American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-8, Issue-7, pp-01-13
www.ajer.org
Research Paper Open Access

Algorithm of a numerical-analytical method for calculating magnetic devices of information control systems

professor R.E. Ismibeyli, E.Z.Gunbataliev
Ph.D. in engineering, associate
Ph.D in mathematics Azerbaijan Technical University
Corresponding Author: R.E. Ismibeyli

ABSTRACT: *In the paper we consider the calculation and simulation of magnetic elements of automatics by a numerical-analytical method based on the finite elements method. An algorithm and block-diagram of the program for calculating magnetic elements are given. The numerical implementation of the algorithm on a computer according to theblock-diagram of the calculation program is considered, the applications with calculations of flow distribution and determinationof error with respect to experimental data and calculation by the finite elements method (FEM) are given.*

KEYWORDS: *simulation, magnetic elements, numerical-analytical method, finite elements method, algorithm, block-diagram.*

Date of Submission: 21-06-2019 Date of acceptance: 05-07-2019

I. INTRODUCTION

Effective use of magnetic elements and devices of information control systems and computing devices [1-2] that are different in functional parameters, requires the development and implementation in practice of new computation methods of analysis and synthesis, based on the improvement of the computing device through algorithmization and creation of mathematical models that most fully reflect variety of specificity of properties of these elements.

These goals are fully met by numerical-analytical methods of analysis, that enable to formalize and algorithmize the performed calculation, reduce the number of symbols used in intermediate operations when drawing up calculation formulas and are distinguished by a strict sequence of calculation operations. The development and implementation of these methods in practice, in its turn is associated with a wider and more efficient use of the latest computer technology, which in its turn requires the development of more economical algorithms and programs.

Wide spectrum of numerical analytical methods is possible to analyze complex magnetic elements of automatics. We generalized development of numerical-analytical methods in conformity to analysis of magnetic elements of automatics on the base of the finite element method [3-7].

The finite elements method is based on the idea of approximation of a continuous function (potential) by a discrete model that is constructed on the set of piecewise continuous functions determined on a finite number of subdomains in the form of elements. A polynomial whose order is determined by the number of nodes of the elements in used as an approximating element.

If as a finite element we consider a rectangular element, it is characterized by a (simplest) polynomial of the form:

$$u_i = a_0 + a_1 y + a_2 x + a_3 xy \qquad (1)$$

Interpolational polynomial is determined from the continuity condition of a potential and its derivatives on the common bounds or in the vertices of the elements. Thus for a rectangular element with nodes of variables $u_i, \partial u_i / \partial x, \partial u_i^2 / \partial x \partial y$, the potential is determined by the coordinates x, y:

$$u(x,y)=\sum_{i=1}^{4}\varphi_1\mu_1+\varphi_2\partial u/\partial x+\varphi_{3i}\partial u_i/\partial y+\varphi_{4i}\partial u_i^2/\partial x\partial y, \qquad (2)$$

where u is a scalar magnetic potential:

$$\varphi_{1i}=\varphi_{0i}(x)\varphi_{0i}(y);\ \varphi_{2i}=\varphi_{0i}(x)\varphi_{1i}(y); \qquad (3)$$
$$\varphi_{3i}=\varphi_{1i}(x)\varphi_{0i}(y);\ \varphi_{4i}=\varphi_{1i}(x)\varphi_{1i}(y);$$

$$\varphi_{0i}(x)=\frac{(x_{i+1}-x)^2}{(x_{i+1}-x_i)}\left[1+2\left[\frac{x-x_i}{x_{i+1}-x_i}\right]\right];$$

$$\varphi_{0i}(y)=\frac{(y_{i+1}-y)^2}{(y_{i+1}-y_i)}\left[1+2\left[\frac{y-y_i}{y_{i+1}-y_i}\right]\right]; \qquad (4)$$

