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NUMERICAL CALCULATION OF ELECTRONIC CIRCUITS WITH NONLINEAR ELEMENTS.

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Abstract: *Non-linear elements are widely used in various automation devices, converting and measuring equipment. They are often presented in the form of diode-resistive circuits. In single-circuit electrical circuits, their calculation by a numerical method reduces to compiling nonlinear equations and solving it using the Newton-Raphson method with specifying reasonable initial conditions for the calculation. The article is aimed at determining the dimensions of the Jacobi matrix in numerical calculations of nonlinear chains. Using the example of numerical calculation of two simplest schemes with nonlinear elements, it is shown that by eliminating the coordinate chain (system equations) from the system of equations that do not contain nonlinear elements, the Jacobi matrix is reduced in size.*

Key words*: automation, diode, electronic nonlinear elements, diode-resistive circuits, numerical calculation methods, Newton-Raphson, Jacobi matrices.*

Non-linear elements are widely used in various automation devices, converting and measuring equipment. Often they are presented in the form of diode-resistive circuits. In single-circuit electrical circuits, their calculation by a numerical method reduces to compiling nonlinear equations and solving it using the Newton – Raphson method with specifying reasonable initial conditions for the calculation. [1,2,3,4]

For multi-loop (multi-node chains), the calculation is reduced to compiling a system of non-linear equations of the chains and solving it by the Newton – Raphson method, which leads to the determination of the Jacobi matrix, the residual vector and further iteration procedures before entering the specified error region. [5,6,7,8]

Let us conduct a numerical analysis of an electronic circuit with a nonlinear diode (diode-resistive) element. First, imagine that an electric circuit has one nonlinear element, that is, iteration is carried out in one variable. An example of such a circuit is shown in Fig. 1.

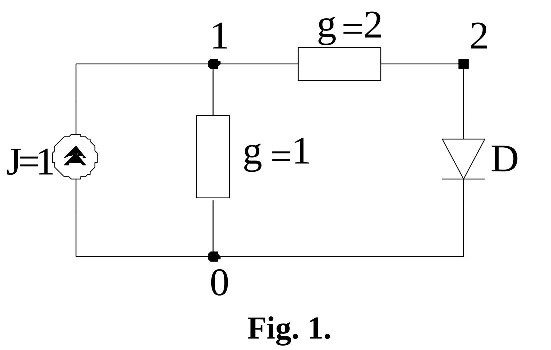

Fig. 1.

Suppose the current through the diode is determined by the equation:

$$I_D = I_0 \ [\exp(U_D/\varphi_T) - 1] \quad (1)$$

where: I_0 - thermal current through p-n junction;

φ_T – thermal potential, expressed, as well as electrical potential, in volts.

For silicon diodes at temperature К=300^0 φ_T = 0,025 В.

Given the value of φ_T and neglecting, due to its smallness, the value of I_0, we arrive at the approximate equation of the diode current [4],

$$I_D = \exp(40U_D) - 1; \qquad (2)$$

Using the method of nodal potentials with the indicated parameters of the circuit leads to two equations:

$$\begin{cases} 3U_1 - 2U_2 = 1 \\ -2U_1 + 2U_2 + (\exp(40U_2) - 1) = 0 \end{cases} \qquad (3)$$

Expressing U_1 in the first equation through U_2

$$U_1 = \frac{1}{3} + \frac{2}{3}U_2 \ ;$$

and substitute it in the second, we get

$$f(U_2) = \frac{2}{3}U_2 + \exp(40U_2) - \frac{5}{3} = 0 \qquad (4)$$

In accordance with the Newton method for *k +1* - th iteration, we have the relation

$$f(x^{k+1}) = f(x^k) - \frac{f(x^k)}{f'(x^k)} = f(x^k) + \Delta x^k \qquad (5)$$

where: Δx^k is called the residual vector
For the numerical calculation of equation (4) by the Newton method, we determine its derivative entering into (5)

$$f\,'\,(U_2) = \frac{2}{3} + 40 \cdot \exp 4\, U_2 \qquad (6)$$

As the initial value, we take $U_2{}^0 = 0{,}1$ B.
Calculations are performed according to formula (5) for each next *k-th* iteration.

