed) flow amplitudes; d_n - coordinate of modules' centers, counted usually from the center of the aperture and measured in radiation wave lengths; $u = \sin s \in [u_1, u_2]$ - generalized angular coordinate of view point, the angle s is counted from the normal to the plane of the aperture; $E(u)$ - given (synthesized) distribution of the radiated field.

It is expedient to represent the problem (3) as discrete:

$$\sum_{n=1}^{N} a_n e^{if_n} e^{i2pd_n u_m} = E(u_m),\ m = 1,..,\ M \qquad (8)$$

where $u_1,..., u_M$ - angular points closely spaced within the view region.

The problem (4) is the complex mathematical problem, as the phases $f_n, n = 1,.., N$ enter it as the exponential arguments, i.e. in non-linear mode. Till now it is not solved, as well as most of other non-linear problems. There is a set of the different individual approaches, but the best of them hasn't been selected yet. The sphere of the numerical methods applicable for the solution of a non-linear set of equations also is not properly studied. The main problem is the difference between the number of unknown parameters N and the number of equations M. As a rule, for good approximating of the field distribution $E(u)$ it is necessary to have $M >> N$, but for the solution of the system with N unknown parameters N equations are required. There is a problem what to do with the shortage of the equations?

As to linear methods - there is the classic method of low squares, that is now days sometimes called the method of the generalized inverse (pseudo inverse) of matrixes[43].

The Newton-Gauss method (the method of linearization) is the basic approach for the solution of the equation systems of N non-linear equations with N unknown parameters. It is expedient to aggregate these two methods with the usage of the vector-matrix approach, well recommending itself for the solutions of the amplitude synthesis of WPTS problems[11].

Computer through the usage of mathematical software MATLAB realized the described algorithm.
With the help of the program a number of practically important problems of the phase synthesis of WPTS was solved, including the problems of creation of an uniform distribution of a field on a surface of the receiving aperture, the problems of the synthesis of a radiation field with a lower radiation level in some angular sectors or some angular directions, that is all important for the construction of WPTS that answers the ecological requirements.

Here is one of the particular examples. The equal- amplitude antenna system of 10 sub apertures was taken. The initial phase distribution was zero. The distribution of the radiated field in Fresnel zone is shown on Fig.3

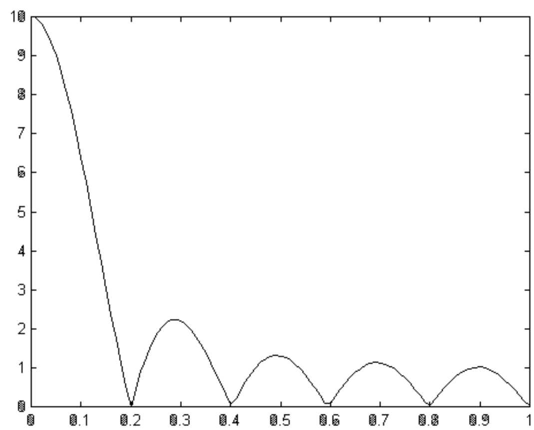

Fig. 3. The initial field distribution.

It was required to suppress the level. It was required to suppress the level of the radiation in the zone of the second side lobes keeping the maximum possible value of the power transmission coefficient.

After 3 iterations in accordance with the described algorithm the level of the second side petal has decreased for more than 20 dB while the power transmission coefficient has fallen by less than 2%.

The synthesized phase distribution is shown at Fig.4.