$$\varphi_{1i}(x)=\frac{(x_{i+1}-x)^2}{(x_{i+1}-x_i)}(x-x_i);$$

$$\varphi_{1i}(y)=\frac{(y_{i+1}-y)^2}{(y_{i+1}-y_i)}.$$

As a potential is determined by multiplying two polynomials of third degree, then it is described by the 6-th degree polynomial. The number of coefficients of the polynomial is $4\times 4=16,$ so that it is incomplete (for a complete polynomial of sixth degree, the number of coefficientsis $N=0,5(6+1)(6+2)=28$) and for finding these coefficients there are 16 conditions (by four at each vertex $u_i, \partial u_i/\partial x, \partial u_i/\partial y,\ \partial u_i^2/\partial x\partial y$).

On any of the sides of a rectangular element the potential is expressed by the third-degree polynomial and as the four values $u_i, \partial u_i/\partial x, \partial u_i/\partial y,\ \partial u_i^2/\partial x\partial y$ uniquely characterize the third degree polynomial, then the potential becomes continuous in all calculation areas.

Formation of equations by means of FEM (matrix of coefficients and matricesof the column of the right hand side) is performed in two stages: in stage I the matrices of the coefficients of separate elements are formed, in stage II –throughout the area. The system of algebraic equations (according to the finite elements method) is written based on the equation

$$div\mu_a\, gradu-\lambda_{2a}u=-\rho, \qquad (5)$$

where $\rho=div\mu_a\times\vec{H}_0$ is the bulk density of magnetic charges.

In the expression (1) the coefficients α must be connected with the potentials u in such a way as to ensure the condition of the minimum of field energy, that determines correspondence of the desired distribution of potential to Maxwell equations.

The solution of differential equation is equivalent to minimizing the energetic functional $J(u)$:

$$J(u)=\int_v \varepsilon_a\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial u}{\partial z}\right)^2\right]\partial\nabla-2\int_v \rho u\partial V. \qquad (6)$$

According to FEM the calculated area is determined by the totality of elements, therefore the energetic functional may be written as a sum of functionals

$$J=\sum_{i=1}^{m}J_i, \qquad (7)$$

where J_l is a functional of the element; l is the number of the element.

For obtaining equations associating the potential of vertices of the elements, it is necessary to substitute to the functional $J(u)$ the values $u(x,y,z)$ and calculate the derivatives $\partial J / \partial U_i$:

$$\frac{\partial J}{\partial U_i} = \sum_{i=1}^{m} \frac{\partial J_l}{\partial U_i} = 0, \qquad i = 1,2,\ldots,N. \tag{8}$$

Since are the potentials of nodes the desired potentials then the equations by the finite elements method turn to be algebraic equations associating unknown potentials.

Thus, FEMischaracterized by the type of basic functions φ_l that differ from zero by the polynomials in bounded parts of the space and by the method for determining potentials of nodes calculated from the condition of minimum of energetic functional.

An algorithm for calculating magnetic elements by FEMwe consider in the following way:

1) partition the considered magnetic element or devices into finite number of elements (areas) in the form of rectangular elements (the number of nodes $q = 4$) or in the form of triangular elements $q = 3$;

2) denote the obtained finite elements and nodes;

3) denote the coordinate system x, y, z with respect to the magnetic element or device under consideration;

4) writefor each node of the finite element an interpolational polynomial $u(x, y, z)$(1), where the number of the coefficients corresponds to the number of nodes of the finite element;

5) write for each I finite element the interpolation polynomial (2) corresponding to $K-$ nodes, i.e. obtain for each $I-$finite element a system of equations consisting of three (in the case of a triangular finite element) $K-$nodes written with respect to the potentials;

6) calculate the derivatives of the potential of the $i-$node $\partial u_i / \partial x,\ \partial u_i / \partial y$ according to the corresponding coordinates x, y and also vector derivatives $\frac{\partial^2 u_i}{\partial x \partial y} \partial^2 u_i$.

