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I.V. Prasol

MODELS AGGREGATION IN ELECTRONIC DEVICES COMPUTER-AIDED SYSTEMS

Kharkiv National University of Radioelectronics, Kharkiv, Ukraine

E-mail: prasol_iv@mail.ru

Abstract. *The paper deals with problems of aggregation of electronic device models in computer-aided design systems. Solution of this problem provides effective implementation of procedures of parametrical synthesis and analysis. The general approach to mathematical representation of aggregated models of electronic devices is represented. The ways to estimate adequacy of the represented aggregated models are given. The concept of the region of adequacy for the studied devices is defined.*

Keywords: computer-aided design systems; electronic circuits; parametrical synthesis; aggregated models; estimation of adequacy.

Introduction

Design of modern electronic devices in various applications is impossible without usage of computer-aided design (CAD) systems. Such systems ensure decreasing time and costs of design. At the same time, they allow increasing reliability and quality of the designed electronic devices. An important factor, which ensures efficiency of CAD systems, is availability of the appropriate mathematical models.

The basic theoretic problem of the above stated devices development is creation of methods for a macromodel forming based on the full mathematical model of a device at the level of its components model.

Such approach uses an initial state of the scheme elements equations and provides decreasing an order of the set of equations in bounds of a permissible error. This problem may be solved by means of aggregation when some aggregated model of a less complexity is determined with sufficient accuracy. The aggregation problem is especially important for parametrical synthesis because it includes multiple procedures of analysis and therefore is sufficiently labour-intensiveness. So usage of the aggregated models has significance not only for improvement of efficiency of the parametrical synthesis, but in many cases ensures its successful implementation.

The problems of models aggregation are closely connected with determination of their adequacy. Development of methods for aggregation of mathematical models for implementation of analysis and parametrical synthesis of electronic devices in CAD systems has theoretical and practical significance and is of great importance for basic trends of electronic technique design automation.

Analysis of the last researches and publications

Based on analysis of the scientific-technical literature [1, 2] it is possible to make conclusion that creation of macromodels and their usage in CAD systems do not coincide in time. This requires long previous macromodeling and testing of macromodels in different modes with subsequent record in the library of standard models. To correct this disadvantage it is necessary to create the simplified models of electronic devices of the wide class. It makes also necessary to solve the problem of mathematical model aggregation. Implementation of aggregate models gives the possibility to unite developing and using mathematical models in the single automated design process. This paper deals with solution of this problem.

As a result of the above stated problem solution, the efficiency of the CAD systems application increases, especially, at the stage of the parametric synthesis consisting of multiple procedures.

The problem statement

Creation of the simplified models of electronic devices may be formalized in the following way. The primary model of a scheme based on the circuit nodes potentials may be represented as a set of equations [3]

$$\mathbf{GX} = \mathbf{J}\,, \tag{1}$$

where $\mathbf{G} = [g_{ik}]$, $(i,k = \overline{1,n})$ is the model matrix; $\mathbf{X} = [x_1, x_2, ..., x_n]$ is the vector of phase variables; $\mathbf{J} = [j_1, j_2, ..., j_n]$ is the vector of the right part of the set (1); $\mathbf{J} = \mathbf{K}_1\mathbf{J}_{in} + \mathbf{K}_2\mathbf{J}_n + \mathbf{K}_3\mathbf{J}_d$; $\mathbf{J}_n = F_n(\mathbf{X})$; $\mathbf{J}_d = F_d(\mathbf{X})$; $\mathbf{J}_{in}$ is the vector of input influences;

$\mathbf{K}_1, \mathbf{K}_2, \mathbf{K}_3$ are some topological matrices; $\mathbf{F}_n, \mathbf{F}_d$ are some nonlinear and differential operators respectively; n is dimension of the set of equations (1).

Only some components of the vector $\mathbf{X}$, which define secondary parameters and scheme characteristics, are of interest for analysis and parametrical synthesis of electronic devices. Taking into consideration this aspect, for these design procedures it is possible to consider the following relationships instead of the set (1)

$$\mathbf{GX} = \mathbf{J}; \quad \mathbf{Y} = \mathbf{AX}, \tag{2}$$

where $\mathbf{A} = [a_{ik}]$, $(i = \overline{1,p}, k = \overline{1,n})$; $\mathbf{Y} = [y_1, y_2, ..., y_p]$ is the vector of outputs.