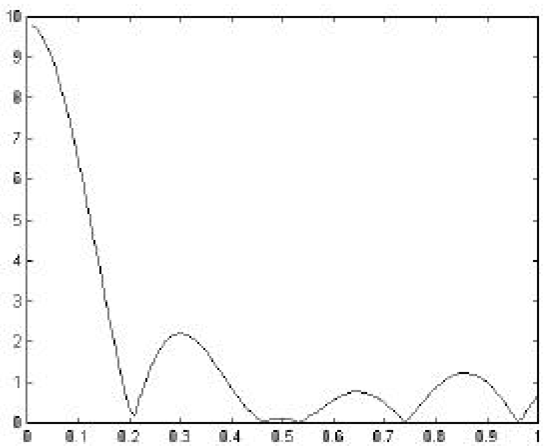

Fig.4. The synthesized field distribution

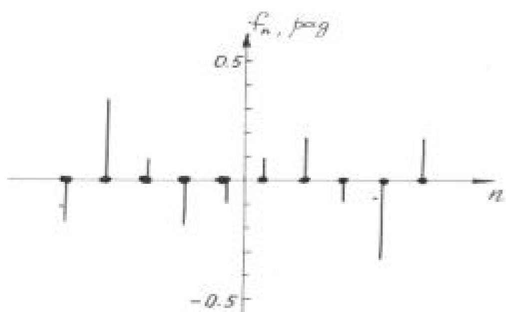

Fig.5. The synthesized phase distribution

Fig. 5 shows the synthesized phase distribution. It is interesting, that it has a specific ant symmetric view.

When we have the synthesized radiating field the field on the observer side is unusual. The second side lobe is decreased very much. It is shown at the Fig. 2.

LIMITATION OF THE SPS SQUARE

In 2050 ten billions people will consume 70 ÒÂò power [46]. It was the challenge of the World Energy Council (WEC). It is 6.7 kWt per capita. In work[46] the basic features of solar power stations are stated and it was shown how to realize the challenges of the WEC. The energy should be ecologically clean. It should be much below the cost. For this purpose the new sources of energy can be used. This paper discusses the possibility of using of the Solar Power Systems, which can yield 600 000 ÒWt-h a year (it is 70 TWt all the time). At the first acquaintance with SPS always comes an idea that the GEO Solar Satellites in geostationary orbits about Earth and the Moon, which can be a place for the SPS transmitting part are so far from the Earth (36 000 and 386 400 km accordingly), that at once there is a doubt, whether a Fresnel area could be approached and in which focusing of a wave beam can be carried out. As it is known the following condition must be satisfied:

$$d \approx \frac{2\pi ab}{c\lambda}, \qquad (9)$$

From this formula it is visible, that if $c \approx 3$ and d=386 400 km, then $a \cdot b \approx 23 km^2$ (if d=36 000 km, then $a \cdot b \approx 2.15 km^2$). To estimate an admissibility of such size of antennas, it is necessary to take into account the density of an energy flow (DFE) on them. If the transmitting energy is equal 70 TWt then DFE is too large. It is wrong for this situation.

Really, the density value of an energy flow in the radiating antenna accepted earlier in the Japan SPS'2000 project is equal to 30 kWt/m^2 and at the center of rectenna it must be equal 230 Wt/m ^{2}. Such low size of DFE is taken because there are ecological requirements and the rectenna uses Shottky diodes, which fails at higher DFE. Let's accept them the same value. In that case the linear sizes of the rectenna and the radiating antenna are 550 and 48 km. According to (1) at such size of antennas the Fresnel factor will be more than 400. It is obvious, that such value c is not available for the SPS.

The solving of this problem exists. It is necessary to divide antenna into independent parts. Each of antennas is divided into independent from each other parts. It is very convenient technologically, since it allows the creating of SPS on independent stages.

The shown variants of rectennas location on the Earth by the electric power allow to estimate alternatives and to help to accept the qualified decision on a power problem in 21 centuries. The reception of energy from the Sun is possible though the systems immensity as it is described here, is doubtful. And the problem of the report is to show the real scales of the structures. Useful result of the report is the qualified choice of parameters of the module (one of the identical parts) for this enormous power system, which, in cases of creation of the first module, will allow adding of identical power stations additionally. As the transmission of solar power is gradual, the quantity of the created parts can be adequate to the development and creation of other sources of power supply. It will be expedient to attract by engineering study of such system and its economic estimation if the danger of a planet heating prove to be true at the excessive of emissions CO_2 and, simultaneously, appears impossible to develop the power based on the control thermo nuclear reaction

5. Conclusion

It is shown that there are some ways of reduction of the active part sizes of the radiating aerial at preservation of efficiency of all system. It permits an opportunity of some decrease of its cost and approaches terms of the positive decision about the creation of Space Power Station in the first quarter of the 21century. The new problems of the synthesis of optimum WPT systems phase control are exposed and the effective algorithms for their solution are explained in this work

The new investigations are needed in field of the three dimension discontinuous problems and especially for the not equidistant and the phase synthesizes apertures.

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