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ENVIRONMENTAL AND ELECTROMAGNETIC COMPATIBILITY ASPECTS OF MICROWAVE WIRELESS POWER TRANSMISSION

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A numerical model of the radiation field from a microwave wireless transmission line is developed, and the levels of the side lobes in the plane of the receiving antenna for different versions of the ground transmission line are calculated. It is shown that the problem of an environmentally clean and safe microwave wireless power transmission can be solved by optimizing the amplitude–phase distributions of the field over the surface of the transmitting antenna.

Modern studies of the generation and transformation of microwaves into d. c. power have formed a basis for implementing highly effective systems of wireless power transmission (WPT) [1]. In addition to problems of the high efficiency and relatively low cost of such systems, problems associated with the environmental safety of such systems and the reduction of background radiation outside the receiving antenna, which is especially important for ground transmission lines, have come to the foreground of such studies [2]. The project of the first ground wireless transmission line (Réunion island, French overseas department) presupposes supplying a small village at the bottom of a deep crater of an extinct volcano, where laying ordinary power lines is difficult because of the complex terrain and the high cost of construction [3].

It is highly important for the level of background radiation outside the receiver–converter site of a ground microwave transmission line not to exceed the environmentally safe level. According to western safety standards, microwave radiation is considered safe if its power density is below 100 W m^{-2}. This level of background radiation can be achieved by searching for the optimal amplitude–phase distributions of the field over the surface of the transmitting antenna.

The Fresnel–Kirchhoff diffraction theory can be used to determine the characteristics of a microwave beam in the plane of the receiving antenna. The most often used transmitting antennas are axisymmetric with linear polarization of the electric field. The complex-valued electric-field strengths at the transmitting ($\hat{E}_A$) and receiving ($\hat{E}_R$) antennas are related as follows:

$$\hat{E}_R(r) = -j\frac{k}{D}e^{-j(kD+kr^2/2D)}\int\limits_0^{R_1}\hat{E}_A(r')e^{-jkr'^2/2D}J_0\left(\frac{krr'}{D}\right)r'\,dr', \tag{1}$$

where $\hat{E}_A = E_A e^{j\Psi_A}$, $\hat{E}_R = E_R e^{j\Psi_R}$, with E_A and E_R the amplitude distributions of the electric field at the transmitting and receiving antennas and Ψ_A and Ψ_R the corresponding phase distributions, k is the wave number, D is the distance between the antennas, $J_0(z)$ is the zeroth-order Bessel function, r and r' are the current radiuses in the coordinate system of the transmitting and receiving antennas, and R_1 is the radius of the transmitting antenna.

The focusing quadratic phase distribution $\Psi_A(r) = kr^2(2D)^{-1}$ ensures maximal concentration of the emitted power into a fixed receiving aperture. Such phase distribution is optimal in efficiency and will be used in what follows. Equation (1) implies that the phase front of the beam impinging on the receiving antenna is divergent, while the phase distribution has the form

$$\Psi_R(r) = \frac{\pi}{2} - kD - \frac{kr^2}{2D}.$$

Equation (1) then yields

$$E_R(r) = \frac{k}{D}\int\limits_0^{R_1} E_A(r')J_0\left(\frac{krr'}{D}\right) r'\,dr'. \tag{2}$$

We will assume that the amplitude distribution at the transmitting antenna is continuous and can be represented as follows:

$$E_A(r) = E_{\max}\sum_{n=1}^{N} nk_n\left(1-\frac{r^2}{R_1^2}\right)^{n-1}, \quad r \le R_1, \tag{3}$$

where $E_{\max}$ is the radiation field at the antenna's center, and the k_n are the expansion coefficients normalized in a way such that the absolute maximal value of the sum in (3) is unity. Then equation (2) becomes

$$E_R(r) = E_{\max}\frac{kR^2}{2D}\sum_{n=1}^{N} k_n\Lambda_n\left(\frac{kR_1 r}{D}\right), \tag{4}$$

where $\Lambda_n(z)$ is the nth order lambda function of the first kind,

$$\Lambda_n(z) = \sum_{k=0}^{\infty}\frac{n!}{k!\,(n+k)!}\left(\frac{iz}{2}\right)^{2k} = \Gamma(n+1)\left(\frac{2}{z}\right)^{n} J_n(z), \tag{5}$$

which can be expressed in terms of the Bessel function $J_n(z)$ of the first kind and the gamma function $\Gamma(z)$ with $z = kR_1r/D$. The power density distribution $p_R(r)$ in the plane of the receiving antenna is

$$p_R(r) = p_A\left(\frac{kR_1^2}{2D}\right)^2\left[\sum_{n=1}^{N} k_n\Lambda_n(2\tau r/R_2)\right]^2, \tag{6}$$

where $p_A = Z_0^{-1}E_{\max}^2$ is the maximal power density at the transmitting antenna, R_2 is the radius of the receiving antenna, $Z_0 = \sqrt{\mu_0/\varepsilon_0} = 120\pi$ is the impedance of free space, and ε_0 and μ_0 are the permittivity and permeability of vacuum. The levels of the transmitted power (P_T) and the received power (P_R) are determined by integrating expressions (3) and (4) over the areas of the respective apertures of the transmitting and receiving antennas. The efficiency of the system in question is equal to the ratio P_R/P_T and, in the final analysis, is independent of p_A and the transmitted power P_T and is determined solely by the expansion coefficients k_n of (5) and the value of the wave parameter $\tau = \pi R_1 R_2/\lambda D$, where λ is the wavelength at which the power is transmitted. Maximal efficiency is achieved with a Gaussian amplitude distribution at the transmitting antenna [2].