7) calculate the potential of the I element according to relation (2);

8) determine the derivative of the energetic potential J by the i nodes for every l finite element $\partial J / \partial U_i$:

$$\frac{\partial J}{\partial U_i} = \sum_{i}^{m} J_i^l,$$

where

$$J_i^l = 2\int_{v_i} \mu_{ag} \tau \frac{\partial g^\tau}{\partial u_i} dv_i; \qquad g^\tau = \left[\frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial u}{\partial z}\right],$$

$$\frac{\partial g^\tau}{\partial u_i} = \left[\frac{\partial}{\partial u_i}\left(\frac{\partial u}{\partial x}\right), \frac{\partial}{\partial u_i}\left(\frac{\partial u}{\partial y}\right), \frac{\partial}{\partial u_i}\left(\frac{\partial u}{\partial z}\right)\right].$$

The relations written throught the basic function φ_l have the form:

$$J_i^l = \sum_{i=1}^{N} K_{ik} u_k,$$

where $K_i^l = 2\int_{v_i} \mu_a \left(\frac{\partial \varphi_i}{\partial x}\frac{\partial \varphi_k}{\partial x} + \frac{\partial \varphi_i}{\partial y}\frac{\partial \varphi_k}{\partial y} + \frac{\partial \varphi_i}{\partial z}\frac{\partial \varphi_k}{\partial z}\right) dV_i.$

Having denoted I

$$I_i^{lT} = \left\lfloor I_{11}^l, I_{12}^l, I_{13}^l, \ldots, I_{1N}^l \right\rfloor \text{имеем} \left\| K^l \right\| \left\| u \right\| = \left\| I_i^l \right\|,$$

where the K^l matrix of the element l has the form:

$$K^l = \begin{bmatrix} k_{11} & k_{12} \ldots k_{1N} \\ k_{12} & k_{22} \ldots k_{2N} \\ \ldots & \ldots \quad \ldots \\ k_{N1} & k_{N2} \ldots k_{NN} \end{bmatrix}.$$

$$J_{2i}^l = \sum_{k=1}^{N} b_{ik} u_k, \quad b_{ik} = 2\int_{vl} \lambda^2 \varphi_i \phi_k dV_l, \quad \left\| I_2^l \right\| \left\| B^l \right\| = \left\| u \right\|,$$

where the B^l matrix of the element1 has the form similar to K^l

$$I_{3i}^l = -2\int_{v1} \rho \phi_I dV_l = C_i, \quad C^{IT} = \left[C_1, C_2, C_3, \ldots, C_N \right]$$

$$I_{ui}^l = -2\int_{v1} \mu_a f \phi_i dS_l = d_i.$$

Thus, calculating the above relations, we determine the elements K_{ik}, b_{ik}, C_i, d_i corresponding to the matrices $\left\| K_{ik}^l \right\|, \left\| B^l \right\|, \left\| C^l \right\|, \left\| D^l \right\|;$

9) calculate full matrices of the magnetic element under consideration :

$$K = \sum_{l=1}^{M} K^l + \sum_{l=1}^{M} B^l; \; F = \sum_{l=1}^{M} f^l = \sum_{l=1}^{M} C^l + \sum_{l=1}^{M} D^l,$$

where f^l is a matrix-column independent of the desired potentials and determined by the external sources of density ρ and second kind boundary conditions given on the sides of the element

$$\sum_{l=1}^{M} \frac{\partial J_l}{\partial u_l} = \left\| K \right\| \left\| u \right\| = \left\| F \right\|;$$

10) calculate magnetic flux for each $i-$th element according to the relation

$$\phi_l = \oint \bar{A} \, d\bar{l},$$

where $\bar{A}$ vector magnetic potential is calculated according to the expression

