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EVALUATION OF THE QUALITY OF MICROWAVE DEVICES IN RELATION TO ACTIVATION RESISTANCES

The paper illustrates simulation quality estimation in terms of reliability, validity and adequacy of the obtained results in order to determine the possibility of reliable application of the simulation procedure for designing microwave-range devices.

***Keywords**: simulation, microwave device, functional characteristic, reliability, adequacy, validity.*

Introduction

Complexity in evaluating the quality of simulation of microwave devices (MD) [1 – 3] in relation to activation parameters consists in the impossibility, in general case, to confirm the results obtained in terms of scattering matrix by direct experimental studies, which is possible only when MD are investigated with the application of standardized paths as the loads connected to their inputs-outputs [4]. At the same time, estimation of the quality level of simulation results (and, therefore, of the quality of corresponding mathematical models, on the basis of which the simulation is performed) is essential for their reliable and efficient application in practical activities regarding implementation of both MD and RES where such devices are used.

In general case simulation must satisfy definite requirements that are feasible to be divided into three groups characterizing reliability, validity and adequacy of the simulation-based results:

– simulation reliability characterizes the degree of confidence in the obtained results in terms of the ability of their representation under given conditions with given accuracy and definite probability;

– simulation validity characterizes the degree of confidence in that the obtained results reflect regularities under study, i.e. indicate the dependence of MD functional characteristics (FC) on the activation parameters;

– simulation adequacy characterizes correspondence of the obtained results to the actual processes and dependences occurring when MD are connected into the real path (i.e. correspondence of the simulation results to real practice).

Division of MD quality evaluation problem into three components, mentioned above, does not contradict the basic principles of simulation process realization and enables separate consideration of each component.

Reliability of simulation results

The category of reliability of the simulation results determines the degree of confidence in the obtained statistical indices (mathematical expectation, dispersion, mean square deviation, etc.) of MD under study. Solution of this problem is connected with the implementation of the known algorithms [5] of determining confidence intervals for statistical indices chosen for representation of simulation results.

The obtained results indicate that statistical indices and their confidence intervals depend not only on the number of numerical experiment realizations, but also on the values of MD FC. The wider is the interval of variations of FC values, the greater variability of the corresponding confidence intervals is observed. As the calculations show, e. g. for frequency filter simulation, FC parameters (amplitude frequency characteristics – AFC) of which are changing in wide intervals, obtaining acceptable value of the confidence interval for different frequency values requires quite different numbers (ten-times difference) of the corresponding numerical experiment realizations.

Fig. 1 presents, as an example, dependences of the confidence interval of mathematical expectation M [L] of L value on number K of the numerical experiment realizations for different initial values of L (i.e. the values which occur when coordinated loads are connected to MD). In this case (and in subsequent calculations) confident probability is assumed to be 0,95.

From Fig. 2 it is evident that the increase of the number of numerical experiments reduces the confidence interval length, but this quantity is also considerably influenced by the initial value of L. The confidence interval is smaller for higher initial values of L. It should be noted that for K>60 the confidence interval reduction practically stops.

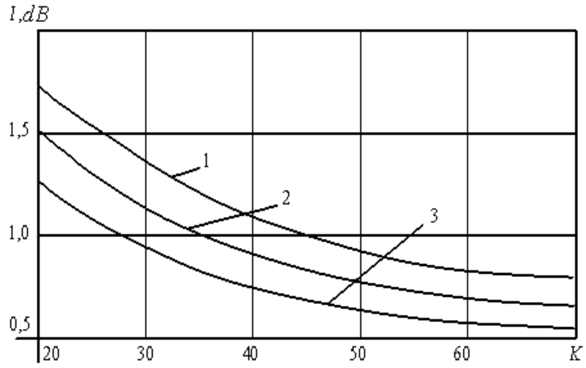

Fig. 1. Dependence of the confidence interval of the mathematical expectation of L value on the number of numerical experiment realizations for initial values of L = 0 dB (curve 1); L = 3 dB (curve 2); L = 10 dB (curve 3) ($K_{U\max 1} = K_{U\max 2} = 2$ for $-\pi/2 \le \psi_i \le \pi/2; i = 1,2$)

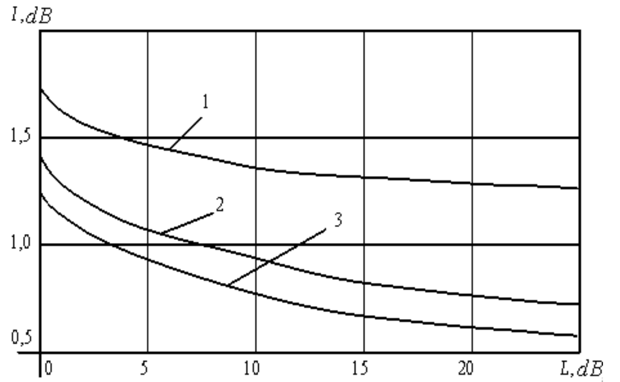

Fig. 2. Dependence of the mathematical expectation of the confidence interval of L value on the initial values of this quantity for the following numbers of numerical experiment realizations: 20 (curve 1), 30 (curve 2) and 40 (curve 3)
($K_{U\max 1} = K_{U\max 2} = 2$ fo $-\pi/2 \le \psi_i \le \pi/2; i = 1,2$)

Numerical calculations show similar dependences also in relation to the length of confidence interval of the quadripole transfer coefficient.

It should be noted that the above also holds true for the reflection coefficient, namely: confidence intervals of the reflection coefficient statistical parameters are greater for its smaller initial values.

Thus, for rational simulation process organization it would be feasible to set the confidence interval length depending on the value of MD FC. Using this method, total number of the numerical experiment realizations can be considerably reduced and, therefore, the efficiency of the process can be increased without reduction of the statistical indicators of reliability.

In order to solve the above-mentioned problem, for calculating mathematical expectation and mean square deviation of a certain MD parameter, we propose application of recurrent formulas that could be obtained on the basis of respective relationships [5] to determine the corresponding parameters :

$$M_{k+1} = \frac{kM_k + y_{k+1}}{k+1}; \tag{1}$$

$$\sigma_{k+1} = \sqrt{\frac{k}{k+1}\left[\sigma_k^2 + \frac{(y_{k+1} - M_k)^2}{k+1}\right]}, \tag{2}$$

where $M_0 = 0$; $\sigma_0 = 0$; y_k, y_{k+1} – value of MD FC for the k-th and $(k + 1)$ numerical experiment respectively; M_k, $\sigma_k = 0$ - mathematical expectation and mean square deviation of FC determined on the results of processing the sample consisting of k elements; M_{k+1}, $\sigma_{k+1} = 0$ - the same values but determined on the results of processing the sample from $(k + 1)$ elements.

Application of the relationships (1) and (2) makes it possible to rationalize the simulation process providing an acceptable length of the confidence intervals for variable values of MD FC. For this it is sufficient to perform calculations of the above intervals with simultaneous increase of the number of numerical experiment realizations (e. g. starting with the K-th realization at each step or with the periodicity of m realizations).

Taking the above-mentioned into consideration, algorithm of carrying out the numerical experiment on studying the influence of activation parameters on MD FC could be presented as follows:

1) to define the model of activation parameters in accordance with the character of MD application;

2) to assume that $M_0 = 0$, $\sigma_0 = 0$;

3) to generate activation parameters in accordance with the defined model;

4) to calculate the required FC of MD for the obtained values of activation parameters at its arms;

5) to use the obtained FC of MD for determining their statistical parameters (mathematical expectation and mean square deviation) using relationships (1), (2);

6) to follow steps 3 – 5 until the chosen number K of realizations is reached;

7) starting with the K-th realization, to calculate current values of the confidence intervals with the selected periodicity m after preliminary choice of the acceptable confidence probabilities;

8) provided that the calculated values of the confidence intervals are not worse than the acceptable ones, calculations are stopped, otherwise calculations are continued starting from step 3.

Validity of the simulation results

Validity of the obtained simulation results means that they are those results for receiving which the corresponding numerical experiment has been realized and reflect the regularities under study.

Validity of the simulation results, obtained on the basis of introducing the category of pseudo-device [3], could be proved by the analysis of their coincidence with the results received using other known algorithms (within the scope of adopted assumptions) [6, 7].

The problem of determining the input impedance of the quadripole loaded by the random impedance $Z_l = R_l + jX_l$ from the side of the output arm will be solved in terms of transfer matrix of the classical theory of circuits.

To build the transfer matrix of pseudo-device [3] $\tilde{\mathbf{a}}$, we consider a cascade connection of the quadripole under study, given by matrix $\mathbf{a}$, and a quadripole formed by a sequential reactive impedance that coincides with the reactive component of the input impedance Z_l, i.e. is equal to $-jX_l$.

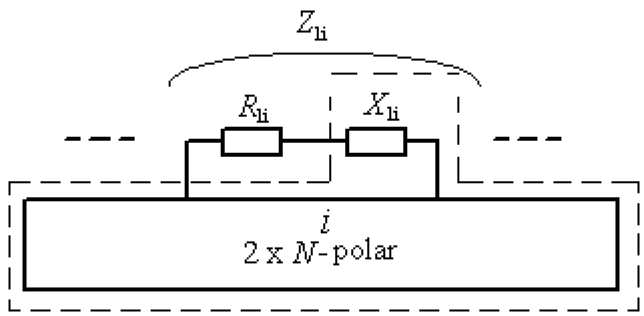

Fig. 3. 2 × N-polar loaded on complex impedances
(dashed line indicates boundaries of the pseudo-device)

Transfer matrix of the quadripole, formed by impedance jX_l, is determined according to [6, 7] as

$$\mathbf{a}_x = \begin{bmatrix} 1 & jX_l \\ 0 & 1 \end{bmatrix}. \tag{3}$$

Therefore, transfer matrix $\tilde{\mathbf{a}}$ of the pseudo-device will be given by

$$\widetilde{\mathbf{a}} = \mathbf{a} \times \mathbf{a_x} = \begin{bmatrix} a_{11}^{(r} & a_{12}^{(r} \\ a_{21}^{(r} & a_{22}^{(r} \end{bmatrix} \times \begin{bmatrix} 1 & jX_l \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} a_{11}^{(r} & a_{12}^{(r} + ja_{11}^{(r}X_l \\ a_{21}^{(r} & a_{22}^{(r} + ja_{21}^{(r}X_l \end{bmatrix}, \tag{4}$$

where (^{r}) marks the elements of the real quadripole matrix.

In accordance with [6], input impedance of the real quadripole with load Z_l is determined as

$$Z_{inp}^{(r)} = \frac{a_{11}^{(r}Z_l + a_{12}^{(r}}{a_{21}^{(r}Z_l + a_{22}^{(r}} = \frac{a_{11}^{(r}R_l + a_{12}^{(r} + ja_{11}^{(r}X_l}{a_{21}^{(r}R_l + a_{22}^{(r} + ja_{21}^{(r}X_l}. \tag{5}$$

Since $Z_l^{(p)} = R_l$ and $\widetilde{\mathbf{a}}$ – transfer matrix of the pseudo-device, taking into account (4) and (5), input impedance of the pseudo-device is given by

$$Z_{inp}^{(p)} = \frac{a_{11}^{(p}Z_l^{(p} + a_{12}^{(p}}{a_{21}^{(p}Z_l^{(p)} + a_{22}^{(p}} = \frac{a_{11}^{(r}R_l + a_{12}^{(r} + ja_{11}^{(r}X_l}{a_{21}^{(r}R_l + a_{22}^{(r} + ja_{21}^{(r}X_l} \tag{6}$$

((^{p}) marks the elements of the pseudo-device matrix).

From (5) and (6) it is evident, that provided the pseudo-device is formed in accordance with fig. 3

$$Z_{inp}^{(r)} = Z_{inp}^{(p)}.$$

Thus, the obtained input impedances of the real quadripole loaded on the complex impedance and of the pseudo-device loaded on the complex impedance of real character (with reactive component of the load resistance being included into MD) coincide on the analytical level. This proves validity of the simulation results, obtained on the basis of the introduced category of pseudo-device.

Adequacy of the simulation results

Adequacy of the simulation results characterizes their correspondence to the actual FC dependences when MD are connected into a real path.

The existing measuring equipment and corresponding techniques are designed to measure functional characteristics of microwave devices only in standardized paths. In general case it is practically impossible to measure FC of MD when arbitrary loads (not saying about complex ones) are connected to its inputs/outputs. Therefore, it is also impossible to provide comprehensive experimental verification of simulation results.

Under such conditions adequacy of the results could not be confirmed by direct methods but by by reduction of the problem to be solved to a simpler one. Analytical calculations show that reflection coefficient from the pseudo-device input coincides completely with the reflection coefficient of MD loaded on complex impedance.

To confirm the above, we present proofs of coincidence of power scattering matrices in terms of which reflection coefficients of the real device and of the pseudo-device are determined.

It is known that power scattering matrix of MD loaded on an arbitrary impedance is determined on the basis of relationship [8]:

$$\widetilde{\mathbf{S}}^{(\mathbf{V})} = \mathbf{F} \times \left[\mathbf{Z} - \mathbf{G}^{\dagger}\right] \times \left[\mathbf{Z} + \mathbf{G}\right]^{-1} \times \mathbf{F}^{-1}, \tag{7}$$

where

$$\mathbf{F} = diag\left[\frac{1}{2\sqrt{\operatorname{Re} Z_{ref1}}}, \frac{1}{2\sqrt{\operatorname{Re} Z_{ref2}}}, \ldots, \frac{1}{2\sqrt{\operatorname{Re} Z_{refN}}}\right],$$

$$\boldsymbol{G} = diag[Z_{ref1}, Z_{ref2}, \ldots, Z_{refN}],$$

$\mathbf{Z}$ – MD impedance matrix.

In general case reference impedances are of complex nature, i.e. they are given by

$$Z_{ref\,i} = R_{ref\,i} + jX_{ref\,i}. \tag{8}$$

Using (8) and known mathematical statements:

$$\widetilde{\mathbf{S}}^{(\mathbf{V})} = \mathbf{F}\times\left[\mathbf{Z}-\mathbf{G}^{\dagger}\right]\times\left[\mathbf{Z}+\mathbf{G}\right]^{-1}\times\mathbf{F}^{-1} =$$
$$= \mathbf{F}\times\left[\mathbf{Z}-diag[R_{ref\,1}-jX_{ref\,1},\ldots,R_{ref\,N}-jX_{ref\,N}\right]\times$$
$$\times\left[\mathbf{Z}+diag[R_{ref\,1}+jX_{ref\,1},\ldots,R_{ref\,N}+jX_{ref\,N}\right]^{-1}\times\mathbf{F}^{-1} =$$
$$= \mathbf{F}\times\left[\mathbf{Z}+diag[jX_{ref\,1},\ldots,jX_{ref\,N}]-diag[R_{ref\,1},\ldots,R_{ref\,N}]\right]\times$$
$$\times\left[\mathbf{Z}+diag[jX_{ref\,1},\ldots,jX_{ref\,N}]+diag[R_{ref\,1},\ldots,R_{ref\,N}]\right]^{-1}\times\mathbf{F}^{-1},$$

Let us define the "new" matrix of impedances as a pseudo-device impedance matrix:

$$\widetilde{\mathbf{Z}} = \mathbf{Z}+diag[jX_{ref\,1},\ldots,jX_{ref\,N}]. \tag{9}$$

Denoting the impedance matrix of the "additional" multipole as $\mathbf{Z}_X = diag[jX_{ref\,1},\ldots,jX_{ref\,N}]$, we present relationship (9) in the following form:

$$\widetilde{\mathbf{Z}} = \mathbf{Z}+\mathbf{Z}_X. \tag{10}$$

Taking into account (10):

$$\widetilde{\mathbf{S}}^{(\mathbf{V})} = \mathbf{F}\times\left[\widetilde{\mathbf{Z}}-diag[R_{ref\,1},\ldots,R_{ref\,N}]\right]\times$$
$$\times\left[\widetilde{\mathbf{Z}}+diag[R_{ref\,1},\ldots,R_{ref\,N}]\right]^{-1}\times\mathbf{F}^{-1} =$$
$$= \mathbf{F}\times\left[\widetilde{\mathbf{Z}}-diag[R_{ref\,1},\ldots,R_{ref\,N}]\right]\times\mathbf{F}\times$$
$$\times\mathbf{F}^{-1}\times\left[\widetilde{\mathbf{Z}}+diag[R_{ref\,1},\ldots,R_{ref\,N}]\right]^{-1}\times\mathbf{F}^{-1} =$$
$$= \left[\mathbf{F}\times\widetilde{\mathbf{Z}}\times\mathbf{F}-\mathbf{F}\times diag[R_{ref\,1},\ldots,R_{ref\,N}]\times\mathbf{F}\right]\times$$
$$\times\left[\mathbf{F}\times\widetilde{\mathbf{Z}}\times\mathbf{F}+\mathbf{F}\times diag[R_{ref\,1},\ldots,R_{ref\,N}]\times\mathbf{F}\right]^{-1}.$$

In what follows we shall take into consideration that

$$\begin{aligned}&\mathbf{F}\times diag[R_{ref\,1},\ldots,R_{ref\,N}]\times\mathbf{F} =\\ &= diag\left[\frac{1}{2\sqrt{R_{ref\,1}}},\ldots,\frac{1}{2\sqrt{R_{ref\,N}}}\right]\times diag[R_{ref\,1},\ldots,R_{ref\,N}]\times\\ &\times diag\left[\frac{1}{2\sqrt{R_{ref\,1}}},\ldots,\frac{1}{2\sqrt{R_{ref\,N}}}\right] = \frac{1}{4}\times\mathbf{I}\end{aligned} \tag{11}$$

and

$$\mathbf{F}\times\widetilde{\mathbf{Z}}\times\mathbf{F} = \frac{1}{4}\widetilde{\mathbf{Z}}_{norm} \tag{12}$$

where $\widetilde{\mathbf{Z}}_{norm}$ – impedance matrix of the imaginary (virtual) microwave device (pseudo-device) normalized in relation to the active components of the reference impedances (loads).

Then, taking into account (11) and (12),

$$\widetilde{\mathbf{S}}^{(\mathbf{V})} = \left[\mathbf{F}\times\widetilde{\mathbf{Z}}\times\mathbf{F}-\mathbf{F}\times diag[R_{ref\,1},\ldots,R_{ref\,N}]\times\mathbf{F}\right]\times$$
$$\times\left[\mathbf{F}\times\widetilde{\mathbf{Z}}\times\mathbf{F}+\mathbf{F}\times diag[R_{ref\,1},\ldots,R_{ref\,N}]\times\mathbf{F}\right]^{-1} =$$
$$= \frac{1}{4}\left[\widetilde{\mathbf{Z}}_{norm}-\mathbf{I}\right]\times 4\left[\widetilde{\mathbf{Z}}_{norm}-\mathbf{I}\right]^{-1} = \left[\widetilde{\mathbf{Z}}_{norm}-\mathbf{I}\right]\times\left[\widetilde{\mathbf{Z}}_{norm}-\mathbf{I}\right]^{-1}.$$

Thus, the obtained dependences prove that power scattering matrices (including reflection coefficients) of the real device and the pseudo-device coincide at the analytical level.

Coincidences of the reflection coefficients from the input of the real MD loaded on the complex impedance and from the pseudo-device are also confirmed experimentally and can serve as the evidence of adequacy of the adopted mathematical model and of the simulation results. Moreover, provided that activation parameters do not have an imaginary component (i.e. are active), application of the pseudo-device category leads to the known results connected with a microwave device description in terms of scattering matrices of any type [8 – 11] or in terms of the corresponding matrices of the circuit theory.

Conclusions

The obtained estimates of the quality of MD simulation results regarding activation parameters provide the possibility of reliable application of the proposed simulation methodology for designing different MD classes with the ability to predict distortions of FC of MD included into real RES and to formulate substantiated requirements regarding its other elements for satisfactory operation of the system as a whole.

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