We believe that it is most rational to replace a transmitting antenna of a large radius with a phased array of standard emitters. Hence, we will now analyze the characteristics of a system with a discrete amplitude distribution of the field at the transmitting antenna and "partition" the antenna into N concentric rings. The amplitude distribution will then be

$$E_A(r) = \begin{cases} E_n, & r_{n-1} \le r \le r_n, \quad n = 1, 2, \ldots, N, \\ 0, & r \succ r_N = R_1, \end{cases} \tag{7}$$

where E_n and r_n are the amplitude and radius of the nth step, N is the number of steps in the discrete amplitude distribution, $E_{N+1} = 0$, and $r_0 = 0$. Then (2) yields

$$E_R(r) = E_{\max}\frac{kR_1^2}{2D}\sum_{n=1}^{N}\Delta\varepsilon_n x_n^2\Lambda_1(2\tau x_n r/R_2), \tag{8}$$

where $E_{\max} = \max\limits_{1 \le n \le N} \{E_n\}$, $\Delta\varepsilon_n = \varepsilon_n - \varepsilon_{n+1}$, and $\varepsilon_n = E_n/E_{\max}$ and $x_n = r_n/R_1$ are the relative amplitude and radius of the nth step.

The expression for the power density at the surface of the receiving antenna becomes

$$p_R(r) = p_A \left(\frac{kR_1^2}{2D}\right)^2 \left[\sum_{n=1}^{N} \Delta\varepsilon_n x_n^2 \Lambda_1(2\tau x_n r/R_2)\right]^2, \tag{9}$$

$$p_R(0) = p_A \left(\frac{kR_1^2}{2D}\right)^2 \left[\sum_{n=1}^{N} \Delta\varepsilon_n x_n^2\right]^2. \tag{10}$$

The values of the transmitted and received power can be found by integrating the respective power density over the entire surface of the antenna.

To find the optimal distribution for which the transmission line is characterized by a high efficiency and generates a fairly low level of background radiation, let us do a comparative analysis of several versions of the system with different amplitude distributions at the transmitting antenna. The radiating power of the transmitting antenna amounted to about 14 kW in all versions with a fixed distance between the antennas $D = 700$ m and the transmitting antenna radius $R_1 = 2.4$ m.

For a uniform amplitude distribution of the field at the transmitting antenna (version *1* in Fig. 1), we calculated the output characteristics of the system at two frequencies, 2.45 GHz and 5.8 GHz. At $\tau = 1.5$, the transmission efficiency may be as high as 81.7% with the receiving antenna radius equal to 17.1 m at 2.45 GHz and 7.2 m at 5.8 GHz. The level of suppression of the first side lobe amounted to −17.57 dB with respect to the power density at the center of the receiving antenna (curve *1* in Fig. 2). Optimization of the amplitude distribution at the transmitting antenna makes it possible to significantly increase the efficiency of transmission and to lower the level of background radiation. For a power density $p_A = 1.7$ kW m^{-2} at the center of the transmitting antenna and a Gaussian distribution of the field (a −9.5 dB decrease in power at the edge of the antenna), an efficiency as high as 88.7% can be achieved. The transmitted power in this case amounted to 13.3 kW, while the received power amounted to 11.8 kW. The power density at the center of the receiving antenna was as high as 3 mW cm^{-2} and decreased toward the antenna edge by −9.5 dB. The level of suppression of the first side lobe amounted to −23.4 dB with respect to the power density at the center of the receiving antenna (curve *2* in Fig. 2). The calculated radius of the receiving antenna was 17 m.

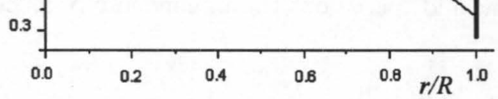

Fig. 1

Types of amplitude distribution (AD) of the field at the transmitting antenna: (*1*) uniform, (*2*) uniform Gaussian, (*3*) two-step, and (*4*) ten-step Gaussian.

Fig. 2

Dependence of the distribution $E_R^2(r)/E_R^2(0)$ in the plane of the receiving antenna on the current radius: (*1*) for a uniform amplitude distribution, and (*2*) for a uniform Gaussian amplitude distribution.