Iteration 1.

$$f(U_2^0) = \frac{2}{3}U_2 - e^{40 \cdot U_2} - \frac{5}{3} = 0{,}06666 + 2{,}71828^2 \cdot 2{,}71828^2 - \frac{5}{3} =$$
$$= 0{,}06666 + 54{,}591 - 1{,}6666 = 51{,}99791 \ ,$$

$$f(U_2^0) = \frac{2}{3} + 40e^4 = 0{,}06666 + 40 \cdot 54{,}591 = 0{,}06666 + 2183{,}9164 = 2184{,}58306$$

$$\Delta U_2^0 = \frac{f(U_2)}{f'(U_2)} = -\frac{21{,}99791}{2184{,}58306} = -0{,}024259$$

$$U_2' = U_2^0 + \Delta U_2^0 = 0{,}1 - 0{,}024259 = 0{,}075741$$

Iteration 2.

$$f(U_2') = \frac{2}{3} \cdot 0{,}075741 + 2{,}71828^{40 \cdot 0{,}07574} - \frac{5}{3} = 0{,}05049 + 2{,}71282^{3{,}03} - 1{,}6666$$
$$= 0{,}05049 + 20{,}12 - 1{,}6666 = 18{,}50383$$

$$f'(U_2') = \frac{2}{3} + 40 \cdot 20{,}12 = 804{,}8$$

$$\Delta U_2' = -\frac{f(U_2{}')}{f'(U_2{}')} = -\frac{18{,}50383}{804{,}8} = -0{,}02299$$

$$U_2^2 = f(U_2') + \Delta U_2' = 0{,}075741 + 0{,}02299 = 0{,}05275$$

The remaining iterations are summarized in table 1.

Table 1.

К	U_2^K	ΔU_2^{K+1}
1	0,075741	-0,024259
2	0,052750	-0,02299
3	0,032705	-0,02
4	0,018883	-0,013822
5	0,013356	-0,055267
6	0,012654	-0,070199
7	0,012644	-0,099424
8	0,012644	-0,019579

As can be seen from table 1, the final value $U_2 = 1{,}2644 \cdot 10^{-2}$ B.

Substituting the value of U_2 into the expression for U_1 we obtain,

$$U_1 = \frac{1}{3} + \frac{2}{3} U_2 = 3{,}41762 \cdot 10^{-1} \text{ B.}$$

For multi-circuit (multi-node) circuits in which a system of nonlinear equations of the form is obtained:

$$\begin{aligned} f_1(x_1, x_2, \dots x_n) &= 0 \\ f_2(x_1, x_2, \dots x_n) &= 0 \\ \dots \dots \dots \dots \dots \dots \dots \dots \\ f_n(x_1, x_2, \dots x_n) &= 0 \end{aligned} \qquad (7)$$

the Newton-Raphson method is used. In this method, each of equations (7) is linearized by expanding them into a Taylor series and restricting them only to linear members of the series.

In the general case, the expansion of equations from system (7) into a Taylor series with respect to the point x^k is performed in the following form:

$$f_i(x_1, x_2, \dots x_n) = f_1\left(x_1^k, x_2^k, \dots\ x_n^k\right) + \frac{\partial f_k(x^k)}{\partial x_1}\left(x_1 - x_1^k\right) + \frac{\partial f_k(x^k)}{\partial x_2}\left(x_2 - x_2^k\right) + \dots + \frac{\partial f_k(x^k)}{\partial x_n}\left(x_n - x_n^k\right) \qquad (8)$$

Wher, $x = x^k$ - k-th approximation

The linear members of the series (8) are the first two members, and the rest – higher order members including $(x_i - x_i^k)^m$;

where, $m > 1$; $i = 1,2, \dots n$.

