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The System of Automated Circuit Simulation of Electronic Devices

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***Abstract*—The geometric dimensions of the structural elements of the electronic devices and their placement on the printed circuit board (PCB) should meet the tolerances specified in the design documentation. Changing the PCB parameters within the tolerance leads to a variation of values relative to the idealized value, forming, thereby, the allowable intervals. The paper considers the mathematical apparatus of the simulation method, which allows calculating the spreads of normalizing values. It also has the greatest accuracy and it can be easily implemented, taking into account the computational capabilities of modern electronic computers**.

Keywords— circuit simulation, Monte-Carlo method, electronic devices, electrical radio elements, automated system, database

I. Introduction

An important stage of the design process of electronic devices (ED) is the stage of circuit design. This stage is the process of developing electrical circuit diagrams (ECD) and specifications in accordance with the requirements of the Statement of Work (SOW), while this process is often manual labor. Before the existence of Electronic Design Automation (EDA), there was no opportunity to obtain a circuit diagram by computer simulation with such element parameters that allow the output characteristics of the circuit to remain within the specified interval with an appropriate probability.

However, with the existence of EDA, it became possible to carry out computer simulations of ECD and get the necessary output characteristics without creating layouts of printed circuit boards (PCB). Thus, computer simulation helps in adjusting the parameters values of the circuit elements to obtain such output characteristics, which will be within the boundaries of a given interval. But it is necessary to take into account that this does not guarantee that the layout of the printed circuit board will produce the same output characteristics, since the external elements, such as temperature, vibration, and etc. still act on the circuit elements. It should be noted that modern CAD system allow modeling thermal, physical and other processes, but in the process of obtaining the necessary ECD output characteristics, there is still a lot of manual labor, for example, recalculation of the elements nominal values considering changes in their temperatures, selection of technological tolerances of elements, etc. d. Consideration of all these factors increases the time for calculating the values of the ECD elements parameters of and, accordingly, the stage of circuit design takes longer.

As a result, we can conclude that circuit design is a long process of selecting the necessary parameters of elements to meet the specified characteristics of the circuit requiring the automation.

II. The Main Parameters of ED Elements and Their Impact on the Output Characteristics of the Circuit

Any electronic device consists of elements that can be grouped as follows:

- Structural elements or parts intended for mechanical connections, transmission and direction of movement.
- Accessory elements permitting to combine the performance of mechanical functions with electrical ones.
- Electrical elements have independent functional purpose, the most numerous are resistors, capacitors and inductors. They are called elements of general use or electro radio elements (ERE).

The main parameters of ERE are [1,2]:

- Nominal value of magnitude (nominal value) - resistance - for resistors, capacitance - for capacitors, inductance - for inductors.
- The limits of permissible deviations of parameters (as a percentage of the nominal value) —a closed interval within which the actual value of the element parameter can be located is called the technological tolerance.
- Rated power - the maximum allowable power that an element can dissipate during its guaranteed service life under continuous electrical load and certain environmental conditions.

From the point of view of the system approach, any electronic device can be represented as a black box model (figure 1).

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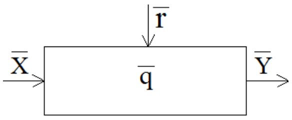

Fig. 1. Representation model of electronic device

The black bow elements are:

- $\overline{X}$ — vector of input parameters that affects the output parameters. For this case, the input parameters can be the voltage of an independent voltage source or the current value of an independent current source.
- $\overline{q}$ — set of internal parameters that affects the output parameters. In the role of internal parameters can be the nominal values of ERE or their technological tolerances.
- $\overline{r}$ — vector of external parameters (environmental parameters), which affects the internal parameters and, consequently, the output parameters. External influences can be the ambient temperature, as a result the circuit elements heat up more.
- $\overline{Y}$ — output parameter vector. All this set of effects on the circuit (input, internal and external parameters) leads to some output value. Often, the output voltage in the specified circuit nodes acts as the output value in the circuit.

In the circuit design, the designer is guided by the technical assignment, in which, among other things, the interval is specified, beyond which the output value of the designed circuit should not go under any circumstances specified in the Statement of Work (SOW). Circumstances can be as follows: ambient temperature, humidity, input parameters of the scheme, technological tolerances of ERE, etc.

The designer, at the stage of circuit design, has to work on adjusting the nominal values and calculating the technological tolerances of the ERE, taking into account the fact that the elements heat up during operation. This is a laborious job that takes up a significant portion of the time in the circuit design phase. The time to perform this part of the design of an ECD can be reduced if all calculations are provided to the computer capacities.

III. Stages of Automated System Design

In this work created automated system must adjust the nominal values and calculate manufacturing tolerances of ERE with the ambient temperature and ERE heating so that the output voltage of the circuit will be within a predetermined interval.

As a result, the goal of this work is to develop an automated system for designing ECD at the stage of circuit simulation of electronic devices. The main functional tasks of the developed system are: search, access, extraction of data from the database (DB) of the system; creating and opening projects; adjustment of the nominal values of ERE taking into account the influencing environmental factors, through sensitivity analysis; calculation of technological tolerances ERE using the Monte Carlo method.

At the first stage, the task was set to design the context diagram of the automated system (AS), which would allow displaying the structure and functions of the system, information flows and material objects transformed by these functions. This diagram, as well as the diagram of the second level (decomposition), is presented in figures 2 and 3, made according to the methodology of functional modeling and graphic notations IDEF0. Diagram describes the process of adjusting the nominal values of ERE and the subsequent calculation of their technological tolerances.

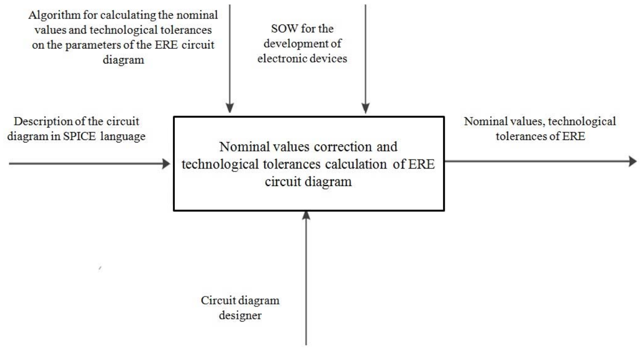

Fig. 2. AS context diagram at the stage of circuit simulation of electronic devices

The designed system appears as a set of interconnected functional blocks. Each of the four sides of the function block has its specific meaning. At the input of the system, a text is submitted describing the concept in the SPICE language. All calculations are made according to a specific algorithm. Also, the regulatory impact is the SOW for the design of the ED, which contains the requirements for the characteristics of the scheme. The executor of the system functions is a computer on which the system and the designer of circuit diagrams are installed. They use the program in solving problems of analysis and optimization at the stage of circuit simulation of electronic devices.

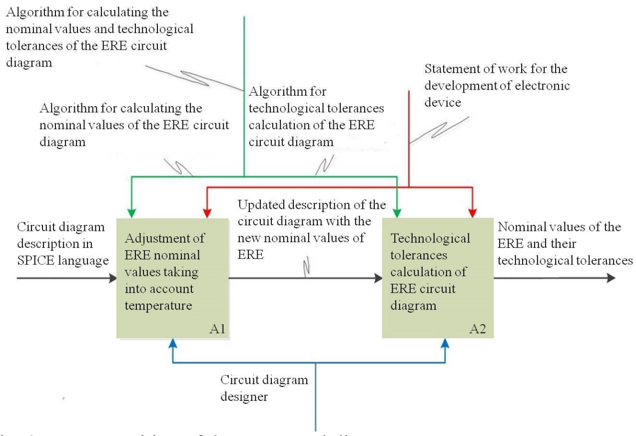

Fig. 3. Decomposition of the contextual diagram

All functions of the program can be divided into two blocks. The first block receives at the input a description of the concept in the SPICE language, after calculating the nominal parameters according to a certain algorithm. The function block provides the updated SPICE text of the circuit with the adjusted nominal values of the ERE. The next block calculates the technological tolerances on the parameters of the ERE scheme. The input of the second block is supplied with the description of the circuit diagram with the updated nominal values of ERE. The block functions are performed according to a certain algorithm for calculating the technological tolerances on the ERE parameters, which includes the Monte Carlo method.

At the second stage, the task was set to develop an infological model of the subject area, which can be described by an "entity-relationship" model, which is based on the division of the real world into separate distinguishable entities that are in definite connections with each other.

Figure 4 shows the infological model created by using Chen's notation.

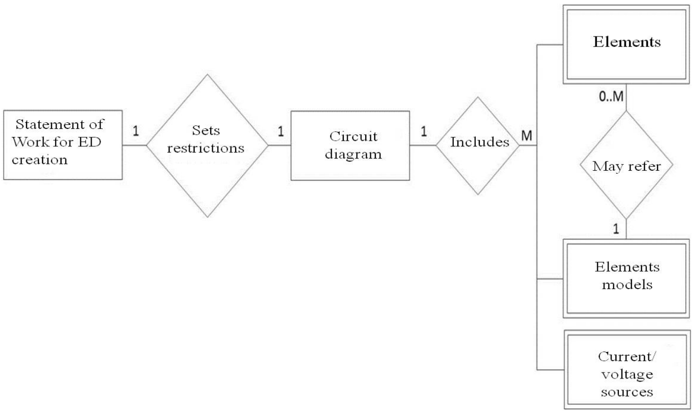

Fig. 4. Infologic model of ECD design

The essence of the "Statement of Work (SOW) for the creation of an ED" contains information about the restrictions imposed on elements of ECD. In turn, elements may contain references to models that characterize the parameters of this type of element. The attributes of this entity are: the number of the SOW; maximum and minimum ambient temperatures (necessary for obtaining the temperature of the elements); tolerance field for output parameters (sets a closed interval within which the output voltage should be guaranteed with a certain confidence level); input parameters of the circuit (set a constant value of the voltage or current source).

Attributes of the "Elements" entity are: the name of the element; technological tolerance (represents a closed interval within which the nominal value is guaranteed to be); model (represents a link in the form of a model name describing the parameters of the same element type); connection nodes (describe the two nodes to which the element is attached); nominal value (describes some physical parameter of the element, resistance, capacitance, inductance).

Attributes of the "Element models" entity are: model name; the coefficient of proportionality (a parameter that is multiplied by the nominal value of the element having a reference to the model); temperature coefficient (used when calculating the temperature of the element).

Attributes of the "Current/Voltage Sources" entity are: name of the current/voltage source; connection nodes (represents the two nodes to which sources are attached); nominal value (characterizes a constant value of voltage or current).

The physical database model was developed in the Microsoft Management Studio environment in SQL Server DBMS. The database consists of ten interrelated (table 1), the main characteristics of them are presented below.

TABLE I. THE MAIN CHARACTERISTICS OF THE DATABASE TABLES

№	Table name	Table characteristic
1	Projects	Contains data on the parameters of the ECD (the lower/upper value of the technical requirement, in this case the min/max output voltage of the circuit, as well as the positive/negative the output voltage measuring node) and the environment (lower/upper ambient temperature, in this case, the min/max temperature at which, according to the SOW, the circuit must supply a voltage within the technical requirements). It also stores binary text code describing schema elements that were not loaded into the rest of the database tables.
2	Independent voltage sources	Contains attributes (positive/negative node to which the voltage source is connected), which fully describe the necessary characteristics of an independent voltage source.
3	Independent current sources	Contains attributes (positive/negative node to which the current source is connected) that fully describe the necessary characteristics of an independent current source.
4	Resistors	It contains attributes (positive/negative node to which the resistor is connected, temperature coefficient of resistance (TCR), when the temperature of the resistor is lower/higher than the nominal temperature, Boundary range of the TCR resistor), which fully describe the necessary characteristics of the resistor, as well as the results of the program.
5	Resistive series	It contains general information about resistive series (resistors technological tolerance of a specific resistive series).
6	Resistive series values	Contains information about the values of the resistive series (value or multiples of it, which may have resistors of a specific resistive series).
7	Capacitors	Contains attributes (unique name of the model within one project/one scheme, positive/negative node to which the capacitor is connected, number or expression that specifies the capacitance value, temperature coefficient of capacitance (TCC), when the capacitor temperature is lower/higher than the nominal temperature, change limit TCC capacitor), which fully describe the necessary characteristics of the capacitor.
8	Capacitor models	Contains attributes that describe the characteristics of a capacitor, independent of a specific capacitor in a schematic diagram (unique name of the capacitor model within the project (circuit), number or expression that specifies the coefficient of linear/quadratic voltage dependence, coefficient multiplied by the capacitor capacitance value).
9	Inductors	Contains attributes that fully describe the required characteristics of an inductor (positive/negative node to which the inductor connects, a number or expression that specifies the value of the inductance, temperature coefficient of inductance when the temperature of the coil is lower/higher than the nominal temperature).
10	Inductor models	Contains attributes that describe the characteristics of inductors that do not depend on a specific inductance in a circuit diagram (the unique name of the model of inductance within the project (circuit), the number or expression that specifies the coefficient of linear/quadratic dependence on current, coefficient multiplied by the inductance value inductors).

IV. THE CALCULATION OF TOLERANCES ON TEMPERATURE ERE MONTE-CARLO

Calculation tolerances on ERE temperature that are included in the ED are an important task, while ensuring the reliability of the devices. Comparison of the measured temperature of the elements with the limits of tolerances allows us to decide on how suitable the controlled ERE is, and accordingly decide which of the samples are valid or defective. As a result, for each n-th ERE, it is necessary to find the tolerance interval $[T_n^{min}, T_n^{max}]$, of the vector of measured temperatures $\overline{T_n}$, the necessary condition of which is $\overline{T_n} \in [T_n^{min}, T_n^{max}]$ [3-6].

At present, when calculating the thermal control of the ED, various methods are used, however, in this work, the Monte-Carlo method is used to obtain a tolerance for the ERE temperature. This is a numerical method for solving problems by simulating a random variable. On a computer, using a special program, a random number generator is created, which outputs random values in accordance with the laws of their distribution. At each realization of the parameter received from the generator, the values of the output characteristics are calculated using the ERE model. This operation is repeated a certain number of times, for various combinations of parameters. As a result, histograms of output characteristics are built, which show the distribution laws and allow determining the expectation and standard deviation of these values. In our case, the output characteristics are the temperature of the elements. The accuracy of the method is determined by the number of tests and, as a rule, is 5-10%.

As a result, at the calculated temperatures, a multiple (K times) analysis of the electrical mode of the circuit is carried out. On each implementation, the values of the electrical parameters of the elements take random values determined by the formula:

$$Q_{ei}=q_{ei}^{nom}(1+\xi_k\, \delta_{qei}). \quad (1)$$

Where q_{ei}—the current value of the i-th electrical parameter at the k-th implementation, q_{ei}^{nom}—nominal value of the i-th electrical parameter, ξ_k—random value ($-1<\xi_k<1$), generated by a random number generator, $\delta_{q эi}$—relative tolerance for the i-th electrical parameter.

The values of the random variable ξ_k are given in accordance with the given distribution law. As a rule, a normal distribution law is specified on the interval (–1,1) with zero expectation and standard deviation σ=0,33.

The heat generation power values obtained for the k-th implementation for each circuit element are transferred to the calculation of the thermal mode of the ERE design, which is also performed K times to determine the expectation and standard deviation of the temperature of the heat generation elements on each element by the Monte Carlo method.

$$q_{Tj}=q_{Tj}^{nom}(1+\xi_k\, \delta_{qTj}). \quad (2)$$

Where q_{Tj}—current value of the j-th thermophysical parameter on the k-th implementation, q_{Tj}^{nom}—the nominal value of the j-th thermophysical parameter, δ_{qTj} is the relative tolerance on the j-th thermophysical parameter, which is calculated by the following formula 3 and 4:

$$\delta_{qTj} = (q_{Tj}^{nom} - q_{Tj}^{min})/q_{Tj}^{nom} = (q_{Tj}^{max} - q_{Tj}^{nom})/q_{Tj}^{nom}. \quad (3)$$

$$Q_{gl} = q_{gl}^{nom}(1+\xi_k\, \delta_{qgl}). \quad (4)$$

Where q_{gl} — the current value of the l-th geometric parameter on the k-th implementation, q_{gl}^{nom} is the nominal value of the l-th geometrical parameter, δ_{qgl} is the relative tolerance on the l-th geometrical parameter.

$$T_{env} = T_{env}^{nom}(1+\xi_k\, \delta_{Tenv}). \quad (5)$$

Where T_{env}—the current value of the ambient temperature at the k-th implementation, T_{env}^{nom}—temperature nominal value of the environment, δ_{Tenv}—relative tolerance for ambient temperature.

Thus, after conducting K calculations of the thermal regime of the ERE design, K temperature values at each element are obtained. From these values, for each element, the expectation $m(T_n)$ and the standard deviation $\sigma(T_n)$ of its temperature are determined.

The mathematical expectation of the element temperature is calculated by the following formula:

$$m(T_n) = \frac{\sum_{k=1}^{K} T_n^k}{K}. \quad (6)$$

Where T_n^k— temperature value of the n-th element on the k-th implementation.

The temperature dispersion $D(T_n)$ is determined, for example, by the formula:

$$D(T_n) = \frac{\sum_{k=1}^{K} \left(T_n^k - m(T_n)\right)^2}{K-1}. \quad (7)$$

The standard deviation $\sigma(T_n)$ of the temperature of the n-th element is calculated by the formula:

$$\sigma(T_n) = \sqrt{D(T_n)}. \quad (8)$$

In order to determine the range of possible values of the temperature of the n-th element $[T_n^{min}, T_n^{max}]$, it is necessary to specify the confidence probability β, with which the actual value of the temperature of the n-th element can lie in this range and is determined from the formula:

$$\beta = P(T_n^{min} \le T_i \le T_n^{max}). \quad (9)$$

For the selected value of β, the value of the coefficient χ is determined. The value of χ shows the number of standard deviations for the normal distribution law that need to be postponed to the right and left of the expectation so that the probability of hitting the resulting region is β.

Minimal T_n^{min} and maximum T_n^{max} temperature value of the n-th element for a given probability β of the actual temperature value falls into this range is determined by the formulas:

$$T_n^{min} = m(T_n) - \chi\sigma(T_n),\; T_n^{max} = m(T_n) + \chi\sigma(T_n). \quad (10)$$

As a rule, the value of the confidence probability is chosen to be β = 0,9973 and χ = 3.

Thus, as a result of calculations, the range $[T_n^{min}, T_n^{max}]$, is determined, in which the temperature of the n-th element can be. In the future, this range is used to control the quality of ERE in the temperature field, by comparing the measured temperature of the elements with the values T_n^{min} and T_n^{max}.

According to the results of the comparison, a decision is made about the presence or absence of a defect in the ERE (if the temperature values fit into this range, then such samples are considered valid; if they go beyond the calculated limits, they are considered defective).

V. Computer-Aided Simulation of Electronic Tools

The developed program uses external modules for electrical modeling and for obtaining temperatures of circuit elements. The electrical simulation module is part of the PSpice A/D program called “PSP_CMD.EXE”. The input data for the module is a file with a description of the circuit diagram (Circuit file), the results of the module are saved in the output file (* .out) [7-12].

The module for receiving the temperature of elements at the input accepts an array of lines with the following structure: the first line is “TEMP”, meaning thermal calculation, the second line is the ID of the circuit, the third line is the ambient temperature, and the other lines are the heat output of each circuit element. The results are presented in the form of an array of strings of the type “Name of the element temperature”.

The main window of the program is divided into three parts. The upper part - the menu contains buttons that control the functions and parameters of the program. The left part of the window contains an open or created Circuit-file of an open or created project (scheme); in this form the program generates text from the data in the database. The right part of the window contains a button, by pressing it the program performs the functions that lead to updating the data in the program database. The adjustment of the parameters of the circuit elements based on temperature, the calculation of the technological tolerance on the parameters of the circuit elements, the entry of the calculated data in the database and project files for later viewing of the data and the possibility of transferring the project to another computer are performed.

Before performing the adjustment of nominal values, it is necessary to create a project that will contain the necessary information about the concept, the results of the adjustment of nominal values and the calculation of technological tolerances. These data will be stored in the program's database, but if necessary, the project will be transferred to another computer, this program will be able to load all the necessary data about the project into the database, thereby ensuring the independence of the projects from their location.

When you click the "Create project" button in the main window menu, a file selection window appears with a description of the concept in SPICE. After selecting a file and checking it for errors, a form opens to select the storage location for the project folder and its name. After successfully entering the project name and location, the program creates a project folder and copies the concept description file in the SPICE language. Next, the program reads the data from the copied file and from the output file of the PSPICE A/D program after performing the electrical simulation.

The Project Parameters window has been created to specify data from the SOW for the development of ED (temperature coefficients of ERE, output voltage interval, output voltage measurement nodes, etc.) which is required when the program performs functional tasks. After specifying all the parameters in this window, the program saves the information in the database and displays the text with the description of the concept in the SPICE language on the main window.

To perform the correction of nominal values without taking into account the temperature, you must click on the "Calculate the nominal values of ERE without taking into account the temperature" in the right part of the window. After making adjustments, a window appears with the results of adjustments to nominal values.

To calculate the technological tolerances of ERE, one should click the button "Calculation of technological tolerances of the ERE".

To find the upper and lower limits of the tolerance for the element temperature, formulas (6-10) are used, below formulas are used for the output voltage value. The mathematical expectation of the circuit output voltage $m(U)$ is calculated by the formula:

$$m(U) = \frac{\sum_{k=1}^{K} U_k}{K}. \quad (11)$$

Where U—output circuit voltage, U_k—output circuit voltage while k-th implementation, K—number of implementations.

The variance of the output voltage $D(U)$ is calculated by the formula:

$$D(U) = \frac{\sum_{k=1}^{K} (U_k - m(U))^2}{K-1}. \quad (12)$$

The standard deviation of the output voltage $\sigma(U)$ is calculated by the formula:

$$\sigma(U) = \sqrt{D(U)}. \quad (13)$$

Lower output tolerance limit U_l is calculated by the formula:

$$U_l = m(U) - \chi\sigma(U). \quad (14)$$

Where χ—the number of standard deviations that need to be set aside to the left so that the probability of falling into the confidence interval is equal to a certain probability β.

The upper limit of the tolerance for the output voltage is calculated by the formula:

$$U_u = m(U) + \chi\sigma(U). \quad (15)$$

If the lower and upper tolerances are within the confidence interval, then the scheme can be considered as working, taking into account the technological tolerances of the elements, but it cannot be considered as working while taking into account the technological tolerances and heating of the elements.

After performing the Monte-Carlo calculations, a window appears with a histogram of the output voltage distribution (figure 5).

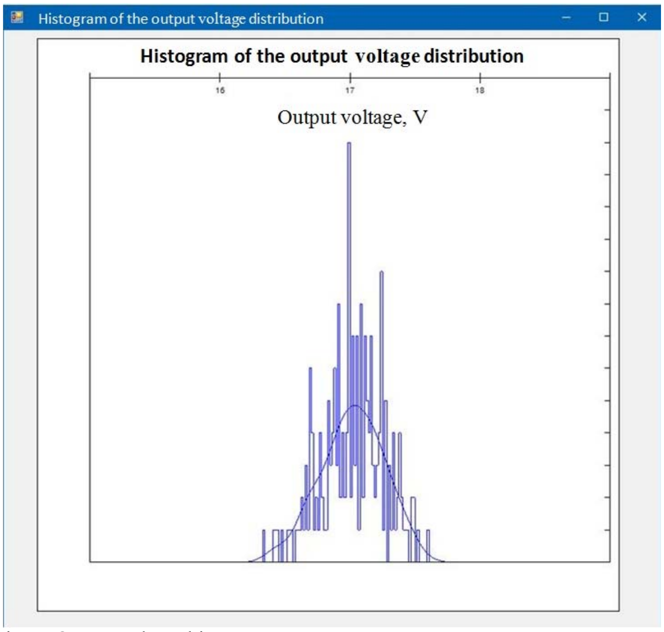

Fig. 5. Output voltage histogram

After the closure of this form, the probability of the distribution of the output voltage over the confidence interval along the approximating function is calculated. If the calculated probability is greater than one minus the confidence level, the program automatically narrows down the technological tolerance of the ERE with the highest sensitivity coefficient and re-calculates the Monte-Carlo method. If the probability is less than one minus the confidence level, the program opens the last window with data on the resistive rows of each resistor. According to the data presented in this window, the confidence level of each resistor in its resistive series can be called. The resistance (nominal value) is equal to the coefficient multiplied by a factor.

VI. Conclusion

The result of this work is a list of design solutions, as well as the developed computer-aided design system for ECD at the stage of circuit simulation of electronic devices, including a designed database and interface for working with it, as well as ready-made functions for creating and opening projects, functions for reading and writing input and output information. Output files of the PSPice electrical modeling unit, functions for calculating the nominal ERE values and tolerances for them by applying the mathematical modeling method which as a result can be used in the analysis of the ED technical state.

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