MODIFIED METHODS OF CIRCUIT SIMULATION OF RADIO ENGINEERING DEVICES IN THE TIME DOMAIN

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DOI: 10.36724/2664-066X-2020-6-2-7-11

ABSTRACT

Today, different modeling methods are used for computer analysis of circuits of radio engineering devices (RED) in the time and frequency domains. The article provides a comparison and highlights the features of using the methods of nodal potentials and variable states. Developed methods of optimization of electrical circuits and discusses the possibility of calculating the margin of stability when changing the parameters of the circuit elements and the search of critical parameter values; theoretically and experimentally confirmed the advantages of using MEAs in the analysis of RED; proposed and implemented ways to eliminate the major disadvantages of the IPU; expanded and improved methods for obtaining the mathematical model of the circuit; the mathematical method allows to obtain the characteristic polynomial of a circuit without calculating its transfer function; the developed block for processing parameters of electrical circuit elements using scaling coefficients can significantly improve the accuracy of calculations; the use of speed-optimized algorithms makes it possible to analyze fairly complex circuits on a medium-performance PC. Developed software allows to analyze a wide class of linear, linearized, and nonlinear circuits for the RED, containing the active elements. The analysis of real electrical circuits proves the validity of all the proposed methods.

KEYWORDS: *circuit modeling, nodal potential method, variable state method, CAD, design automation*

INTRODUCTION

Several methods are used for radio electronic designs (RED) modeling: the method of contour currents, no-load and short-circuit, superposition, nodal potentials and state variables. For computer modeling, it is advisable to use the last two. Method of nodal potentials. The advantage of this method is the comparative simplicity of the process of representing the mathematical model of the scheme when forming a system of equations of the scheme [4]. In the method of nodal potentials, the mathematical model has the form.where Y is the matrix of nodal conductivities; X is the vector of nodal potentials; J is the vector of right-hand sides (the setting vector).

Another advantage of the nodal potential method is that you can immediately get the potential values of all the nodes of the RED, which greatly facilitates further analysis, i.e. to determine the current in the branch or the voltage between two nodes, you do not need to solve a system of equations every time. However, the disadvantage of this method is the complexity of constructing frequency characteristics and evaluating the stability of the RED. To build frequency characteristics, it is necessary to calculate the required parameter (current or voltage) for each frequency value. This is because the method of nodal potentials does not have the ability to obtain the characteristics of the chain in the form of an algebraic expression.

Stability estimation in the nodal potential method can only be performed indirectly since this method does not allow obtaining the characteristic polynomial of the transfer function. To assess stability using the nodal potential method, various stability criteria can be used that do not require knowledge of the characteristic polynomial. However, these criteria in the case of an unstable system do not provide information on how to change it to make it stable.

I. Circuit Simulation

Modern circuit modeling programs include five main stages [4]: entering a graphical description of the circuit, entering a text description of the circuit, an analysis task, modeling, and output of the analysis results.

At the first stage, the user creates a schematic or equivalent diagram of the device in a graphical format, i.e., as it is shown in the drawing. All elements of the scheme are conventional graphic designations in accordance with Spice Standard.

At the second stage, the graphic image of the diagram is converted to a text format. This procedure is usually hidden from the user and is performed by the computer itself. However, if necessary, the user can change or add some additional information to the text description (parameters of active element models, electric power sources, etc.). A text description is the main format that contains all the necessary information about the circuit: its topology (the relative position of elements), the ratings of passive elements, the parameters of active element models, and the parameters of electric power source models. It is based on this format that a mathematical model of the scheme is created.

At the third stage, after converting the schema to a text format, the user sets the type and parameters of the analysis. There are generally three main types of analysis: transient analysis (in the time domain), frequency response analysis, and DC transfer function analysis.

At the fourth stage, the circuit is modeled. It includes creating a mathematical model of the scheme and calculating its characteristics in accordance with the type of analysis and task data.

Finally, at the last stage, the results of the analysis are displayed. The results of the analysis are either graphs or tables. At the request of the user, they can be output to a printing device or to a magnetic data carrier.

A simplified diagram of the algorithm of the RED circuit modeling system is shown in Fig. 1.