If in equation (8) as the next term of approximation we take $x = x^{k+1}$, then we arrive at an equation of the form:

$$f_i\left(x_1^{k+1}, x_2^{k+2}, \dots\ x_n^{k+n}\right) = f_i\left(x_1^k, x_2^k, \dots\ x_n^k\right) + \frac{\partial f_i(x^k)}{\partial x_1}\left(x_1^{k+1} - x_1^k\right) +$$

$$+\frac{\partial f_i(x^k)}{\partial x_2}\left(x_2^{k+1}-x_2^k\right)+\cdots\frac{\partial f_i(x^k)}{\partial x_n}\left(x_n^{k+1}-x_n^k\right) \tag{9}$$

Neglecting the higher order terms in equation (9), we obtain an approximate relationship in the form of a linear equation for the *k+1*- th iteration interval:

$$f_i(x^{k+1}) = f_i(x^k)+\frac{\partial f_i(x^k)}{\partial x_1}\left(x_1^{k+1}-x_1^k\right)+\frac{\partial f_i(x^k)}{\partial x_2}\left(x_2^{k+1}-x_2^k\right) \tag{10}$$

Since we believe that $x^{(k+1)}$ is a solution of equation (10), we put $f_i(x^{k+1}) = 0$ and get the following system of equations:

$$f_i(x^k)+\frac{\partial f_i(x^k)}{\partial x_1}\left(x_1^{k+1}-x_1^k\right)+\frac{\partial f_i(x^k)}{\partial x_2}\left(x_2^{k+1}-x_2^k\right)+\cdots$$
$$\cdots\frac{\partial f_i(x^k)}{\partial x_n}\left(x_n^{k+1}-x_n^k\right)=0 \tag{11}$$

For values *i= 1,2,3,..n* equation (11) means a system of equations and can be written in the following matrix form:

$$Я(x^{k+1}-x^k) = -f(x^k) \tag{12}$$

or $$Я\Delta x^k = -f(x^k) \tag{13}$$

where, $Я$ – Jacobi matrix (Jacobian).

In general form for equation (12), Jacobian has the form:

$$Я = \begin{bmatrix} \frac{\partial f_1}{\partial x_1}, \frac{\partial f_1}{\partial x_2}, \cdots \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1}, \frac{\partial f_2}{\partial x_2}, \cdots \frac{\partial f_2}{\partial x_n} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \frac{\partial f_n}{\partial x_1}, \frac{\partial f_n}{\partial x_2}, \cdots \frac{\partial f_n}{\partial x_n} \end{bmatrix} \tag{14}$$

and matrices - columns for variables will be:

$$x^{k+1} = \begin{bmatrix} x_1^{k+1} \\ x_2^{k+1} \\ \cdots \\ x_n^{k+1} \end{bmatrix}; \quad x^k = \begin{bmatrix} x_1^k \\ x_2^k \\ \cdots \\ x_n^k \end{bmatrix}; \quad \mathrm{f}(x^k) = \begin{bmatrix} f\ (x_1^k) \\ f(x_2^k) \\ \cdots \\ f\ (x_n^k) \end{bmatrix} \tag{15}$$

The solution of equation (12) is found in the form

$$x^{k+1} = x^k - [Я(x^k)]^{-1}\cdot f(x); \tag{16}$$

However, in practice, the Jacobi matrix is not negatively inverted, therefore, denoting

$$\Delta x^k = x^{k+1} - x^k, \tag{17}$$

we find the solution from equation (13) using LU factorization or the Gauss method and substituting it into expression (17) we find

$$x^{k+1} = x^k + \Delta x^k \tag{18}$$

From the above sequence, the following algorithm for determining the vectors of variables follows:

1) using CBM or MKT, the equation of a given electrical circuit is determined;

