

Wireless Power Transmission Antenna Peculiarities for the Space Power Systems

Sergey S. Shaposhnikov¹

Abstract

Space Solar Power Stations are costly because of the great size of their radiating and receiving antennas. These sizes are the result of the divergence of the wave beam, which transmits the energy from space to the Earth. This is a matter of radiating and receiving antennas and their interaction. It is shown that a correct choice of the field distribution on the radiation antenna allows us to increase the wireless power transmission efficiency and to lessen its cost.

Introduction

The problem of energy transmitting by electromagnetic wave beam for large distances with small losses is a central one in the problem of energy sources in the 21-century. The use of GEO Solar Power Satellites (SPS) is the optimum decision of this global problem in many respects. The possibility of creation of the global means for the feeding of Earth with free Sun energy has been considered long ago [1,2]. Nuclear power stations are poorly suited for Future Energy Generation. But the SPS creation price is so big that Humanity is not yet ready for this. Yet the technology for this is clearly available, if costs can be addressed and managed.

There are many useful applications for a super-large space power design but most of them can't yet justify the great expenses required for it. Investigation in this field can be justified only when the necessity of the Space Power Station (SPS) will be accepted as a unique means.

Modern technique enables us to create a platform in space carrying solar batteries, generators converting electric current worked out by them into the Electromagnetic field energy of ten-centimeter range and antenna forming electromagnetic wave beam. On the Earth the other antenna (rectenna) receives this beam and it is converted into electric current again. Antenna and rectenna sizes are chosen so that the rectenna is situated in the antenna's Fresnel's area (but not in -the far area as in the ordinary radio communication). It is necessary to create the powerful electromagnetic waves beam hundreds meters in width and thousands kilometers in length transmitting the energy with small losses (about

¹ IEEE Member, Leading Scientist, Moscow Radiotechnical Institute of Russian Academy of Sciences, 132 Warshawskoe shosse, 113519, Moscow, Russia; phone 7-095-315-3125; ssshmrti@orc.ru

10%). This idea has been discussed for several decades in magazine literature and at the numerous conferences. The first projects of its physical modeling in centimeter ranges are being prepared [3,4,5]. The technical problems also exist, which require energy transmitting for the long distances with small losses too but between two points on the Earth.

One of the principal questions of the high price of the SPS is the great size of radiating and receiving antennas. These sizes are the result of the divergence of wave beam, which transmits the energy from space to the Earth. This question is not completely elaborated theoretically. This is a matter of electrodynamics of the Wireless Power Transmission. That is radiating and receiving antennas and their interaction. The energy transmission is the optimal when the minimal part of the transmitting energy passes by the receiving antenna. The distribution of currents on the transmitting antenna is focused in the center of the receiving one and has a taper distribution. But this distribution is not optimal. It has a serious defect.

The proposed report is devoted to the problem of electromagnetic waves beam creation as super-long path for energy transmitting from satellite power station to the Earth has small losses. As we know, there are many papers, devoted to this problem or to the whole problem of GEO Solar Power Satellites.

The author and his team have been working upon this problem in the frame of the International and Technology Center (ISTC) project for the last several years and the report contains mainly new results received by us, which have not been published or reported yet. Great attention was paid to the problem of the beam optimum formation. Thus, the author tried to interpret the highly ambiguous concept of optimum, analyzing and comparing, if possible, various criterions of the optimum.

As usual, in real technical problems various criterions create to various requirements, often incompatible, and it is necessary to take into consideration many factors at the same time when choosing the decision.

The main disadvantage of microwave Wireless Power Transmission (WPT) is that the significant part of the radiating energy does not reach the given area of space because of the diffraction divergence. As the transmission distance increases as compared to diffraction length of the radiating antenna this disadvantage is most conspicuous. The size of the radiating and receiving antennas must be selected so as not to exceed the diffraction length of the radiating aperture. It shouldn't go out of the Fresnel area.

Lately in literature great attention is given to microwave power transmission systems with discontinuous antennas [6]. The novelty of this problem has attracted the attention of number scientists from the different countries. On International antennas conferences in Moscow in 1998 and in Davos in 1999 were carried out the special sessions on wireless transfer of energy. The problem was discussed at International and CIS meetings and also in May, 2001 at the 3-nd International conference (WPT'01) in France (Reunion Island).

One of the main theoretical problems is the synthesis of optimal antenna systems including transmitting and receiving antennas. The main theoretical results are received for WPT apertures including discontinuous antennas [7].

Gauss-like optimal field distribution in the aperture of the round or square transmitting antennas is well known..

It is supposed to use the solution of quasi optical problem to minimize the losses. In WPT the correlation between wave length λ , the distance between the antennae d and the transmitting and receiving antenna half sizes a and b is defined by the Fresnel parameter

$$C = 2\pi \frac{ab}{\lambda d} \quad (1)$$

Usually it equals about 2-3. The receiving antenna is situated near of the Fresnel area.

As it is shown from (1) the increase of the distance d requires for the increase of the ratio $\frac{ab}{\lambda}$.

The transmission is considered to be optimal, when the receiving antenna does not intercept the minimal part of the transmitted energy. The distribution of current on the transmitting antenna is the taper type (usually it is used Gauss field distribution). The radiation from the transmitting antenna is focused in the center of the receiving one. This distribution is not optimal !

There are two peculiarities in the taper field distribution:

The first: The maximum of energy flow density at the transmitting antenna can't be made unlimitedly large, the admitted power density limits it. If this maximum is fixed, the noticeably more energy may be transmitted by means of best filling of the aperture, for instance at the uniform distribution. Of course in that case the losses of the transmission will be bigger. But as the accounts [7] shows we will create more energy at the receiving end of power transmitting system.

The second: The side maximums are not so small at the "Gauss" transmission. They occur because the Gauss function is limited (it is cut at the edge of antenna). The first diffraction maximum at the level of - 13dB occurs at the uniform distribution (a table form function).

The side maximums of the cut Gauss distribution depend on a value of coefficients σ in the expression of the Gauss curve

$$e^{-\frac{\sigma r^2}{a^2}} \quad (2)$$

If the value σ is large the cutting of Gauss curve takes place at the low level and the side maximums on the receiving side are small but effectiveness of WPT is small too because the antenna surface is used very poorly. It is found that the optimal field distribution has a taper form too. If the value σ is small the level of the wave field out of the receiving aperture reaches also about - 13dB.

The product of the effective cross sizes of two antennas (receiving and transmitting antennas) is increasing at the change of the taper distribution to the uniform one. Therefore the field is contracted at the receiving side. It means that the field at an edge of receiving antenna is decreased.

Calculations [7] showed that the field at the receiving antenna edge for taper transmission is about equal to the field, which will take place in the diffraction maximum at the uniform distribution.

So from the point of view of the field level at the edge of the receiving antenna the uniform distribution slightly differs from the optimum one. But the aim is to transmit as much energy as possible. It is realized only with the uniform distribution.

The most effective and the most technological method to make a good antenna for the WPT is to use incompletely filled aperture.

If separate parts divide the continuous aperture and these parts (sub apertures) are situated on the radiating plate in the determinate order (discontinuous array), the effectiveness of the WPT is increased. This idea at first was reported at the WPT'95 Conference in 1995 (Japan) [3].

Discontinuous antenna has a wonderful feature. It allows creating on the receiving antenna essentially more energy by comparison with continuous antenna if the efficiency and active antenna squares are equal. It is because they (discrete antennas) use the aperture edges better than the continuous antennas. Of course in that case the sub apertures must be distributed correctly. Apparently unequal distant distribution of sub apertures allows improving the result.

Differently, we substitute the optimal continuous aperture with the same discontinuous antenna, which consists of identical sub apertures with uniform amplitude distribution. Practically equal efficiency leads to the higher transmitted power (if the permitted level of amplitude is limited and its value is in the center of a continuous antenna). It is very good for practical purposes.

Effectiveness of Wireless Power Transmission (WPT) depends on many parameters. Only a part of WPT system is discussed below, which includes radiating and receiving antennas and the environment between them. The wave beam is expanded proportionately to the propagation distance and a flow power density is increased inversely proportional to the square of this distance. However the WPT has some peculiarities, which will be mentioned here.

WPT systems require transmitting almost whole power that is radiated by the transmitting side. So, the useful result is the power quantity at the receiving antenna, but not the value of field amplitude as it is usually required. Efficiency of WPT systems is the ratio of energy flow, which is intercepted by receiving antenna to the whole radiating energy.

Field distribution on the receiving antenna usually is uniform because its size is small comparatively to the width of the beam. For WPT systems this distribution isn't uniform. It has a taper form and it depends on the field distribution on the transmitting antenna.

For increasing of the energy concentration on the receiving antenna the phase distribution on the radiating antenna has usually a spherical form with the center in the point on crossing of the receiving plate and the radiating axis.

Radiating antenna of the WPT systems usually has a taper distribution of the field. This distribution allows to increase the efficiency and to decrease the field out of the receiving antenna.

The efficiency of energy transmission is expressed by the functional

$$\Lambda^2 = \frac{\int_{-\frac{Q}{2}}^{\frac{Q}{2}} |E(\xi)|^2 d\xi}{\int_{-\frac{Q}{2}}^{\frac{Q}{2}} |E(\xi)|^2 d\xi} \quad (3)$$

Here $Q \times Q$ is the total area where the energy of the electric field $E(\xi)$ is radiated and $q \times q$ is the square plate of the receiving antenna. For simplicity we take square of transmitting and receiving apertures, which have separating amplitude distributions $U(x, y) = U(x)U(y)$.

To increase Λ the field distribution on radiating aperture is made as a tapered distribution. It is shown [6] that the best result is obtained at the field distribution which is close to the Gauss one $\exp\left\{-\frac{\sigma x^2}{a^2}\right\}$ and which has edges cut on a definite level. For example, σ is π and the Fresnel parameter C is about 1 (it is usually 2-3).

High value of Λ is supposed to be in the majority of known projects of the WPT systems.

However, the effectiveness of the WPT system is defined not only by the value of Λ . It is also determined by the rectangularity of the field distribution on the radiating aperture, which for the square antenna is equal to

$$\chi = \frac{\left\{ \int_{-a}^a |U(x)|^2 dx \right\}^2}{4a^2 |U_m(x)|^2} \quad (4)$$

where $U_m(x)$ is maximal admissible value of the field on the radiating antenna. It is usually situated in the center of the antenna. The rectangular distribution factor in the theory of antennas is usually called the surface utilization factor χ .

The meaning of these two parameters Λ and χ is discrepant because to increase Λ^2 it is necessary to have the field falling down to edges, but to increase χ it is necessary to have a uniform field. The purpose of this paper is to find the conditions at which this discrepancy is cancelled.

A demand to increase χ has been shown in literature before [7]. The increase of χ permits to increase the transmitting power without the extension of sizes of the radiating antenna but the efficiency Λ^2 is decreased at the same time.

To increase the effectiveness of WPT system it is necessary to increase the product $\Lambda^2\chi$, though the requirements for each of both multipliers are opposite. This product is named a generalize criterion! It is possible to find the way out of this contradiction if the antenna is discontinuous (discrete) one. Let us produce the field distribution in the radiating discrete antenna falling to its edges not by means of creation of non-uniform distribution of the field but with the help of irregular situation of identical sub apertures, each of them having the uniform field distribution. It is supposed that the number of these apertures is sufficiently high in order to admit the approximation of the integral optimum monotonous Gauss distribution by means of step function. The places of sub aperture disposition can be found by the differentiation of this step function.

Discrete distribution of sub apertures presents non-equidistant antenna array consisting of the similar elements. Such optimization is optimal in Chebyshev's sense since the maximum error tends to zero while the number of sub apertures is tended to infinity. So the field in the place of observer's disposition would be similar to step and the monotonous signal source.

The falling to the edge field distribution is typical for the WPT problems. For the discrete-step distributions that means the concentration of sub apertures in the center and their gradual discharge on the edges. Thus all sub apertures are similar and have the uniform distribution of the field with the equal amplitude, which may reach the maximum admissible value. The example of the computer simulation for this case is submitted in the paper [7].

The dismemberment of continuous apertures and slight moving of them apart in the space when all of apertures are equal and uniformly feed increases their effectiveness (the generalized criterion is increased). The generalized criterion determines the quality of the WPT Systems better than usual criterion.

The optimal distribution form may be reached for the large radiating apertures where dismemberment at many parts is easily realized by disposition of sub aperture cloths in places, which correspond to high field intensity (first of all it concerns the center of the radiator) and relieving sub aperture density at edges of antenna. This construction allows to approach to unit the value both of coefficients Λ^2 and χ . As a result the effectiveness of the WPT system will be essentially increased.

Conclusion

The resolve of the synthesis problem of the WPT shows that WPT efficiency may be improved by using special current discontinuous distribution on the antenna. Here we have three possibilities:

1. To use a discontinuous equidistant array with the quasi Gauss distribution.
2. To use a discontinuous non-equidistant array with the uniform distribution.

3. To use uniform continuous phase synthesis antenna array.
All of these methods are original and they have been modeled only in the frame of International Science and Technology Center Project.

The possibility of decrease of the wave beam expansion permits to make the WPT systems less expensive. Such approach to the problem of the continuous radiators and of the real antennas, which can be created, is new.

References

- [1] P.E. Glaser «*Method and Apparatus for Converting Solar radiation to Electrical Power*», U.S. Patent 3 781 647, 1973.
- [2]. P.E. Glaser «*An Overview of the Solar Power Satellite Opinion*», IEEE Transactions on Microwave Theory and Techniques, Vol. 40, No.6, June 1992, P. 1230.
- [3] R. T. David *Microwave Link Transport 30 kW DC over 1 mile*. Microwaves. Oct. 1975. P. 9-
- [4]. G. Pignolet, N. Kaya Lan Sn Luk J-D. Y. Naruo, V. Vanke *Demonstrating SPS-IdR Studies in Reunion Island*, Program and Abstracts of the WPT'95 Conference in Kobe (Japan) p. 15-2. Space Energy and Transportation (USA) v. 1 No 3, p. 168.
- [5] M. Nagamoto, S. Sasaki, Y. Naruo, V.A. Vanke *The Work of the Japan Institute of Space Researches in Space Energetics*. Sov. Fiz. Uspekhi, V.37, No.6, p. 589.
- [6] S.S. Shaposhnikov, B.Z. Katsenelenbaum, R.B. Vaganov, V.A. Permjakov «*Innovative Approach to the Small Divergence Wave Beam*», Report 4-2 at the Second Wireless Power Transmission Conference (WPT'95), 1995 (Kobe, Japan), It was published in Space Energy and Transportation (SET), Vol.2, No., 4, 1997, P.189.
- [7] Garmash V.N., Shaposhnikov S.S, "Matrix Method Synthesis of Transmitting Antenna for Wireless Power Transmission". IEEE Trans. On Aerospace and Electronic Systems, 36. 4. 1142-1148. 2000.