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AN APPROACH TO THE PROBLEM SOLVING OF SENSITIVITY DETERMINING OF ELECTRONIC CIRCUITRY

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ABSTRACT

This article focuses on one of the pressing issues related to the solution of the problem of the electronic device sensitivity to minor changes in the parameters of its elements. The paper gives a general formulation of the mathematical problem, resulting from simulation of transient processes occurring in the electronic circuit when exposed to external factors and changing parameters of the elements that make up the scheme.

A new approach to solving this problem, based on the numerical solution of two problems, is being offered: the first one is considered when the parameters of circuit elements remain unchanged, and the second - when the change of these parameters occurs. For the convenience of numerical implementation of the algorithm for the proposed approach to the problem solution, all of the parameters are considered dimensionless variables.

As an example of the solution the problem is set, an electronic circuit is considered, for which testing of the approach proposed here to solve the problem has been conducted. Various options for changing the parameters of circuit elements are considered. The numerical experiment has been conducted. The results of solving the problem are given in the form of tables and graphs.

To evaluate the sensitivity of the electronic circuit to the change in the parameters of its elements a relative difference between these two solutions has been adopted.

KEYWORDS: Electronic Circuit, Amplifiers, Numerical Experiment

INTRODUCTION

It is known that the electronic circuit are affected by not only external effects (currents, voltages, etc.), but also values settings of circuit components may change under the influence of various factors [1, pp. 152-160]. Factors influencing the change in the parameters of circuit elements can be: modified temperature, wear and tear, aging, weathering, replacement of components and others. In the process of manufacture and operation of electronic devices values of element parameters may differ from the calculated ones.

Obviously, if at some point in time there is a change in the circuit parameters, the process in the scheme is different. These changes in the values of electronic circuit element parameters may be undesirable for the normal functioning of the entire device, as they are responsible for the violation of its operation. Because the quality of the electronic device operation greatly depends on the change in its characteristics.

To evaluate the performance of the developed electronic device a concept called "sensitivity", defining ". . . measure of changes in the characteristics of the circuit (or functions of the circuit), which occurred as a result of a deviation of one or more circuit elements from their nominal values"[2, p. 98] is used.

On the other hand, calculation of the device or devices sensitivity plays an important role in the design of electronic devices used to analyze various embodiments of circuits and selecting the best (optimal) variant [2, p. 101-112]. In a word, the determination of the device or devices sensitivity of the elements will be important for solving the electronic circuit optimization problem according to certain requirements.

In this regard, there is a need to assess the impact of changes in the parameters of the elements to the change in the characteristics of the electronic device. Solution of this problem is relevant.

For the formulation and solution of this problem, we introduce the concept of electronic circuit sensitivity to changes in the elements. Here, the term “sensitivity” refers to the circuit’s reaction to a change in a parameter of its element. Research by many authors was dedicated to the study of the problem of calculating the quantitative assessment of sensitivity. Concept of sensitivity was first introduced in the work by H. Bode (Bode HW, 1945) [3].

To quantify the sensitivity, ratio of the change of the output parameter to a change in the parameter element, which is measured as a percentage, is used [4, p. 156]. In the literature devoted to the study of this problem relative sensitivity, this is determined by the following formula:

$$S_{\alpha}^{y} = \frac{\partial y}{\partial [alpha]} \cdot \frac{[alpha]}{y}.$$

is used. In this formula $[alpha] -$ is the element causing the change, $y -$ parameter being measured, $S_{[alpha]}^{y} -$ relative sensitivity.

If we consider a linear circuit, circuit function can be used instead of the parameter y. Then the notion of "sensitivity of the circuit function", introduced by G.Bode [2, p. 101] is used. Review of the literature devoted to the study of sensitivity showed that the calculation of the sensitivity function "can lead to intractable computational problems for any circuit" [2, p. 127].