2) if the system has linear equations, they are excluded, as was shown on the example of the calculation of the flail (Fig. 1);
3) numerical initial values are set $x_1^0, x_2^0, \dots\ x_n^0$;
4) substituting the initial numerical values $x_1^0, x_2^0, \dots\ x_n^0$;
5) is determined by Jacobian (I) and using (14), (15) and (16) a system of equations for unknowns is compiled Δx_k^0;
6) solving the equation (paragraph 5) using one of the above methods, determines the values of Δx_i^0 at zero approximation;.
7) from the expression $x_i^{'} = x_i^0 + \Delta x_i^0$ we determine the value $x_i^{'}$;
8) using the numerical values $x_1^{'}, x_2^{'}, x_3^{'} \dots\ x_i^{'}$ as the new initial conditions, items 4-8 are repeated again, i.e., we carry out the second iteration;
9) the iterative procedures are completed if, during the last two iteration cycles, the value of the vectors $x_1^{'}, x_2^{'}, x_3^{'} \dots\ x_i^{'}$ coincide, or do not go beyond the boundaries specified at the beginning of the values.

Consider the implementation of the Newton-Raphson algorithm for calculating the circuit (Fig. 1), if there the element g = 1 is replaced by a second diode (Fig. 2).

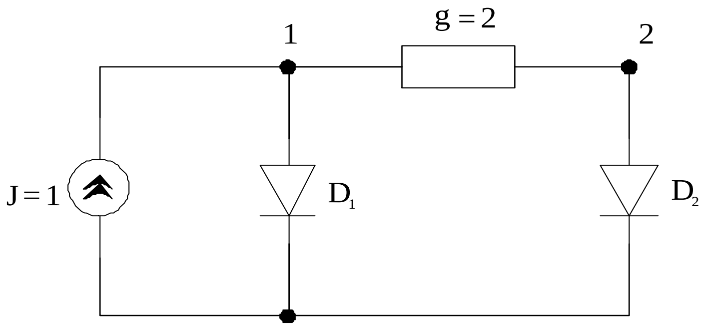

Fig.2.

Let the current of each diode, as in Fig. 1 is represented by an approximate characteristic

$$I_D = \exp(40U_D) - 1;$$

and initial approximation for stresses $U_1^0 = U_2^0 = 0{,}1$.

Using the method of nodal potentials this chain leads to the equation:

$$\begin{aligned} i_D + G(U_1 - U_2) &= j \\ G(-U_1 + U_2) + i_{D_2} &= 0 \end{aligned} \qquad (19)$$

Iteration 1. (performed in accordance with paragraphs 4-7)

Paragraph 4 - substituting the numerical values $U_1^0 = U_2^0 = 0{,}1$ in (19), we obtain the equation:

$$f_1(U_1U_2) = e^{40U_1} + U_1 - U_2 - 2 = e^4 - 2 = 54{,}5979 - 2 = 52{,}5981$$
$$f_2(U_1U_2) = -U_1 + U_2 + e^{40U_1} - 1 = 54{,}5979 - 1 = 53{,}5981$$

Paragraph 5 - define Jacobian

$$Я = \begin{bmatrix} 40e^{40U_1^0} & -1 \\ -1 & 40e^{40U_2^0}+1 \end{bmatrix} = \begin{bmatrix} 2184{,}926 & -1 \\ -1 & 2184{,}926 \end{bmatrix}$$

Based on the Jacobian obtained, we construct a system of equations with respect to ΔU_1^0 and ΔU_2^0.

$$\begin{vmatrix} 2184{,}926 & -1 \\ -1 & 2184{,}926 \end{vmatrix} \begin{vmatrix} \Delta U_1^0 \\ \Delta U_2^0 \end{vmatrix} = \begin{vmatrix} -f(V_1) \\ -f(V_2) \end{vmatrix}$$

which, corresponds to equation (13).
Paragraph 6 - open this equation and solve it

$$\begin{cases} 2184{,}929\Delta U_1^0 - \Delta U_2^0 = -52{,}5981 \\ -\Delta x_1^0 + 2184{,}929\Delta U_2^0 = -53{,}5981 \end{cases}$$

