VALUATION OF WIRELESS POWER TRANSMISSION SYSTEMS EFFICIENCY FOR POWER SUPPLYING SPACECRAFT

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One of the topical tasks of a wireless power transmission system (WPTS) investigation is the analysis of their characteristics for the real operation conditions. Particularly this task is considered in this article in case of power supplying a space craft (SC) by means of WPTS, the transmission part of which is situated at a power-satellite. Peculiarity of those WPTSs consists in the following: during their functioning the remoteness of power transmission can be changed and the alignment of the transmitting antenna and rectenna apertures is disturbed. Valuation of the WPTSs efficiency under the conditions mentioned above is the aim of this article.

The WPTS efficiency is considered as

$$\eta_S = \eta_i \eta_R = \frac{P_{max}}{P_\Sigma} \frac{P_0}{P_{max}},$$

where η_i is the interception efficiency, η_R is the rectenna efficiency, P_{max} is the maximum power absorbed by the rectenna aperture from microwave beam, P_Σ is power radiated by the transmitting antenna, P_0 is DC power in a rectenna load.

Consider the WPTS efficiency dependence on the remoteness of power transmission D using for this purpose the analysis methods from [1-4]. At first examine the most simple case of the single-zone rectenna the aperture of which is filled out by identical receiving-rectifying elements (RREs) connected with the load in series. Assume that the RRE circuit corresponds to Fig.1, diodes having efficiency 90% for frequency 2.45GHz are used and input RRE filters synthesized according to the method [5] have the coefficient of voltage transformation which is nearly equal to unit

$$K_U = U_{in}/e_x \approx \sqrt{R_{in}(f_0)/R_a(f_0)}.$$

Here U_{in}, $R_{in}(f_0)$ - are the voltage and the input resistance on the filter connector on side of the rectifier diode correspondingly, e_x is EMF induced by coming field on the vibrator connector and $R_a(f_0)$ is the vibrator input resistance for working frequency.

Figure 2 shows results of the analysis. Here curve 1 is the dependence of the maximum interception efficiency on the parameter $\lambda D/R_1R_2$ (λ - wavelength, R_1 - transmitting antenna radius, R_2 - rectenna radius), curve 2 is the similar dependence of the WPTS efficiency with the single-zone rectenna having slight maximum. Reducing the efficiency on the right of the maximum is explained by decreasing η_i. On the left of the maximum the DC power collection loss is increased [2], e.g. using the single-zone rectenna for small remoteness is not expedient. The usage of multizone rectennas allows to solve that problem [2]. At one of the variants for that rectenna the zones are filled out by the RREs, the filters of which have different K_U values. Curve 3 on Fig.2 shows the dependence of the WPTS efficiency for the four-zone rectenna on the parameter $\lambda D/R_1R_2$. External boundaries of the rectenna zones and K_U values for the filters are shown in the table (r is a current radius).