Solution to the problem related to the definition of sensitivity for non-linear circuits, has some difficulties of computational nature. This is due, primarily, to difficulties in solving mathematical problems arising as a result of mathematical modeling of the transient process in the circuit due to changes in the parameters of its elements. The difficulties of determining the sensitivity function are primarily associated with the problem of determining the partial derivatives of bulky functions. In such cases, the probability of errors is large enough. Therefore, a simple search for the application of a computer analysis method of the electronic device sensitivity is an important task.

General Problem Statement

Mathematical modeling of the transient process in the electronic circuitry in general leads to solving the following system of differential equations [5-12]:

$$\frac{dx_i}{dt} = f_i(t, x_1, x_2, \ldots, x_n, z(t), [alpha]_1, [alpha]_2, \ldots, [alpha]_m). \quad (1)$$

In this formula: $i = 1,2, \ldots, n,\ t -$ time, $[alpha]_j, (j = 1, 2, \ldots, m)$ - circuit element parameters, $x_i = x_i(t) -$ unknown functions that describe the dimensionless currents or voltages. The solution to this problem is seen in the range of dimensionless time $0 \le t \le 1$.

To solve this system of differential equations (1) the initial conditions are given at some time $t = 0$:

$$x_i(0) = [alpha]_i, \quad i = 1,2,\ldots,n. \tag{2}$$

It is assumed that the transition process in the given electronic circuit is influenced by the perturbing factor, determined by a function $z(t)$. If parameters of the circuit elements are not changed, then the solution of the Cauchy problem (1) - (2) defines the normal transient process occurring in the electronic circuit.

This formulation of the problem assumes the following: determine the change in the occurring process when a parameter (or set of parameters) of circuit elements changes. Suppose that at some point $t = t_0$ in time there is a change in the value of one element (or group of elements) of the aggregate $\{[alpha]\}$. Determining how much the process occurring in this circuit changes, is required.

Stages of General Problem Solution

The solution to this problem may consist of solving some of the Cauchy problems for a system of ordinary differential equations of the first order. These problems can be solved in a certain order.

The solution to this problem will consist of the following steps:

1-stage. Solution of the system of differential equations (1) at constant values of parameters $\{[alpha]\}$ and initial conditions (2):

$$x_i = x_i(t,[alpha]_1,[alpha]_2,\ldots,[alpha]_m), \quad i = 1,2,\ldots,m. \tag{3}$$

2-stage. Determine the solution of the problem (1) - (2) for the time $t = t_0$, i.e. values of functions (3) will be determined:

$$x_i(t_0) = x_i(t_0,[alpha]_1,[alpha]_2,\ldots,[alpha]_m), \quad i = 1,2,\ldots,m. \tag{4}$$

3-stage. Solve the system of equations (1) for the initial conditions (4), when there was a change in the value of one parameter or the values of several parameters of the population $\{[alpha]\}$. In this case, we obtain new values of the required functions for the changes in parameter values $\{[alpha]\}$:

$$\begin{aligned}\overline{x_i} = \overline{x_i}(t,[alpha]_1 + [delta]\cdot[alpha]_1,[alpha]_2 + [delta]\cdot[alpha]_2,\ldots,[alpha]_n + \\ + [delta]\cdot[alpha]_n), i = 1,2,\ldots,m.\end{aligned} \tag{5}$$

4-stage. Difference of two solutions is determined by: a) solving the system of equations (1) without changing the parameters of $\{[alpha]\}$, and b) solving the same system of equations with their values changed:

$$[lambda]_i(t) = \frac{x_i - \overline{x_i}}{x_i} = 1 - \frac{\overline{x_i}}{x_i}, \quad i = 1,2,\ldots,n. \tag{6}$$

In further studies, to assess the sensitivity of the electronic circuit to the change in the values of its parameters, you can consider the dependence of these deviations $[lambda]_i(t)$ on the changes of the parameters of each set $\{[alpha]\}$.