Expressing ΔU_2^0 through ΔU_1^0 from 1st equation we get

$$\Delta U_2^0 = 2184{,}929\Delta U_1^0 + 52{,}5981$$

Substituting it into the second equation, we get:

$$-\Delta U_1^0 + 2184{,}929\ (2184{,}929 \cdot \Delta U_1^0 + 52{,}5981) = -53{,}5981$$
$$-\Delta U_1^0 + 4773900{,}60 \cdot \Delta U_1^0 + 114923{,}1140 = -53{,}5981$$
$$477398{,}4 \cdot \Delta U_1^0 = -114976{,}7121$$

$$\Delta U_1^0 = -\frac{114976{,}7121}{4773900} = -0{,}02408$$

Substituting $\Delta U_1^0 = -0{,}02408$ in the second equation of the system, we obtain

$$0{,}02408 + 2184{,}929 \cdot \Delta U_2^0 = -53{,}5981$$

Where do we find

$$\Delta U_2^0 = -\frac{53{,}6221}{2184{,}929} = -0{,}02454$$

Paragraph 7 – for the 1st iteration, we determine the values of U_1' a U_2'

U_1' = 0,1 – 0,02408 = 0,07592

U_2' = 0,1 – 0,02454 = 0,07546

Thus obtained U_1' = 0,07592, U_2' = 0,07546 are the initial condition for the second iteration. The second iteration starts from paragraph 4. The Jacobian parameters change on it, since the calculated values U_1' a U_2'. The calculated data for the remaining iterations can be entered in another table.

From a comparison of the calculations of the first and second schemes, it can be seen that for the same number of nodes or loops, the equations of basic coordinates (nodal or loop equations) in which nonlinear elements are not present are excluded from the total number of equations of the systems. In this regard, the sizes of Jacobi matrices are reduced. For example, if the system of equations of a chain consisted of four equations and one of them does not contain a nonlinear element, then the size of the Jacobi matrix is one; if the nonlinear element is absent in two equations, then the size of the matrix is reduced by two.

Thus, using the example of numerical calculation of two simplest schemes with nonlinear elements, it is shown that when using the Newton-Raphson method, those equations that do not contain nonlinear elements are excluded from the system of chain equations. This helps to reduce the size of the Jacobi matrix.

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METROLOGICAL CERTIFICATION AND TEST CONDITIONS FOR VERIFICATION EQUIPMENT

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Abstract: *The article analyzes the metrological certification and test conditions for verification equipment. The main tasks of metrological certification, test conditions, accuracy characteristics of verification equipment, primary, repeated and periodic, expert and inspection certification of verification equipment are considered in the article. Besides, the major tasks of the testing equipment certification are considered as well. They are: establishing the current testing equipment eligibility in accordance with its purpose, establishing the actual reproducibility values of test conditions implemented by testing equipment and assessing the technical characteristics compliance of testing equipment with the safety, hygienic and other special requirements.*

Key words: *metrological certification, testing, certification, verification equipment, measuring instruments, metrological characteristics, conformity assessment.*

Effective cooperation with other countries, joint development of scientific and technical programs, further development of trade relations require growing mutual trust in measurement information, etc. The development of a unified approach to measurements guarantees mutual understanding, the possibility for unification and standardization of methods and measuring instruments, mutual recognition of the measurement results and product testing in accordance with the international system of commodity exchange. The Law of the Republic of Uzbekistan "On Metrology" has created the necessary legal basis for introducing significant innovations in the metrological service organization in the Republic of Uzbekistan [1].

Metrological certification of measuring instruments - is the recognition of a measuring instrument (MI) legalized for use.

The main tasks pursued in the framework of such certification include: