THE INVESTIGATIONS ON WIRELESS ENERGY TRANSMISSION AT THE KHARKOV NATIONAL UNIVERSITY OF RADIO ELECTRONICS

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ABSTRACT

The brief characteristic of the investigations carried out at KNURE in the field of wireless energy transmission is given. The basic researches were aimed at the development of the rectennas theory. A procedure of rectennas main parameters (their efficiency and spurious radiation level) computation is set forth for low-element and multi-element rectennas in cases of their uniform and non-uniform excitation. Ways of enhancing the rectennas efficiency and reducing their spurious radiation are pointed out. New directions of investigations in the field of wireless energy transmission being developed today are indicated.

The investigations on the problem of wireless energy transmission (WET) have been carried out at the Kharkov National University of Radio Electronics since early eighties. At the initial stage, main efforts were directed to studying characteristics of separate receiving rectifying elements (RRE) forming a rectenna being a terminal device of WET systems by microwave beam. As RRE is one of classes of antennas with nonlinear elements (ANE), then for its study the rather rigorous and general method of analyzing such antennas is used [1,2]. As applied to RRE, the corresponding procedure is set forth in the monograph [3]. Following the indicated procedure there were studied in detail the dependencies of RRE main characteristics on the radiator type (symmetric, folded, shunt dipoles); rectifying circuits (half-wave and full-wave); the presence or the absence of the input low-frequency filter at the RRE circuit; parameters of this filter and of the output filter; parameters of the Schottky diode; RRE load; a level of energy incident on RRE. The obtained results are given in [3]. They enable to judge about properties and parameters of RRE different types, show ways of increasing their efficiency and decreasing the spurious radiation, of the improvement of their operational performances. These data are basic for the next stage of our investigations − the analysis of rectenna arrays (RRE set). There were being studied both low element rectennas (LER) and multi element (large) rectennas . Procedures of studying these types of rectennas are different. As LER we consider rectennas at which the operating regime of every RRE is different due to different influence of adjacent elements on it. In LER, a number of RRE equals from several units to several tens. At such a number of elements it is possible, using the elementwise approach in combination with general methods of the ANE analysis described in [1-3] to perform calculations completely at modern PC. In the basis of the analysis of large rectennas with uniform excitation, the approximation of the infinite array is used. The task is reduced to calculation of one RRE incorporated in the infinite array, which consists of similar ones. Computations of large rectennas have been performed both for wire and printed radiators of composite geometry, which formed the two-dimensional array.

Especial attention has been paid to the analysis of large rectennas in the case of non-uniform excitation of their apertures. Usually this has been realized for the sake of the increase of the rectenna resulting efficiency η. The value η may be represented, conditionally, as product of three partial efficiencies: the efficiency of the microwave beam energy intercepted by the rectenna η_i, the efficiency of rectenna rectification η_r and the DC power collection circuit efficiency η_c:

$$\eta = \frac{P_{HF}}{P_\Sigma}\frac{P_{RM}}{P_{HF}}\frac{P_R}{P_{RM}} = \eta_i\eta_r\eta_c,$$

where P_{HF} is the HF energy extracted by the rectenna from the beam; P_Σ is the radiated by a transmitting antenna power multiplied by the efficiency of transmission line; P_{RM} is the sum of output DC power obtained from all RRE under the condition of each RRE working into the matched load; P_R is the DC power in the rectenna load. As a rule, following

[4], it is assumed that the incident power flux density Π over the rectenna with a circular aperture obeys the Gauss law:

$$\Pi(r) = \Pi_{max} exp[- 2\tau(r/L)^2],$$

where r is the variable radius; Π_{max} is the energy flux density in the center of the rectenna; $\tau = \sqrt{S_t S_r} / \lambda D$ is a wave parameter (S_t and S_r are areas of the transmitting antenna and rectenna; D is the distance between them; λ is the working wavelength).

With the increase of the excitation non-uniformity (values of wave parameters τ), the interception efficiency grows, and already under the condition of $\tau \geq 1{,}5$ its value $\eta_i \geq 90\%$. However, in this case values of η_r and η_c decrease. As for value η_r, it can be calculated having known the efficiency of separate RRE at a known value of energy incident on it and under assumption that RRE operates with the optimal load. Herewith it is convenient to divide the entire aperture into a number (N) of zones and to assume the excitation within each of them to be constant and equal to its meaning in the center of the zone. Further for each zone the approximation of infinite array with the uniform excitation is used. The procedure of η_r determination will be significantly simplified, because the RRE efficiency is to be computed only at N levels of their excitation. It is more difficult to calculate the efficiency of the power collection circuit (PCC). The solution of this problem is based on the consideration of RREs forming the rectenna as direct-current generators (DCG) [7]. Their parameters (emf, current, internal resistance), which depend on the energy flux density incident on RRE are being found on the basis of the analysis of loading (volt-ampere) characteristics at a load of RRE [3]. The rectenna on the whole is considered as a set of the large number of not identical DCG of N types that work into a common load. Depending on the PCC topology and number of zone where RRE is located, its load will be different. It is important to note that as RREs work at loads non-optimal for them, this can lead to noticeable power losses [8]. Namely these losses (thermal ones and power losses of rectenna radiation at a basic frequency and harmonic frequencies) define the PCC efficiency, characterize its essence.

It is obvious, that direct series or parallel connection of not identical DCGs will result in the appreciable decrease of the PCC efficiency. The latter and the efficiency of the rectenna as a whole can be increased in two ways: either smoothing parameters of equivalent DCG on the aperture or improving the collection circuit topology [7-9]. The results of computation of a number of concrete structures, which realize the pointed above ways, have shown that they enable to increase the rectenna efficiency by about 20 %.

In the course of studying the rectenna arrays, significant attention was paid (in addition to the efficiency) to the analysis of their spurious radiation, complicating the electromagnetic compatibility of radio electronic systems, and, in cases of large levels of the transmitted energy, the ecological situation. The results of the carried out analysis of spurious radiation of RRE different types are given in [3,10]. One can find there the data of radiation power and the radiation pattern of a separate RRE at different frequencies, about "weight" of different harmonics in the reradiated signal, about ways of the decrease of the RRE spurious radiation. The most radical is emplacement of the input low-frequency filter reducing a spurious radiation by several orders. In a certain measure it is possible also to control the "weight" of different harmonics by radiator type fitting, but this method is of limited nature.

The computation procedure for spurious radiation of large rectennas for cases of uniform and non-uniform excitation of their aperture is described in [10]. In the first case in the beginning the spurious radiation characteristics of one RRE are being found under approach of the infinite array, and then, using the known rule of multiplication, the spurious radiation of the entire array is being determined. When the aperture is excited non-uniformly, there is being found initially the spurious radiation field of each rectenna zone at the characteristic for this zone level of its excitation. Then the fields of separate zones are summarized.

Beside of theoretical works, the experimental investigations of the WET system have been carried out [11]. For this, the experimental device, which incorporated the rectenna consisting of 144 RREs was assembled. Using this device we managed to confirm some of obtained theoretical mechanisms characterizing changes in parameters of rectenna and the entire WET system depending on a number of factors.

Recently the front of the investigations being carried out at KNURE in the field of WET has been widened significantly. The most important of new directions are as follows.

1. The analysis of interconnection of the transmitting antenna parameters with the efficiency of the microwave energy conversion into DC energy at the receiving end (rectenna parameters). It is shown [12] that the optimal amplitude-phase distribution (APD) of sources on the transmitting antenna depends on non-linear properties of the rectenna RRE.
2. The investigations by methods of SAT [13] of the influence of randomness in the transmitting antenna on the rectenna characteristics – the decrease of its mean efficiency and the increase of its spurious radiation. On this basis, the requirements to the value of permissible errors of the realization of the amplitude-phase distribution of sources on the transmitting antenna are formulated.
3. The development of foundations of the theory for antennas with the distributed non-linearity [14,15]. Elaboration on its basis of the theory of rectennas of the mm waveband. At this waveband, the non-linearity of RRE as a rule are to be considered as distributed.
4. Study of features of WET systems for moving objects. In particular, study of the WET systems characteristics, when a distance between the transmitting antenna and the rectenna, as well as their orientation with respect to each other change [16,17]. The solution of this problem in the statistical setting of it.
5. Study of the expediency of transition to adaptive WET systems.

CONCLUSIONS

The given in the paper main results of the carried out at KNURE investigations in the field of WET systems show that by now the theory of these systems (especially, rectennas) has been essentially advanced. The key point here is the presence of the developed by the authors theory of antennas with nonlinear elements. This provides the possibility of rectenna parameters computation, enables to analyze its dependence on different factors, and indicates ways of their improvement. The results obtained so far, as well as results of the investigations being carried out today and planned for the nearest future, without doubts will contribute to the development of different high-quality WET systems, enhancement of the effective use of similar systems for solving some practically important problems.

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