In this case $[lambda]_i(t)$ are dimensionless quantities that depend on the dimensionless time

A Numerical Method for Solving the Problem

The system of equations (1) in the general case is a nonlinear system of first order differential equations that are solved for the first derivatives of the unknown functions. Analytical solution of this system of equations is not possible; therefore a numerical method of solution is used. Numerical solution is feasible in terms of the use of computer analysis for the problem of determining sensitivity.

Well-known replacement of the first derivatives of the unknown functions available in the right-hand sides of differential equations with the following finite-difference ratios of the first order is used [9; 14-15]:

$$\frac{dx_i}{dt} = \frac{x_i^{(k+1)} - x_i^{(k)}}{\tau}, \quad i = 1,2,\dots,n. \tag{7}$$

Here, $x_i^{(k)} = x_i(t_k), \quad x_i^{(k+1)} = x_i(t_{k+1}), \quad t_k = \tau \cdot k, \quad k = 0,1,2,\dots,N-1, \quad N = \frac{1}{\tau};$

$x_i^{(0)} = x_i(0) = a_i$, $\tau -$ time increment on t.

Substituting (7) into the right part of the system of equations (1), we obtain the following system of difference equations

$$x_i^{(k+1)} = x_i^{(k)} + \tau \cdot f_i(t_k, x_1^{(k)}, x_2^{(k)}, \dots, x_n^{(k)}, z_k, [alpha]_1, [alpha]_2, \dots, [alpha_m]). \tag{8}$$

Here $z_k = z(t_k) -$ discrete values of the given function at the splitting points of the segment $0 \le t \le 1$.

Formulas (8) are recurrence relations, which for given initial conditions allow us to determine the discrete values of the unknown functions

$$x_i(t), \quad (i = 1,2,\dots,n).$$

Here, formulas (8) are used twice: for the first initial conditions (2) and then for the initial conditions (4). The results are compared to times when $t > t_0$. Using formulas (6) relative changes $x_i^{(k)}$ and $\overline{x_i}^{(k)}$ are determined, i.e. values of $[lambda]_i(t)$. are determined. From these values, we can determine the impact of changes in a particular parameter $[alpha]_i$ to changes in the desired functions $x_i(t)$. This allows estimating the sensitivity of the electronic circuit to change in the parameters of each of its elements.

A Special Case

To implement the proposed approach to solving this problem it is advisable to consider the particular problem - the problem of estimating the sensitivity of a simple electronic circuit to change in the parameters of its elements.

Let us now consider a circuit with a non-linear element (Figure 1). As an example, the circuit considered in [6; 12], consisting of two capacitors and a nonlinear element (NE) is taken.

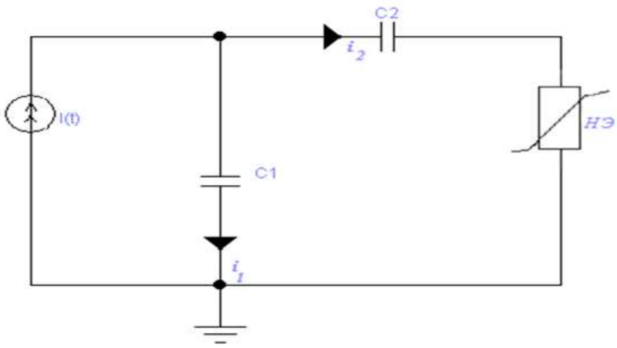

Figure 1: Electronic Circuit with a Nonlinear Element

Solution to the problem of a transient process in the nonlinear scheme should be used to analyze the sensitivity of this circuit. This allows you to determine the effect of parameter changes in the nonlinear element on the sensitivity of an electronic circuit. Method of circuit state equation formulation is based on the application of Kirchhoff's laws.

Suppose that the following expression $i_{NE} = \frac{U_0}{R} \cdot g(x),$ is used for approximation of the nonlinear current-voltage characteristics of the element (NE) , where $x = \frac{u_{NE}}{U_0}$ - dimensionless voltage, $g(x)$ - approximating function of the relationship between current and voltage in the non-linear element. Moreover, the voltage in the non-linear element is defined by the formula $u_{NE} = x \cdot U_0$.

If $i_{NE} = i_2$, then for the circuit in question, the following equation can be written [7;13]:

$$\begin{cases} i_2 = C_2 \cdot \frac{du_2}{dt}; \quad i_1 = C_1 \cdot \frac{du_1}{dt}; \\ i_1 + i_2 = i(t); \quad u_{NE} = u_1 - u_2; \\ i_2 = \frac{U_0}{R} \cdot g(x) \end{cases}$$

In this system of five equations; the unknowns are the five variables $i_1, i_2, u_1, u_2, u_{NE}$. These five equations are equations to determine the five unknown parameters of this electronic circuitry.

For convenience in the calculations, it is appropriate to use the dimensionless parameters. To do this, the following characteristic values will be further used : U_0 - voltage $\frac{U_0}{R}$ - current. The following change of variables is performed:

$$i_2 = y_2 \cdot \frac{U_0}{R}; \quad i = z \cdot \frac{U_0}{R}; \quad i_1 = y_1 \cdot \frac{U_0}{R}; \quad x_1 = \frac{u_1}{U_0};$$

$$x_2 = \frac{u_2}{U_0}; \quad x = \frac{u_{NE}}{U_0}; \quad t = \frac{\tau}{T}.$$

Here $x, x_1, x_2, y_1, y_2, t -$ dimensionless quantities.

If u_1 and u_2 are found then it is easy to determine u_{NE} ; therefore it is sufficient to solve the system of following four equations for the four unknown functions x_1, x_2, y_1, y_2 :

$$y_1 = [alpha]_1 \cdot \frac{dx_1}{dt}; \quad y_2 = [alpha]_2 \cdot \frac{dx_2}{dt}, \; y_1 + y_2 = z(t); \quad y_2 = g(x). \tag{9}$$

Here the dimensionless voltage in the nonlinear element is determined by the formula $x = x_1 - x_2$; constants $[alpha]_1 = \frac{RC_1}{T}$ and $[alpha]_2 = \frac{RC_2}{T}$ are dimensionless quantities; RC_1 and RC_2 - time constants.

Thus, we obtain the following system of three differential equations [7; 13] for the unknown functions $x(t), x_1(t), x_2(t)$:

$$\begin{cases} \frac{dx}{dt} = -\frac{[alpha]_1 + [alpha]_2}{[alpha]_1 \cdot [alpha]_2} \cdot g(x) + \frac{1}{[alpha]_1} \cdot z(t); \\ \frac{dx_1}{dt} = \frac{1}{[alpha]_1} \cdot \left[z(t) - g(x) \right]; \\ \frac{dx_2}{dt} = \frac{1}{[alpha]_2} \cdot g(x) \end{cases} \tag{10}$$

Differential equations included in this system, contain a function $g(x)$, that is non-linear with respect to $x(t)$. Therefore, the system of equations (10) is considered as non-linear.

For the electronic circuit considered here, it is assumed that at the initial time current (or voltage) is absent, so to solve this system of differential equations (10), the following initial conditions are adopted:

$$x_1(0) = 0; \quad x_2(0) = 0; \quad x(0) = 0; \tag{11}$$

To determine the sensitivity of this circuit to changing the parameters C_1, C_2 - capacitor capacitances, values of

x_1, x_2, y_1, y_2 are computed for different values of these parameters. Due to the transition to dimensionless quantities, in this case, instead of values C_1, C_2 parameters $[alpha]_1$ and $[alpha]_2$ are considered.

The Initial Data

To perform these calculations it is necessary to make some assumptions. Let the current of the source be considered alternating and its change is given in the form of a sine wave $z(t) = \sin(2\pi \cdot \omega \cdot t),$ where frequency is $\omega = 50$ Hz. The following values of the constant parameters: $C_1 = 1{,}5$ u F, $C_2 =$ 3 u F, $R = 10$ k Ohm, $T = 0{,}1$ sec are assumed. Therefore, the values of the dimensionless parameters are defined as follows: $[alpha]_1 = 0{,}15;\ [alpha]_2 = 0{,}30.$

These values of the dimensionless parameters $[alpha]_1 = 0{,}15$ and $[alpha]_2 = 0{,}30$ are assumed primary, and for them the values of voltages and currents in the circuit are determined. Then it is assumed to calculate the values of voltages and currents for other values of these parameters in order to determine the sensitivity of the circuit when the parameters of circuit elements change.

In this case, changes of the capacitor capacitances in the circuit are considered. For the numerical implementation of these calculations, the values of these parameters are given in Table 1.

Table 1: Values of Parameters $[alpha]_1$ And $[alpha]_2$

Options	1 (Primary)	2	3	4	5
$[alpha]_1$	0,15	0,165 (+10%)	0,15 (0%)	0,165 (+10%)	0,18 (+20%)
$[alpha]_2$	0,30	0,30 (0%)	0,33 (+10%)	0,33 (+10%)	0,36 (+20%)

Here a variation of these parameters as a percentage is shown. Change of dimensionless parameters $[alpha]_1$, and $[alpha]_2$ to a certain percentage leads to a change of the capacitances to the same percentage.

FET is assumed as the nonlinear element (NE). The experimental data and the approximation of these data to determine the current-voltage characteristics of the FET are given in [8; 16]. A polynomial of the fifth degree is adopted as an approximating function, and by solving a system of linear algebraic equations for determining the coefficients of the polynomial of the fifth degree it is possible to define the following function:

$$g(x) = 0{,}005 \cdot x^5 - 0{,}094 \cdot x^4 + 0{,}545 \cdot x^3 - 1{,}210 \cdot x^2 + 1{,}099 \cdot x + 0{,}006.$$

Solution Algorithm for the Special Case

For this special case formulas (8) can be written as follows:

$$x^{(k+1)} = x^{(k)} + \tau \cdot [\frac{z^{(k)}}{[alpha]_1} - \frac{[alpha]_1 + [alpha]_2}{[alpha]_1 \cdot [alpha]_2} \cdot g(x^{(k)})],$$

$$x_1^{(k+1)} = x_1^{(k)} + \frac{\tau}{[alpha]_1} \cdot [z^{(k)} - g(x^{(k)})], \tag{12}$$

$$x_2^{(k+1)} = x_2^{(k)} + \frac{\tau}{[alpha]_2} \cdot g(x^{(k)}), \qquad k = 0,1,2,\ldots,N.$$

Initial conditions

$$x^{(0)} = 0, \;\; x_1^{(0)} = 0, \;\; x_2^{(0)} = 0. \tag{13}$$

Values of the unknown functions $x(t), x_1(t), x_2(t)$ are calculated by the recurrence formulas (12) for the initial conditions (13).

Then the values of these functions for some time $t = t_0$. are determined. Values obtained are used as initial conditions for computing the values of the unknown functions $\overline{x}(t),\ \overline{x_1}(t),\ \overline{x_2}(t)$ by the formulas:

$$\overline{x}^{(k+1)} = \overline{x}^{(k)} + \tau \cdot [\frac{z^{(k)}}{\alpha_1} - \frac{[alpha]_1 + [delta]\cdot[alpha]_1 + [alpha]_2 + [delta]\cdot[alpha]_2}{([alpha]_1 + [delta]\cdot[alpha]_1)\cdot([alpha]_2 + [delta]\cdot[alpha]_2)} \cdot g(\overline{x}^{(k)})],$$

$$\overline{x}_1^{(k+1)} = \overline{x}_1^{(k)} + \frac{\tau}{[alpha]_1 + [delta]\cdot[alpha]_1} \cdot [z^{(k)} - g(\overline{x}^{(k)})], \tag{14}$$

$$\overline{x_2}^{(k+1)} = \overline{x_2}^{(k)} + \frac{\tau}{[alpha]_2 + [delta]\cdot[alpha]_2} \cdot g(\overline{x}^{(k)}), \qquad k = p, p+1, p+2, \ldots, N.$$

To calculate the formulas (14) the initial conditions defined by the formula (4) must be given, which can be written in the following form:

$$\overline{x}^{(p)} = x^{(p)}, \overline{x_1}^{(p)} = x_1^{(p)} \; \overline{x_2}^{(p)} = x_2^{(p)}, \tag{15}$$

where $p = \frac{t_0}{\tau} -$ index value (number) corresponding to the time when there was a change of parameter values $[alpha]_1$ and $[alpha]_2$.

For the given special case formula (6) has the following form:

$$\lambda(t_k) = 1 - \frac{\overline{x}^{(k+1)}}{x^{(k+1)}}, \quad \lambda_1 = 1 - \frac{\overline{x_1}^{k+1}}{x_1}, \quad \lambda_2 = 1 - \frac{\overline{x_2}^{(k+1)}}{x_2}. \tag{16}$$

Thus, a set of formulas (12) - (16), on which the calculations are performed, has been defined . The order of evaluation is as follows:

- Values of the required functions for the case when the values of parameters $[alpha]_1$ and $[alpha]_2$ are constants are calculated by the formulas (12) - (13). Here loop iteration will be organized where the counter is the parameter k. Values of the parameter $k := 0,1,2,...,N$.

- Values of the unknown functions for the case when the values of the parameters $[alpha]_1$ and $[alpha]_2$ have changed and are determined by the formulas (14) and (15). The loop counter in this case varies in the following boundaries $k := p, p+1, p+2, ..., N$.
- Values $[lambda], [lambda]_1, [lambda]_2$ are calculated by the formulas (16)

RESULTS OF NUMERICAL SOLUTION OF THE PROBLEM

Results of the problem are obtained in the form of numerical tables, which reflect the values of the relative differences between the two solutions: a) the case when values of elements (capacitors) do not change; b) the case when the values of these parameters are changed.

Analysis of the results.

- The values of the relative differences between the two solutions increases with the passage of time: some values are given in the following table:

Table 2: Values of $[lambda], [lambda]_1, [lambda]_2$ When Values of $[alpha]_1$ And $[alpha]_2$ have increased by 2%

T	1	5	10	15	20	25	30	35
λ	0,133228	0,326853	0,484267	0,587517	0,658605	0,709341	0,746524	0,774281
λ_1	0,0026008	0,006402	0,009489	0,011517	0,012913	0,013911	0,014643	0,015189
λ_2	0,00213	0,005731	0,008915	0,011194	0,012863	0,014108	0,015053	0,015780

Table 3: Values of $[lambda], [lambda]_1, [lambda]_2$ When Values of $[alpha]_1$ And $[alpha]_2$ have increased by 20%

T	1	5	10	15	20	25	30	35
λ	0,133228	0,326853	0,484267	0,587517	0,658605	0,709341	0,746524	0,774281
λ_1	0,022169	0,054416	0,080660	0,097891	0,109763	0,118243	0,124462	0,129111
λ_2	0,018813	0,054416	0,075776	0,095149	0,109334	0,119918	0,127948	0,134132

- Comparison of the values x listed in Table 1 showed that a change in values $[alpha]_1$ and $[alpha]_2$ a change occurs in the parameter $[lambda]$ that characterizes the voltage change in the non-linear element, which does not depend on the magnitude of changes in the parameters in the capacitors.
- Comparison of values $[lambda]_1$ and $[lambda]_2$ listed in Tables 2 and 3 show that increasing the parameter $[alpha]_1$ and $[alpha]_2$ by 20% leads to a change in the voltages in the capacitors by approximately one order of magnitude higher than the increase by 2%.
- Over time, the values of all parameters $[lambda], [lambda]_1, [lambda]_2$ characterizing the degree of relative

differences tend to some constant values. This conclusion follows from the graphs of changes in $[lambda]$, $[lambda]_1$, $[lambda]_2$ over time (Figures 2,3,4).

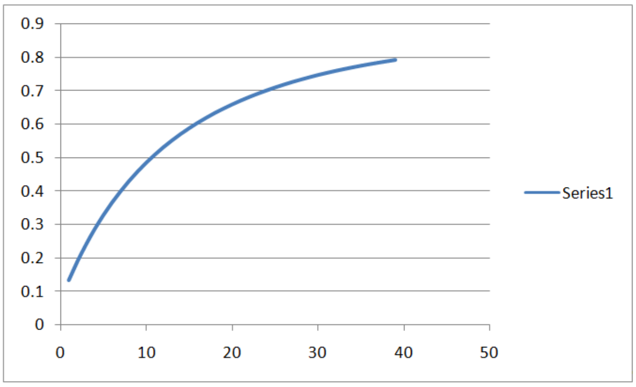

Figure 2: Graph of Change in the Parameter $[lambda]$ by 2%

If the value of the capacitor element does not change, then there is no change in its voltage value.

In all of the options considered, $[lambda]$ takes the same value, the voltage at the non-linear element (NE) is changed according to the same law.

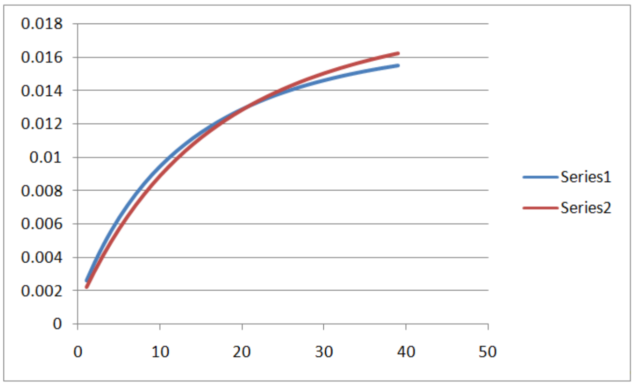

Figure 3: Graph of Change in the Parameters $[lambda]_1$, $[lambda]_2$ by 2%

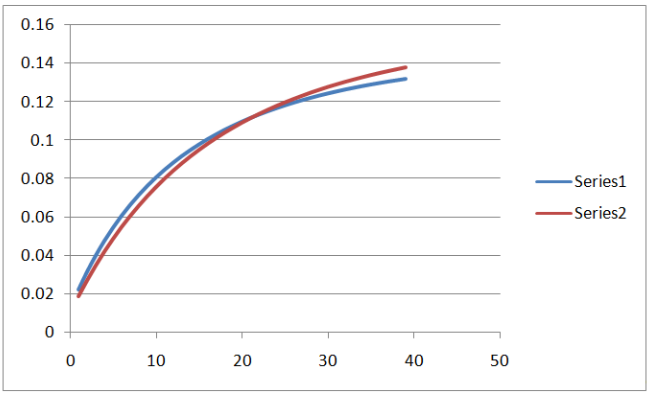

Figure 4: Graph of Change in the Parameters $[lambda]_1$, $[lambda]_2$ by 20%

CONCLUSIONS

Formulation of the problem of determining the sensitivity of the electronic circuit to a change in the parameters of its elements and its solution proposed in this paper, allow the analysis of the state of the whole electronic circuit and its components in particular. Here relative voltage changes in the circuit elements are taken as a measure of the sensitivity. To solve the problem formulated in this article, an approach is used, the essence of which lies in the fact that two problems are solved and the comparative analysis of their results is performed. Numerical method for solving these two problems allows a computer experiment to be conducted.

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