In circuit design automation programs, solving the system of equations (1) is a frequently repeated task. The problems of solving this system using a computer are as follows. When calculating electronic circuits, the y matrix is usually very sparse, i.e. it contains many zero elements. In the process of solving (1), the matrix Y is transformed. At the same time, non-zero elements appear in place of zero elements, which leads to additional costs for the solution time and memory. Therefore, the first problem is to maintain a high degree of sparsity of the matrix Y in the solution process.

Another problem is the problem of maintaining the accuracy of results at the level of rounding errors in the source data.

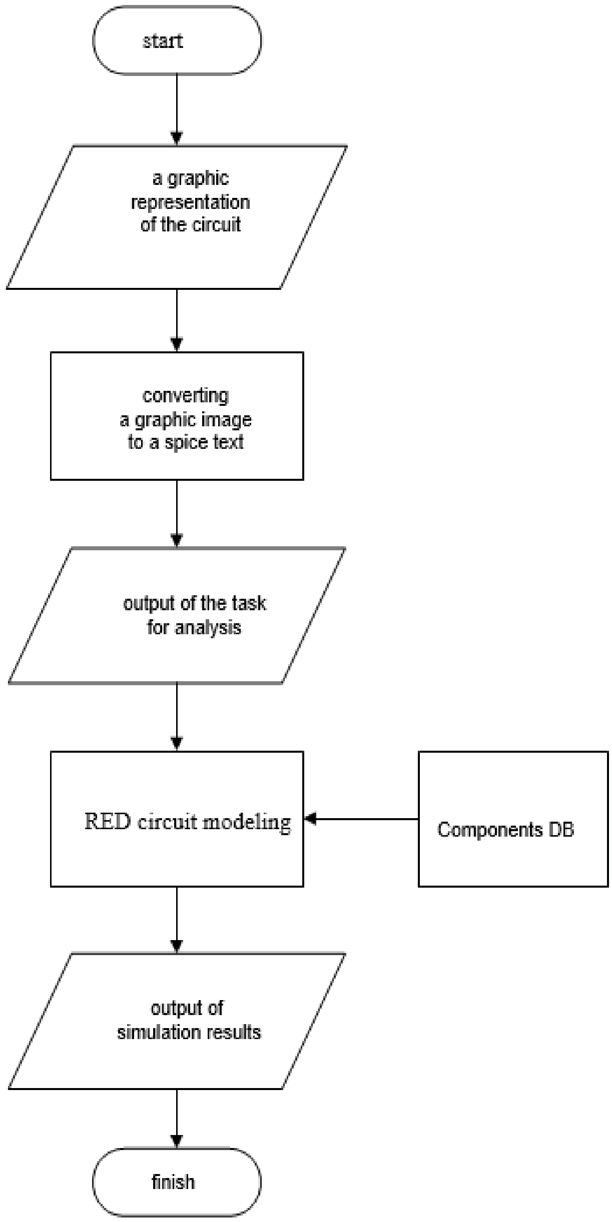

Figure 1. Simplified scheme of the algorithm of the circuit modeling system operation

Method of state variables. A distinctive feature and undoubted advantage of this method is the possibility of obtaining a mathematical model of the designed device in the normal Cauchy form, i.e., allowed with respect to derivatives [1]. Thus, you can use integration programs that are regularly available in the mathematical software of a computer.

This method is effective in designing radio engineering devices for which information is enclosed in the envelope of the carrier signal (high - quality AM and FM filters, amplifiers, correctors, special amplifying devices of multi-channel telecommunications covered by deep feedbacks, etc.), as well as modeling devices, systems and communication networks.

The method of state variables allows you to get the transfer function as a ratio of two polynomials, which is more informative than the complex number that must be found for each frequency value in the nodal potential method. Stability assessment can be performed without resorting to indirect methods, but directly by finding the roots of the characteristic polynomial.

The main disadvantage of the state variables method is the complexity of forming a mathematical model of the scheme and the orientation to explicit methods for solving systems of differential equations, which are practically not suitable for calculating schemes with a large spread of time constants due to restrictions on the calculation step. Implementation of implicit methods is difficult due to the complexity of calculating the Jacobi matrix.

Currently, most modern industrial RED circuit modeling programs use the nodal potential method as the basic one. However, when solving some problems (for example, determining the stability of RED nodes covered by feedback and calculating the stability margin), it is more appropriate to use the method of state variables.

In recent decades, there has been a noticeable trend in the development of electronics to move from the design of individual devices for narrow purposes to the design of complex hardware complexes designed to solve a wide range of tasks in changing external conditions. In this regard, the radio engineering devices (RED) design engineer has several new problems. The main one can be formulated as follows: how to improve the quality of the initial design of the RED, so that it can be partially or completely excluded from working out on a laboratory (material) layout? This is due to the fact that usually the initial design of the RED is very far from meeting the requirements put forward by the technical task for a separate device, system or complex that this device should be part of. Its subsequent improvement on the layout involves significant forces of designers and production workers in the design process, whose work is ineffective due to numerous and unavoidable alterations. As a result of all this, the design process is unacceptably stretched and becomes excessively expensive [2].

In addition to the above, trends in the development of modern radio technology are characterized by a significant increase in the complexity of requirements for electrical and structural parameters of RED, the widespread introduction of semi-conductors and microelectronics, and increased requirements for reliability and serial production of products. Increasing requirements for electrical parameters led to the need to use more complex circuit solutions and optimal selection of parameters of elements and circuit diagrams. Along with the above, the requirements for the size and weight of the RED, as well as for energy consumption, have increased, which necessitated the use of modern element base in these devices. The equivalent schemes used in synthesis and analysis have also become more complex. Particularly noteworthy is the increase in the volume of equivalent circuits due to the use of semiconductor devices and microchips (for example, a linear equivalent circuit of a high-frequency transistor contains at least 15-20 active and reactive elements).

In addition to defining equivalent circuits, the developer of radio equipment needed a more thorough and accurate analysis to optimize the characteristics, as well as deterministic or probabilistic calculation of variations in the characteristics of circuits when analyzing the product's serial capability. Conducting such an analysis using traditional methods is difficult, and in some cases impossible. Known analytical relations are usually derived with many assumptions and simplifications, which significantly narrows the scope of their application and can lead to unacceptable errors. Therefore, the method of full-scale modeling for determining and refining the parameters of RED is widely used. However, the possibilities of the experiment are limited due to high material costs and the fundamental impossibility of solving some design issues. These questions include:

- – determination of average values of device parameters without conducting statistical tests, since it is difficult to select active elements with average values of parameters for the experiment;
- – investigation of the influence on the measured characteristics of par-zit devices structural elements and measuring equipment;
- – investigation of the behavior of the circuit in difficult-to-reproduce external conditions;
- – requirements for reducing development time, etc.

II. Modified Methods

A few methods are used to model radio engineering devices (RED): the method of contour currents, no-load and short-circuit, overlap, nodal potentials and state variables. To calculate the steady-state periodic modes, we will use two representations of the mathematical model scheme.

The first type of model is set by the joint system

$$f\left(x,\ x,\ t\right)\ =\ 0 \tag{1a}$$

$$x\left(0\right)\ -\ x\left(T\right)\ =\ 0 \tag{1b}$$

Here f is a system of differential equations; x(t) is the desired vector function of variables that determine the state of the circuit; T is the period.

Thus, a nonlinear boundary value problem is defined, which can be solved by known methods. The second type of model reflects the properties of an electrical circuit to a greater extent:

$$f(v(t),t)=\frac{d}{dt}q(v(t))+i(v(t))+u(t)=0 \quad (2a)$$

$$v(0)-v(T)=0$$

(2b)

where u(t) is the vector of input signals; v(t) is the vector of nodal voltages; i(v(t)) and q(v(t)) are the vectors of nodal currents and nodal charges (fluxes), respectively.

This type of model avoids the difficulties associated with the problem of charge conservativeness (1).

The use of finite-difference methods for solving the boundary value problem (1) and (2) leads to a system of nonlinear equations, the number of unknowns of which is determined by the number of sampling points. For example, if the inverse Euler method is chosen to approximate the derivative in (1b), we have a system of equations of the form:

$$f_i\left(\frac{x(t_j)-x(t_{j-1})}{h_j}, x(t_j), t_j\right)=0,\ j-1,...,M, \quad (3)$$

where $h_j = t_j - t_j$-1, M is the number of sampling points.

Combining this system with the periodicity conditions (1b), we obtain the system of nonlinear equations necessary for calculating *x(t)* and *x(0)*. The application of the Newtonian iterative process leads to a solution at the iteration step of a linear system of the form:

$$(L + B)\ (xk+1 - xk\ ) = -f(xk) \quad (4)$$

where *k* is the index of the Newtonian iteration.

The L and B matrices have the structure:

$$L=\begin{bmatrix} \frac{C_1}{h_1}+G_1 & & & \\ -\frac{C_1}{h_2} & \frac{C_2}{h_2}+G_2 & & \\ \bullet & \bullet & \bullet & \bullet \\ & & -\frac{C_{m-1}}{h_m} & \frac{C_m}{h_m}+G_m \end{bmatrix}$$

$$B=\begin{bmatrix} 0 & \bullet & 0 & \frac{C_m}{h_m} \\ \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & 0 & 0 \end{bmatrix},$$

where Ci is the capacitance and Gi is the conductivity of the circuit [1].

Another common method for solving problem (1) or (2) is the method of reducing the boundary value problem to the Cauchy problem (shooting method). This method leads to the solution of a system of nonlinear equations (1b) with respect to the vector x(0), and at each step of the iterative process, the vector x(T) is the solution of the Cauchy problem with the corresponding initial conditions. This approach is in good agreement with circuit modeling programs, since it allows using standard integration methods that are well-developed for electrical modeling tasks.

It can be noted that if the system of nonlinear equations

$$x(0) - x(T,\ x(0)) = 0 \quad (5)$$

solve by the method of simple iteration

$$x(0)k+1 = x(T,\ x(0)k) \quad (6)$$

until the condition for the end of the iterative process is met for the specified error e:

$$\| x(0)k+1 - x(0)k \| < e \quad (7)$$

what we get is the application of standard approaches for finding periodic solutions by sequential integration over a large time interval. The main goal, of course, is to reduce the initial cost of modeling [3]. For this purpose, it is advisable to consider the possibility of applying the Newton method for solving system (5), which requires fewer steps. Using the Newtonian process leads, at the iteration step, to a system of linear equations of the form:

$$\left[\frac{\partial x(T)}{\partial x(0)}-I\right]\Delta x(0)^k = x^k(0)-x(T)^k, \quad (8)$$

where I is the unit matrix [2].

The main problem that arises in this case concerns the cost of forming the Jacobian for (8) or the sensitivity matrix $\frac{\partial x(T)}{\partial x(0)}$ under the initial conditions. Representing this matrix as differences requires multiple solutions to the Cauchy problem and is practically inefficient. For this reason, an economical method for calculating derivatives $\frac{\partial x(T)}{\partial x(0)}$ is proposed by finding solutions to systems of equations in variations:

$$\frac{\partial f}{\partial \dot{x}}\bullet\frac{d}{dt}\left(\frac{\partial x(t)}{\partial x(0)}\right)+\frac{\partial f}{\partial x}\bullet\left(\frac{\partial x(t)}{\partial x(0)}\right)=0 \quad (9)$$

The main idea of this proposal is to combine operations performed during system integration (1a) and (9) with implicit methods. This leads to the solution of a system of linear equations with the same coefficient matrix at each step of integration, which significantly reduces costs. Algorithms of this type were for a long time basic for steady-state oscillation modeling programs [5].

However, despite saving operations, methods for reducing to the Cauchy problem with Newtonian iteration do not fully meet the increasing requirements for complexity characteristics. Their main limitations are: the cost of calculating the matrix of derivatives; the cost of Gaussian elimination for solving the system (8) with a dense matrix, proportional to N3, where N is the number of integrable variables.

The main areas of improvement of algorithms are related to attempts to avoid calculating the matrix $\frac{\partial x(T)}{\partial x(0)}$, as well as reducing the cost of solving a system with dense matrices. The development of these computational procedures based on the application of Krylov subspace methods is discussed below [4].

We also indicate the previously popular Skelbo extrapolation algorithm due to its simplicity of implementation. His idea is to use an extrapolation scheme to speed up the convergence of the sequence obtained by simple iteration (6): x(0) 0, x(0) 1, ...

The computational scheme can be represented as: x(0) = yn,

$$\begin{gathered} x(0)r+1 = X\left(x(0)r,\ T\right),\ r = 1,\ 2,\ ...,\ m, \\ yn+1 = EXTRAP\ \left(x(0)0,\ x(0)1,\ ...,\ x(0)m\right) \end{gathered} \qquad (10)$$

III. Conclusion

The advantages of the algorithm are that it allows you to avoid calculating derivatives $\frac{\partial x(T)}{\partial x(0)}$ when solving nonlinear problems, allows you to achieve quadratic convergence, and provides ease of implementation based on the standard integration methods used.

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