Table

Zone number	1	2	3	4
r/R_2	0.217	0.363	0.484	1
K_U	0.983	1.25	1.49	2

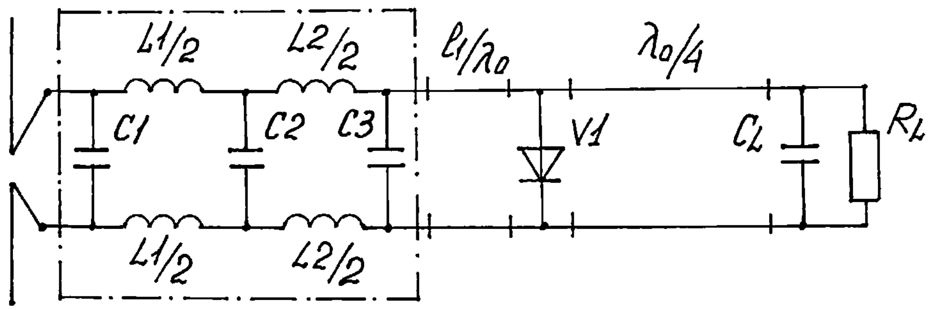

Fig. 1

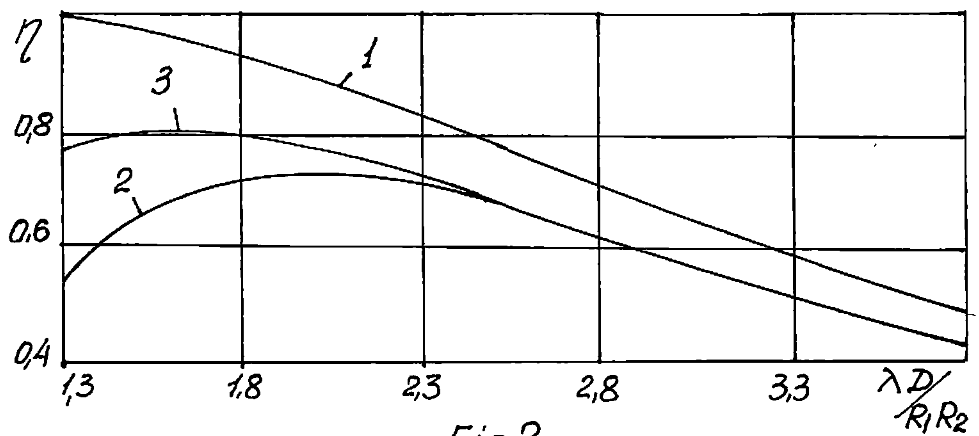

Fig. 2

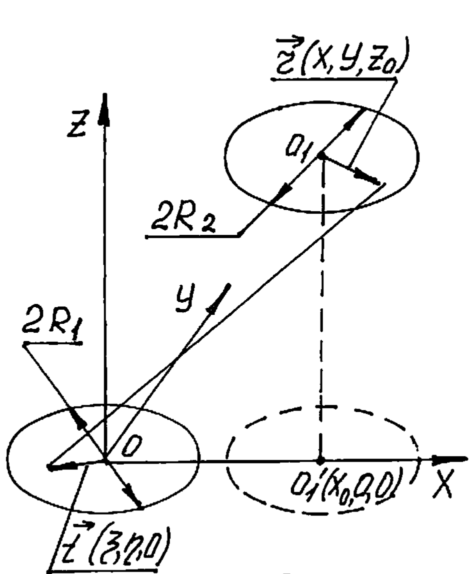

Fig. 3

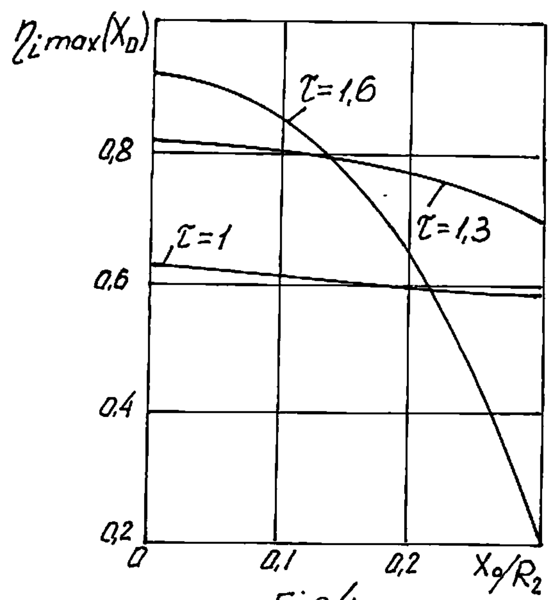

Fig 4

The obtained results show that the rectennas with different variants of aperture constructions have to be used in depend on the remoteness of power transmission in the WPTS. So, in case of the remoteness providing $\eta_i > 70\%$, it is necessary to use the multizone rectennas. Otherwise it is sufficient to utilize the rectennas with the identical RREs that have simpler construction.

The usage of any rectenna type depends on the interception efficiency value realized in the WPTS. Estimate this value change under the condition of the unalignment disposition of the transmitting antenna and rectenna apertures (the aperture alignment has been disturbed). Assume that the transmitting antenna is excited axial-symmetrically, the unalignment disposed antenna and rectenna are situated at parallel planes and the aperture centre of the rectenna is projected on the axis x in accordance with Fig.3. Here X_0 is the value of small axial displacement. Find out for that case the functional of the microwave power interception efficiency. In order to make it find out expressions for P_{max} and P_Σ. Use the aperture method and the known scheme for transportation of obtained expression [3]. As a result it is possible to get the following expression for the interception efficiency