We also calculated the radiation field in the receiving plane for the optimal Gaussian distributions of the field (uniform and ten-step) at the transmitting antenna (versions *2* and *4*, respectively, in Fig. 1, radiation emitted at 2.45 GHz, and $\tau = 1.5$). The curves representing the dependence of the amplitude distribution $p_R(r)$ at the receiving antenna and normalized to the value of the power density at the center, $p_R(0)$ are almost the same (curve *1* in Fig. 3).

Let us now see whether it is possible to build a highly effective transmitting antenna with an amplitude distribution that is more suitable for the technical implementation than a ten-step Gaussian distribution. As an example, we examine a two-step distribution, i. e., one in which the central part of the antenna generates a field whose amplitude is greater than that generated by the outer ring part. Our calculations allowed us to find the optimal ratios for the step widths and the field amplitudes on these steps. In a two-step distribution, the central and first side lobes in the plane of the receiving antenna are practically the same as the similar lobes in the optimal ten-step Gaussian distribution (curves *1* and *2* in Fig. 3). Here the efficiency of microwave power transmission is about 86%, which is only 1.5% smaller than in the optimal Gaussian distribution. The level of suppression of the first side lobe amounted to −21.2 dB with respect to the power density in the central lobe.

The main results of our calculations for different amplitude distributions at the transmitting antenna are listed in Table 1. Clearly, the optimized two-step distribution is characterized by high efficiency and low background radiation somewhat inferior to the version with the optimal Gaussian distribution and differs advantageously from it in the simplicity of technical implementation.

Table 1

Type of amplitude distribution	Uniform	Ten-step Gaussian	Optimized two-step
Transmission efficiency	81.25%	88.22%	86.5%
Level of first side lobe	$0.29\ \mathrm{W\,m^{-2}}$ (−17.5 dB)	$0.07\ \mathrm{W\,m^{-2}}$ (−23.3 dB)	$0.11\ \mathrm{W\,m^{-2}}$ (−21.2 dB)
Radius of first side lobe	29.3 m	31.9 m	31.1 m

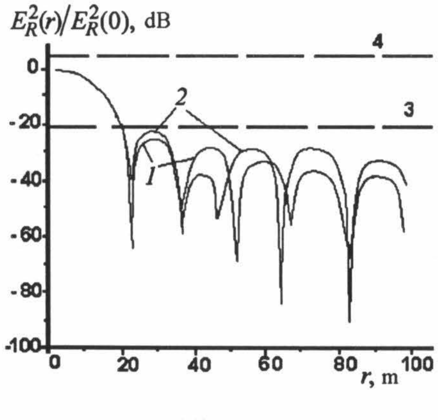

Fig. 3

The distributions $E_R^2(r)/E_R^2(0)$ in the plane of the receiving antenna as functions of the current radius: (*1*) for a two-step amplitude distribution; (*2*) for a ten-step Gaussian amplitude distribution; (*3*) level of safe microwave irradiation (the standard adopted in the Russian Federation); and (*4*) the western standard.

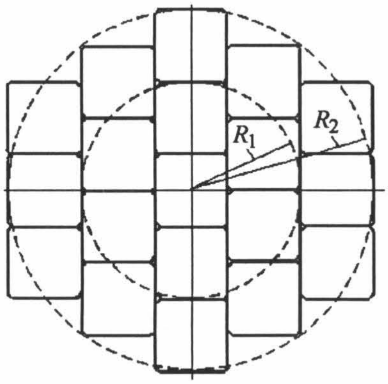

Fig. 4

A transmitting antenna consisting of 19 unified modules: R_1 and R_2 are the radiuses of the first and second steps in a two-step amplitude distribution.

Table 1 and Fig. 3 show that for the analyzed version of the ground microwave transmission line, the background radiation outside the central lobe can be reduced to a level that agrees with the requirements of the standards of the Russian Federation (0.1 $\mathrm{W\,m^{-2}}$). As for the requirements of western standards, a microwave power transmission line of such a scale is absolutely safe even within the central lobe.

The use of a two-step amplitude distribution may substantially reduce the difficulties of designing microwave power transmission systems. Magnetron-based unified emitters with an output power of about 1 kW used in microwave ovens can be employed for this purpose. A schematic of a transmitting antenna consisting of 19 unified emitters is shown in Fig. 4. The power density at the emitters filling the peripheral part of the transmitting antenna is 1.6 times lower than in the central part of the antenna. Some emitters may be displaced by certain distances with respect to each other with the oscillators being sufficiently synchronized. This should facilitate the mounting of an antenna on a steep slope, since in this case both the transmitting antenna and the receiving antenna can be divided into small systems whose planes would be parallel to each other and normal to the direction in which the microwave radiation propagates.

Thus, we have calculated the distribution of the radiation field in the receiving plane for continuous and discrete (step) distributions of the field at the transmitting antenna. We have found the simplest two-step field distribution at the transmitting antenna that ensures an efficiency of power transmission higher than 86% and a safe level of background radiation both outside the receiving antenna and at its center. Such a distribution substantially simplifies the technical implementation of the transmitting antenna whose design can be represented by a system of single-type emitting units.

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22 September 2004 Department of Radiophysics