The vector of new phase variables may be represented in the following form

$$\mathbf{Z} = \mathbf{BX}, \tag{3}$$

where $\mathbf{Z} = [z_1, z_2, ..., z_N]$; $\mathbf{B} \in R^N \times R^n$; N is dimension of the vector $\mathbf{Z}$, $N < n$.

The relationship (3) allows to define a vector of the outputs $\mathbf{Y}$ in (2) with some error $\mathbf{E}$ permissible in practical situations

$$\widetilde{\mathbf{Y}} = \mathbf{CZ}, \ \mathbf{C} \in R^P \times R^N, \tag{4}$$

where $\widetilde{\mathbf{Y}} - \mathbf{Y} \le \mathbf{E}$, $\mathbf{E} \in R^p$, $\|\mathbf{E}\|$ is a priori given.

After these definitions the set of equations of the aggregated model becomes

$$\widetilde{\mathbf{G}}\widetilde{\mathbf{Y}} = \widetilde{\mathbf{J}}, \tag{5}$$

where $\widetilde{\mathbf{G}}$ is a matrix of the aggregated model of dimension $N \times N$ and $\widetilde{\mathbf{Y}} = \mathbf{CZ}$.

Mathematical Description of Aggregated Models of Electronic Devices

The important factor, which in many respects defines strategy and tactics of aggregation, is the choice of phase variables. On the one hand, the initial aggregated model must have the minimal dimension. On the second hand, it must be convenient for the research of its features.

The coordinate base consisting of circuit poles voltages, nonlinear and transit-time elements satisfy these requirements. Poles represent outputs, by means of which sources and receivers of information signals, control signals and feedback circuits are connected up the device. Analog-digital units, to which the analog and digital components are connected up at the same time, are called poles too. To carry out procedures of the analog-digital circuit analysis or parametrical synthesis, such units are divided into two parts such as analog and digital by means of the special interfaces,

The mathematical model of the circuit of electronic devices relative the above stated variables (4) may be considered as an initial aggregated model. In some situations its equations (5), taking into consideration (4), may be written in the following form [4]

$$\begin{aligned} &\mathbf{G}_{pp}\mathbf{\Phi}_p + \mathbf{G}_{pi}\mathbf{U}_i + \mathbf{G}_{pn}\mathbf{V}_n = \mathbf{I}_p; \\ &\mathbf{G}_{ip}\mathbf{\Phi}_p + \mathbf{G}_{ii}\mathbf{U}_i + \mathbf{G}_{in}\mathbf{V}_n = -\mathbf{I}_i \\ &\mathbf{G}_{np}\mathbf{\Phi}_p + \mathbf{G}_{ni}\mathrm{Y}_i + \mathbf{G}_{nn}\mathbf{V}_n = -\mathbf{I}_n; \end{aligned} \tag{6}$$

where $\mathbf{G}_{pp}$ are conductance matrices of dimension $p \times p$; $\mathbf{\Phi}_p = \{\phi_k\}$, $(k = \overline{1,p})$ is the vector of potential poles of dimension p; $\mathbf{U}_i = \{u_k\}$ $(k = \overline{1,i})$, $\mathbf{V}_n = \{v_k\}$ $(k = \overline{1,n})$ are vectors of voltages of capacity elements and nonlinear elements of dimensions i and n correspondingly.

In relationships (6) the vectors of variables $\mathbf{U}_i$ and $\mathbf{I}_i$ are connected with each other by the linear differential dependences and vectors $\mathbf{V}_n$ and $\mathbf{I}_n$ - by the nonlinear algebraic ones.

Components of the model (6) are ordered in such a way that satisfy the equation

$$y_k = f_k(x_k) \ (k = \overline{1, p+i+n}), \tag{7}$$

where y_k, x_k are components of the vector of phase variables and the vector of the right part of (7) correspondingly and f_k is some function.

There are some possible variants of electronic device aggregated models representation.

In the first place, these models may be given in the form of the set of equations with further implementation in the form of program models. A separate case is representation of the aggregated model in the form of the state space equations

$$\begin{aligned} &\mathbf{I}_i = \mathbf{AU}_i + \mathbf{BI}_n + \mathbf{WJ}_p; \\ &\mathbf{\Phi}_p = \mathbf{CU}_i + \mathbf{DI}_n + \mathbf{PJ}_p; \\ &\mathbf{V}_n = \mathbf{SU}_i + \mathbf{QI}_n + \mathbf{TJ}_p, \end{aligned} \tag{8}$$

where matrices $\mathbf{A}, \mathbf{B}, \mathbf{W}, \mathbf{C}, \mathbf{D}, \mathbf{P}, \mathbf{S}, \mathbf{Q}, \mathbf{T}$ are defined by the submatrices of the matrix $\mathbf{G}_{pp}$ in the model (6).

In the second place, aggregated models may be represented in the form of the equivalent circuits. This allows in some practical situations to analyze the intermediate results.

In this case, the model structure may be described by means of the oriented graph $G_a = \{i_i, u_j, l_k^a\}$, where u_i, u_j are numbers of initial and terminal vertexes, which are incident to the arc $l_k^a (k = \overline{1, L})$ correspondingly, here L is a number of branches of the equivalent circuit graph.

Structural features of the aggregated model may be described by the algebraic set $(\widetilde{G}, \widetilde{F}_{MG}, \widetilde{F}_{NG})$, where $\widetilde{G}$ is the system support and $\widetilde{F}_{MG}, \widetilde{F}_{NG}$ are the system signatures. Sets $\widetilde{F}_{MG}, \widetilde{F}_{NG}$ consist of one element only. This element represents the relation of equivalence and operation of the direct sum on graphs of $\widetilde{G}$ correspondingly. This operation is defined in the following way

$$G_a \otimes G_b = G_c = \{(u_i, u_j, l_k^c)\},$$

where

$$(u_i, u_j, l_k^c) = \begin{cases} (u_i, u_j, l_\phi) \text{ for } l_k^a = l_k^b, \\ (u_i, u_j, l_k^a) \text{ for } l_k^a = l_\phi; l_k^b = l_\phi, \\ (u_i, u_j, l_k^b) \text{ for } l_k^b \neq l_\phi; l_k^a = l_\phi, \\ (u_i, u_j, l_k^a) \text{ for } l_k^a \neq l_k^b \neq l_\phi, \end{cases}$$

here l_ϕ means the graph arc, which is absent.

Every graph corresponds to the structural-group formula

$$G_a = G_{a1} \otimes G_{a2} \otimes ... \otimes G_{ap}, G_{ai} \in \breve{G}_{gen} (i = \overline{1, \rho}),$$

where $\breve{G}_{gen}$ is the set of generatrices; ρ is a number of generatrices.

For transition from aggregated model in the form of equations to the equivalent electrical circuit it is necessary to carry out the formal transition in a new coordinate base by means of some representation $X \xrightarrow{\alpha} \Phi$ of the set X on the set Φ, where the relation α defined on this pair of sets is the equivalence relation; $X = \Phi_p \bigcup V_f$, $\Phi = \{\phi_i\}$ $(i = \overline{1, p + f})$.

If believe that elements of the set Φ are the circuit nodes potentials, the isomorphic universal environment of the equivalent scheme will correspond to every equation of the set of equations (6). Such scheme is represented in Fig. 1.

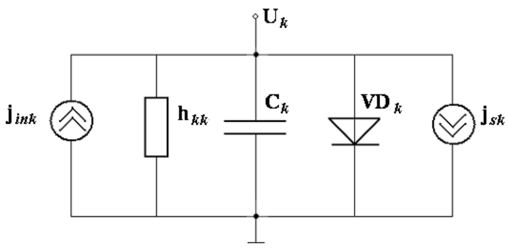


Fig. 1. The universal environment of the equivalent scheme of the aggregated model

The initial mathematical model (8) for the complex schemes has a high order. In this case, it is convenient to create a model in parts. In other words, a model is developed on the level of the multipoint subcircuit. This process consists of three stages. At the first stage, is formed the circuit node model at the level of the subcircuits. At the second stage, the model in the form (6), which consists of subcircuits, is developed. At the third stage, the connection of subcircuit models in compliance with a matrix of the subcircuit connections is implemented.

To analyze nonlinear noninertial circuits, it is necessary to create the model in the following form

$$G_{pp}\Phi_p + G_{pn}V_n = I_p;$$
$$G_{np}\Phi_p + G_{nn}V_n = -I_n, \quad (9)$$

where $I_n = F(V_n)$. Representation $F: R^n \to R^n$ has some properties. It is continuous in R^n, eventually-passive, one-to-one and its origin of coordinates belongs to the region of the operator F. Furthermore, the representation $I_1 = F_1(V_1)$, which characterizes the circuit of $2m$-port network is one-to-one and exists $V_1 \in R^m$, for which $I_1 = 0$. The above stated network may be obtained by means of connection to any n-m pair of outputs of a nonlinear sub-circuit of $2n$-port network of the steady voltage sources. The Sandberg-Wilson theorem allows to make conclusion about existence of the set (9) solution for any input influences. And this solution is unique. Decrease of dimension of the model (9) may be achieved due to determination of nonlinear elements, which may be linearized.

To analyze the frequency characteristics of the linearized electronic circuits, the linear model in the frequency region is created

$$\mathbf{G}_{pp}\mathbf{\Phi}_p + \mathbf{G}_{pi}\mathbf{V}_i = \mathbf{I}_p;$$
$$\mathbf{G}_{ip}\mathbf{\Phi}_p + \mathbf{G}_{ii}\mathbf{V}_i = -\mathbf{I}_i, \quad (10)$$

where i_k is k-th element of the vector I_i, which is defined by the formula

$$i_k = c_k \frac{dv_k}{dt},$$

where c_k is capacity of the k-th capacitor; v_k is its voltage.

To create the aggregated model in some given range of output signal frequencies, it is necessary to introduce representation $f: \hat{C} \to \hat{C}_g$ of a set of all circuit condensers $\hat{C} = \{C_k\}$, $k = \overline{1, i}$ in the set $\hat{C}_g$. This set $\hat{C}_g$ must be a subset of $\hat{C}$, that is $\hat{C}_g \subset \hat{C}$ and $\hat{C} \setminus \hat{C}_g = \hat{C}_v$, where g, v are potencies of the appropriate sets. Influence of elements of the subset $\hat{C}_v = \{C_k\}$, $k = \overline{1,v}$ on frequency characteristics is insignificant.

If a matrix $\mathbf{A} = p\mathbf{C}_{ii}^{-1}\mathbf{C}_{ii}$ has a simple structure for all ω from the given range of frequencies, where $p = j\omega$, and $\mathbf{C}_{ii} = diag\{c_1,...,c_i\}$, it is necessary to introduce a matrix $\mathbf{A}_1 = \omega_{\max}\mathbf{C}_{ii}^{-1}\mathbf{C}_{ii}$. The invariant subspace of this matrix has dimension g. The basis of the subspace corresponds to eigenvalues $X_1,...,X_g$ of the matrix

$$\mathbf{A}_1 \,|\, \lambda_j \,| > 1 \; (j = \overline{1,g}).$$

In this case, the matrix $\mathbf{X} = [X_1,...,X_g]$ is created with a minor if the first rows g differing from zero. After some identical transformations and transition to new variables $\mathbf{Y}_i = \mathbf{P}^{-1}\mathbf{V}_i$ the second block equation of the set of equations (10) becomes

$$\mathbf{P}^{-1} = \mathbf{G}_{ii}^{-1}\mathbf{G}_{ip}\mathbf{\Phi}_p + \mathbf{Y}_i = -\mathbf{P}^{-1}\mathbf{APY}_i,$$

where $\mathbf{P}$ is some additional matrix.

If the right lower block of the matrix $\mathbf{P}^{-1}\mathbf{A}_1\mathbf{P}$ of dimension $v \times v$ has the spectral radius lesser 1, it is possible to pass on to aggregated model equations relative to variables connected with condensers $\hat{G}_g$ only

$$\mathbf{G}'_{pp}\mathbf{\Phi}_p + \mathbf{G}'_{pg}\mathbf{V}_g = \mathbf{I}_p;$$

$$\mathbf{G}'_{gp}\mathbf{\Phi}_p + \mathbf{V}_g = -p\mathbf{D}_{gg}\mathbf{V}_g, \qquad (11)$$

where elements of matrices $\mathbf{G}'_{pp}, \mathbf{G}'_{pg}, \mathbf{G}'_{gp}$ of equations (11) are calculated by some formulae; $\mathbf{D}_{gg}$ is the diagonal matrix; $p = j\omega$.

Aggregation of models for analysis of dynamic processes in nonlinear electronic circuits is directed to usage of implicit methods of solving sets of the differential equations. For models, which are described by the set of equations (6) taking into consideration (8), the dynamic processes will be defined by the spectrum of the matrix $\mathbf{A} = \mathbf{G}_{ip}\mathbf{G}_{pp}^{-1}\mathbf{G}_{pi} - \mathbf{G}_{ii}$. Therefore the method of model dimension decrease must be based on transformations, which keep basic properties of this spectrum.

Methods of model adequacy determination at the stages of analysis and parametric synthesis in CAD systems

Estimation of adequacy region of a model may be carrying out in the following way. If to denote a vector of output parameters calculated on the full model

$$\mathbf{Y}_n = (y_{n1},...,y_{nm})^{\mathrm{T}},$$

an estimation of the degree of aggregated model accuracy may be represented by a vector

$$\mathbf{E} = (\varepsilon_1,...,\varepsilon_n)^{\mathrm{T}}, \qquad (12)$$

where $\varepsilon_j = (y_j - y_{nj})/y_{nj}$ is the relative error of the j-th parameter modeling

The vector estimate (12) may be changed by the scalar one [5]

$$\varepsilon_m = \|\mathbf{E}\|,$$

where $\|\cdot\|$ denotes some vector norm.

In this case, region of adequacy of an aggregated model will represent such region in the space of the external parameters Q_E, for which the condition

$$\varepsilon_m \le \delta,$$

where δ is maximally possible error of aggregated model must be satisfied.

Then the adequacy region (AR) may be represented in the following form

$$\mathrm{AR} = \{\mathbf{Q} \in Q_E \mid \varepsilon_m \le \delta\},$$

where $\mathbf{Q} = (q_1,...,q_k)^{\mathrm{T}}$ is a vector of external parameters.

An adequacy region has complex configuration, therefore check of accessory of the AR points requires sufficient computational burden. In this case, it is necessary to use adequacy region approximation (ARA) based on the simplicial approximation of the bounded hypersurfaces of AR and replacing of these hypersurfaces in the given region. In practical situations it is most convenient to implement the approximation based on algorithm "increase – motion". Unfortunately its implementation is accompanied with large computational; burden too. Approximation by the criterion of the maximum of the minimal rib has not such disadvantage. In the formalized representation this method of approximation looks like

$$\min \max(q_{i\max} - q_{i\min})/q_i^*, \; \mathrm{ARA} \subseteq \mathrm{AR}, \; i \in [1,k].$$

But usage of such approximation does not guarantee determination of the given AR, which belongs to the real adequacy region (RAR).

For example, in the case of the two-dimensional space Q_E with coordinates U_{in} (an amplitude of the input signal) and f (a frequency of another input signal) AR for $\varepsilon_m = \varepsilon^*$ looks like the region represented in Fig. 2.

Approximation of such AR, implanted by the above given criterion, defines ARA represented by the shaded rectangular (Fig. 2). But sometimes application of this method may lead to loss of adequacy as it is shown in Fig. 3*a*. In some cases, the model may be defined as adequate at all the given region of adequacy (Fig. 3*b*). Nesting of the given region in RAR may be checked using conditions of nesting, which may be given in the form of inequalities

$$q^{3}_{i\max} \le q^{f}_{i\max}\ ,\ q^{3}_{\min} \le q^{f}_{\min}\ , i = \overline{1, m}\ ,$$

where the given and real bounds of AR are compared correspondingly.

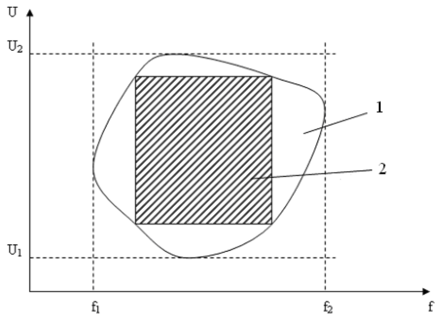
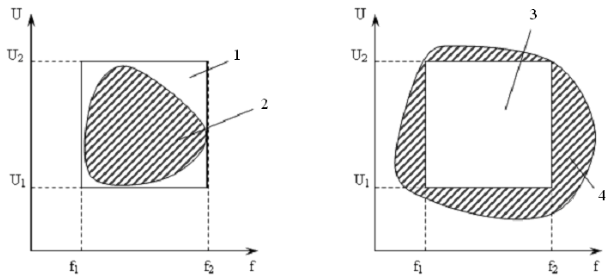


Fig. 2. Determination of model adequacy: 1 is an adequacy region; 2 is an approximated adequacy region



a *b*

Fig. 3. Special cases of AR: 1 is a given adequacy region; 2 is a real adequacy region

For estimation of errors of i-th output characteristic modeling it is convenient to use based interval estimates

$$\boldsymbol{\varepsilon}_i = [\varepsilon_{li}, \varepsilon_{vi}]\ ,$$

where $\varepsilon_{li} = (y^n_{li} - y^m_{li}) / y^n_{li}$; $\varepsilon_{vi} = (y^n_{vi} - y^m_{vi}) / y^n_{li}$ are permissible errors, which correspond to the lower and upper bounds of an interval for the output characteristic.

An error of model linearization for changed input influences and control parameters values may be estimated based on methods of the interval analysis. Such estimation must include some stages such as:

1) estimation of linearization error ξ_i for every nonlinear element depending on voltage applied to it;

2) estimation of change of voltage at every nonlinear element depending on ranges of input signals and control parameters changes;

3) determination of operator $P(\varsigma)$ and an error of potential calculation for some known vector of error interval ξ.

An aggregated model for analysis problem solution is created for a priori given values of external parameters. Therefore the adaptation problem is formulated as the a priori passive model adaptation. The criterion of this problem is the maximum efficiency of model functioning in CAD system environment. The parametrical synthesis has other peculiarities. In this case, a model is set for the definite ranges of change of external variables including control ones. But parameters of both scheme and model are constantly changed during extremum search. In this connection, the necessity to complete the optimization procedure by the additional procedure for model adaptation is arisen. This additional procedure must be a priori passive.

Conclusions

The generalized approach to aggregation of mathematical models of electronic devices, which allows to formalize all stages of model equations forming in the basis of the node potentials is presented. The model aggregation method for parametrical synthesis and analysis of the aperiodic schemes dynamic characteristics, which is oriented on usage of non-implicit methods of differential equations solving, is developed. The way of aggregated model adequacy estimation based on the method of interval estimates is suggested.

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Prasol Igor Victorovich. Doctor of engineering. The professor. The Biomedical Engineering Department,
National University of Radioelectronics, Kharkiv, Ukraine.
Education: Kharkiv, Kharkiv Instutute of Radioelectronics, Ukraine (1979).
Research interests: CAD system of biomedical electronic devices.
Publications: 90.
E-mail: prasol_iv@mail.ru

І.В. Прасол. Агрегування моделей в САПР електронних пристроїв

Статтю присвячено проблемам агрегування моделей в системах автоматизованого проектування електронних пристроїв. Розв'язання цієї проблеми необхідно для ефективної реалізації процедур параметричного синтезу та аналізу. Представлено узагальнений підхід до математичного представлення агрегованих моделей. Надано способи оцінювання адекватності агрегованих моделей. Визначено концепцію оцінювання області адекватності таких моделей для пристроїв, що досліджуються.

Ключові слова: системи автоматизованого проектування; параметричний синтез електронних схем; агреговані моделі; оцінка адекватності.

Прасол Ігор Вікторович. Доктор технічних наук. Професор. Кафедра біомедичної інженерії, Харківський національний університет радіоелектроніки, Харків, Україна.
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І.В. Прасол. Агрегирование моделей в САПР электронных устройств

Статья посвящена проблемам агрегирования моделей в системах автоматизированного проектирования электронных устройств. Решение этой проблемы необходимо для эффективной реализации процедур параметрического синтеза и анализа. Представлен обобщенный подход к математическому представлению агрегированных моделей. Приведены способы оценивания области адекватности агрегированных моделей. Определена концепция оценки области адекватности таких моделей для устройств исследуемого типа.

Ключевые слова: системы автоматизированного проектирования; параметрический синтез электронных схем; агрегированные модели; оценка адекватности.

Прасол Игорь Викторович. Доктор технических наук. Профессор. Кафедра биомедицинской инженерии, Харьковский национальный университет радиоэлектроники, Харьков, Украина.
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