$$\eta_i = \frac{P_{max}}{P_\Sigma} = \frac{kR_1Z_0 \iint\limits_{S_2} \left| \int\limits_0^a F(u) J_0\left(\left(\frac{kR_1}{Z_0R_2}\right)^{\frac{1}{2}} \sqrt{x^2+y^2}\, u \right) u du \right|^2 dxdy}{2\pi\left(X_0^2+Z_0^2\right)R_2 \int\limits_0^a \left|F(u)\right|^2 u du} \qquad (1)$$

where $k = 2\pi/\lambda$, S_2 is a rectenna aperture square, $a = \left(kR_1R_2/Z_0\right)^{1/2}$, $F(u)$ - amplitude distribution over the transmitting aperture, $u = \left(Z_0R_2/k\,R_1\right)^{1/2} t$, $J_0(z)$ - Bessel function for the zero order.

If the axial displacement is absent (Z_0=0), the functional η_i can be presented as the relation of two scalar multiplications of the Gilbert space.

$$\eta_i = (\mathbf{A}F,\mathbf{A}F)/(F,F).$$

Here the scalar multiplication and the operator $\mathbf{A}$ are defined as

$$(f,g) = \int\limits_0^a f(t)g(t)tdt, \quad \mathbf{A}F = \int\limits_0^a J_0(uv)F(v)vdv$$

For X_0=0 the optimal amplitude antenna excitation providing the maximum efficiency is known. It satisfies the equation

$$\mathbf{A}F = \sqrt{\eta_{i\,max}(0)}F \qquad (2)$$

where $\eta_{i\,max}(0)$ is the maximum own value of the operator $\mathbf{A}$ and can be presented by the polynom to the fourth power

$$F(u) = 1 + \gamma u^2 + \beta u^4 \qquad (3)$$

with the coefficients $\gamma = -\frac{a^2}{8}\left(1 - a^4/48\right)$, $\beta = a^4/192$. At the same time $\eta_{i\,max}(0)$ is the maximum value of the functional η_i.

Assume that the transmitting antenna is excited by the field with the optimum distribution. Consider the interception efficiency for the alignment disposition of the antenna apertures. To calculate the interception efficiency $\eta_{i\,max}(X_0)$ for that excitation ($X_0 \neq 0$), use the expressions (1), (2), (3). As a result of simple transformations for $X_0' = aX_0/R_2 < 1$, it is possible to find

$$\eta_{i\,max}(X_0)=\eta_{i\,max}(X_0)\frac{Z_0^2\left(B+C\frac{a^2}{2}+D\frac{a^4}{3}+F\frac{a^6}{4}\right)}{(X_0^2+Z_0^2)\left(1+\gamma a^2+(\gamma^2+2\beta)\frac{a^4}{3}+\gamma\beta\frac{a^6}{2}\right)}. \qquad (4)$$

For this expression

$$B=1+2\gamma X_0'^2+(\gamma^2+2\beta)X_0'^4+2\gamma\beta X_0'^6;$$
$$C=2\gamma+4(\gamma^2+2\beta)X_0'^2+18\gamma\beta X_0'^4;$$
$$D=\gamma^2+2\beta+18\gamma\beta X_0'^2;\quad F=2\gamma\beta;$$

The obtained expression (5) was used for numerical investigation of the maximum interception efficiency in the WPTS with the unalignment apertures of the transmitting antenna and rectenna. Figure 4 shows the $\eta_{i\,max}(X_0)$ dependence on the relative axial displacement X_0/R_2 for different values of the wave parameter $\tau=a^2/2$.

The shown figures allow to draw following conclusions.

Increasing the interception efficiency leads to increasing requirements for the alignment of the transmitting antenna and rectenna and as a result for accuracy of the system for operation of microwave beam disposition in space.

If the high accuracy of the operation system can not be provided it is not necessary to aspire to realization of the large interception efficiency (greater than 80%) because for example, for efficiency 90% the relative aperture displacement nearly 30% leads to the real interception efficiency not greater than 20%. In that case it is more useful to create the WPTS with the maximum efficiency nearly 60% - 80% for the aligned aperture. It allows to reduce the influence of unalignment and under the condition of its increasing up to 70% the interception efficiency is reduced not greater than 10%.

References

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