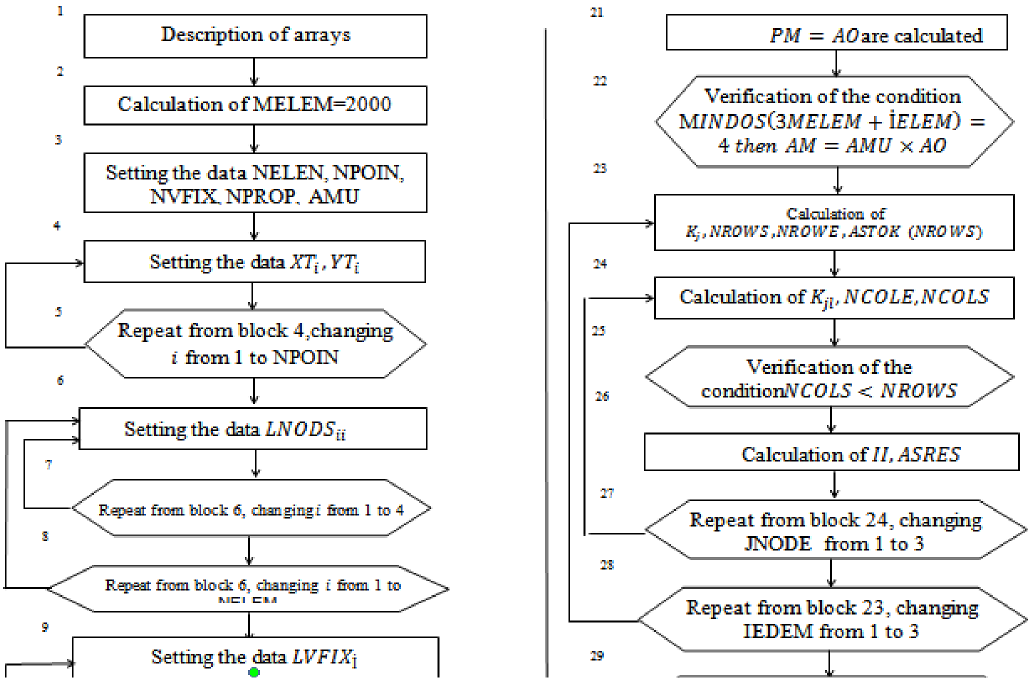
$$\frac{\partial}{\partial x}\left(\frac{1}{\mu_a} \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu_a} \frac{\partial A}{\partial y} \right) = J.$$

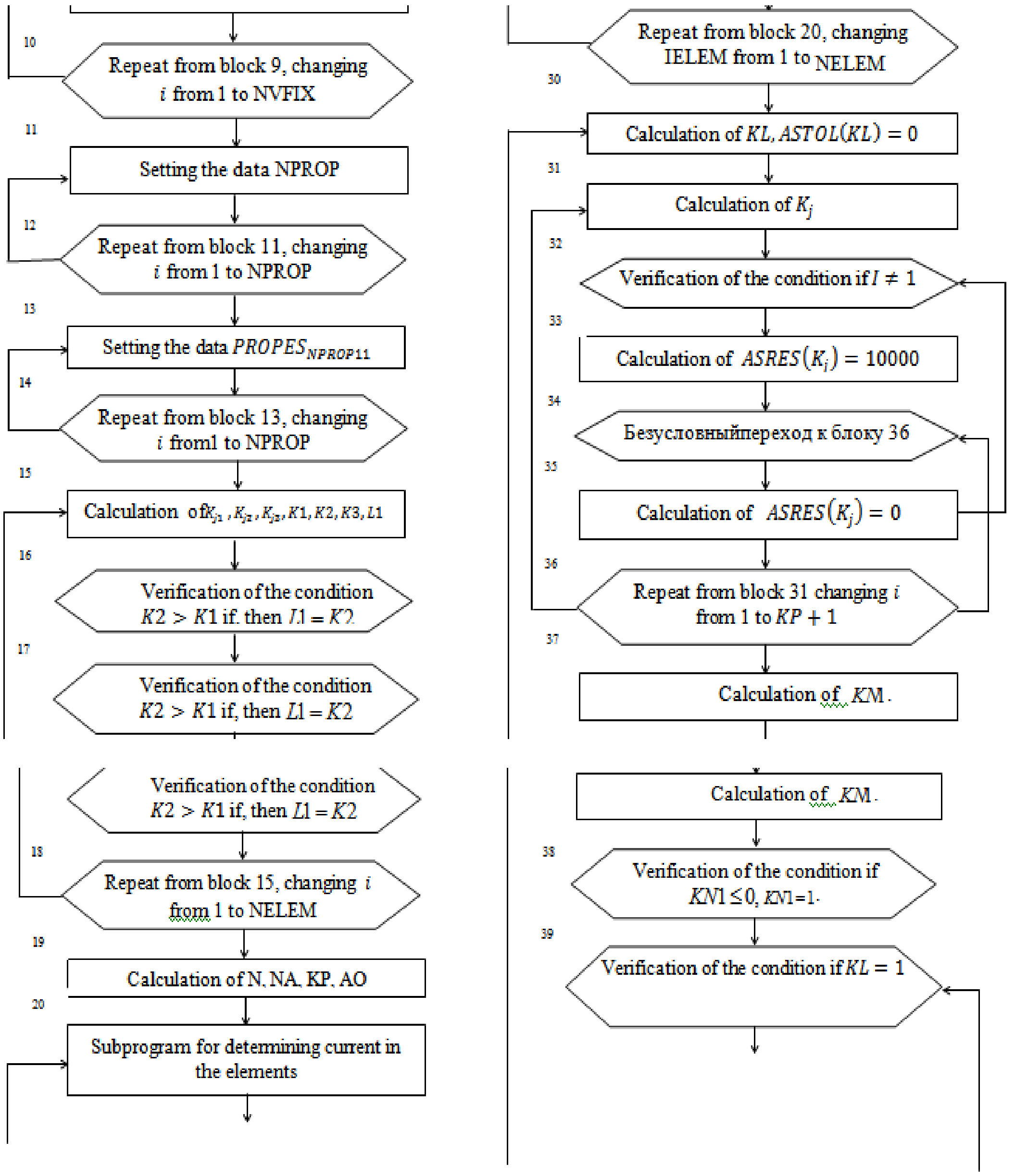
According to the given algorithm the calculated magnetic element or device is partitioned into finite number of rectangular elements. For comparison, the magnetic elements and devices of FEMare calculated in two versions. In the first version the $i-$th topological areas of magnetic elements and devices are considered as finite rectangular elements. In the second version each $i-$thtopological area of the considered magnetic elements and devices is partitioned into 3 ... 5 rectangular elements depending on the linear sizes.

The formed system of algebraic equations is solved by the square root method drawn-up in the form of two subprograms. Implementation of the program requires $N(m+l)+3lN$ units of computer memory (N is the number of nodes, m is maximum difference between the numbers of the nodes of the element).

Having splinted the calculated area into rectangular elements, it is necessary to number them and this time the numbers of neighboring nodes should be minimal. The calculation program contains: 1) the number of elements; 2) the number of nodes, including boundary ones; 3) the number of boundary nodes with boundary conditions; 4) the number of elements with sources (currents); 5) the value of the relative magnetic permeability; 6) coordinates of nodes given in the order of numbering of nodes, starting from the first number; 7) two-dimensional array where the first number denotes the number of the element, the three subsequent ones the numbers of the nodes of the elements starting from any counterclockwise one, the last one is sign (0if the element is in the air, 3if the element is in the magnetic core); 8) the numbers of elements with sources; 9) the current density in the elements where it does not equal to zero; 10) the approximating function $B(H) - aHb(1 + cH)$ is introduced for electrical steel ЭА-1, where $a = 0{,}99483,\ b = 123398,\ c = -0{,}000092.$

Implementation of the program for calculating magnetic elements and devices is performed according to the block-diagram was depicted in Figure 1. The description of the given block-diagram of the calculation program has the following form:




10
Repeat from block 9, changing i from 1 to NVFIX
11
Setting the data NPROP
12
Repeat from block 11, changing i from 1 to NPROP
13
Setting the data $PROPES_{NPROP11}$
14
Repeat from block 13, changing i from1 to NPROP
15
Calculation of $K_{j1}, K_{j2}, K_{j3}, K1, K2, K3, L1$
16
Verification of the condition $K2 > K1$ if, then $L1 = K2$
17
Verification of the condition $K2 > K1$ if, then $L1 = K2$
Verification of the condition $K2 > K1$ if, then $L1 = K2$
18
Repeat from block 15, changing i from 1 to NELEM
19
Calculation of N, NA, KP, AO
20
Subprogram for determining current in the elements
Repeat from block 20, changing IELEM from 1 to NELEM
30
Calculation of $KL, ASTOL(KL) = 0$
31
Calculation of K_j
32
Verification of the condition if $I \neq 1$
33
Calculation of $ASRES(K_j) = 10000$
34
Безусловныйпереход к блоку 36
35
Calculation of $ASRES(K_j) = 0$
36
Repeat from block 31 changing i from 1 to $KP + 1$
37
Calculation of KM.
Calculation of KM.
38
Verification of the condition if $KN1 \leq 0$, $KN1$=1.
39
Verification of the condition if $KL = 1$

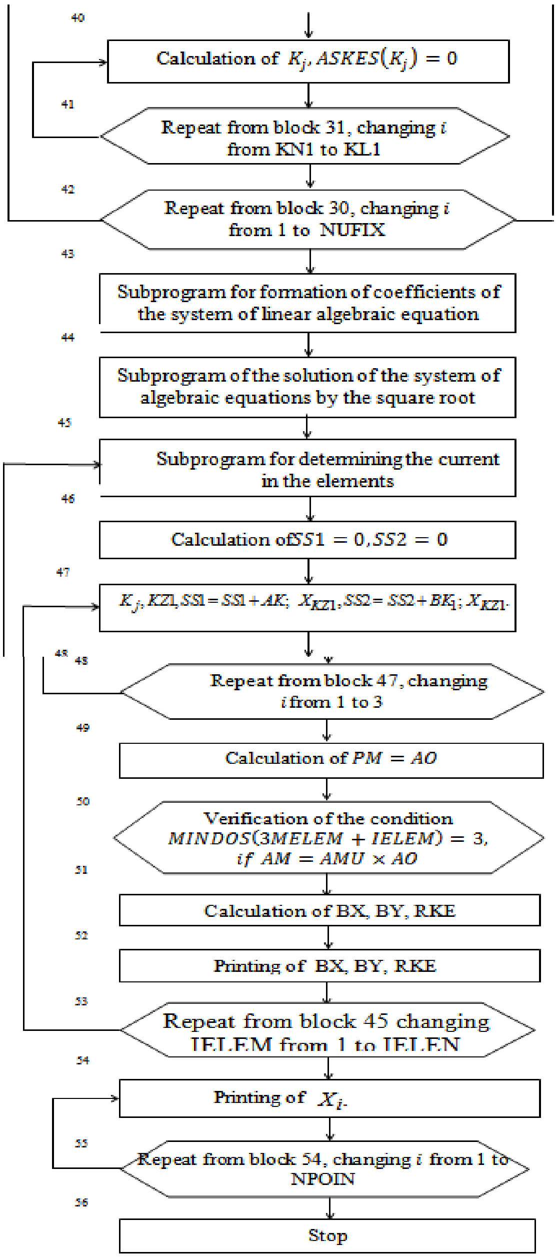


Fig. Block-diagramm for calculating magnetic elements and devices by FEM

1. The arrays: $MNODS, XT, YT, ESRES, AK, BK, CK, PROPES, ASTOK,$ $ASRES, PVFIX, D, LNODS, X, NPROP1$ are described.

2. $MELEM = 2000$ is calculated.

3. The following initial data ue introduced: $NELEN$ is the number of elements; $NPOIN$ is the number of nodes, including boundary ones; $NVFIX$ is the number of boundary nodes with first order boundary conditions; $NPROP$ is the number of elements with current sources; AMU isthe value of the relative magnetic permeability.

4. Thecoordinatesofthenodes XT_i, YT_i, given in the numbering order starting from the first number are set.

5. Organization of the cycle for setting coordinates XT_i, YT_i (4) changing i from 1 up to $NPOIN$ through 1.

6. Setting $LNODS_{ji}$ the two-number array where the first number denotes the numberof the element, the three subsequent ones the number of the nodes of the element, starting from any counterclockwise one, the last is sign (0, if the element is in the air, 3, if the element is in the iron).
7. Organization of the cycle for setting $LNODS_{ji}$, changing i from1 to $NPROP$ through 1.
8. Organization of the cycle for setting $LNODS_{ji}$ (6) changing the i from 1to the number of the elements of the array $NELEM$ through 1.
9. Setting $LVFIX_i$ the number of the nodes lying on the boundaries with first kind conditions.
10. Organization of the cycle for setting $LVFIX_i$ (9) changing i from 1 to $NPROP$ through 1.
11. Setting $NPROP$ 1 the number of the elements with sources.
12. Organization of the cycle for setting $NPROP_i 1$ changing i from 1to $NPROP$ through 1.
13. Setting $PROPES_{NPROP11}$ current density in the elements where it does not equal zero.
14. Organization of the cycle for setting $PROPES$ (13) changing i from 1 to $NPROP$ through 1.
15. $K_{jl}, K_{j2}, K_{j3}, K1, K2, K3, L1$ are calculated.
16. Verification of the condition $K2 > L1$, if it is fulfilled, then $L1 = K2$.
17. Verification of the condition $K3 > L1$, if it is fulfilled, then $L1 = K3$.
18. Organization of the calculation cycle /15-17/ changing i from 1 to $NELEM$ through 1.
19. N, NA, KP, AO are calculated.
20. Conversions to the subproqram where they are calculated in each element.
21. $PM = AO$ are calculated.
22. Verification of the conditions $MINDOS(3MELEM + IELEM) = 3$, if it is fulfilled, then $AM = AMU \times AO$.
23. $K_j, NROWS, NROWE, ASTOK(NROWS)$ are calculated.
24. $K_{jl}, NCOLE, NCOLS$ are calculated.
25. Verification of the conditions $NCOLS < NROWS$, if it is fulfilled, pass to block 27.
26. Calculation $II, ASRES$.
27. Organization of the calculation cycle /24-26/, changing $JNODE$ from 1 to 3 through 1.
28. Organization of the calculation cycle /23-27/, changing $IEDEM$ from 1 to3 through 1.
29. Organization of the calculation cycle /15-17/, changing $IELEM$ from 1 to $NELEM$ through 1.
30. Calculation of $KL, ASTOK(KL) = 0$.
31. Calculation of K_j.
32. Verification of the conditions $I \neq 1$ if it is fulfilled, pass to block 35.
33. Calculation of $ASRES(K_j) = 10000$.
34. Unconditional jump to block 36.
35. Calculation of $ASRES(K_j) = 0$.
36. Organization of the calculation cycle /31-35/ changing i from $KN1$ to $KP + 1$ through 1.
37. Calculation of $KN1$.
38. Verification of the conditions $KL = 1$, if it is fulfilled, then $KN1 = 1$.
39. Verification of the conditions $KL = 1$, if it is fulfilled, pass to block42.

40. Calculation of $K_j, ASKES(K_j) = 0.$
41. Organization of the calculation cycle /40/, changing i from $KN1$ to $KL1,$ through 1.
42. Organization of the calculation cycle /30-41/, changing i from 1 to $NUFIX$ through 1.
43. Conversion to the subprogram of formation of the coefficients of the system of linear algebraic equations.
44. Conversion to the subprogram for solving the system of algebraic equations by the method of square root.
45. Conversion to the subprogram for determining the current in the elements.
46. Calculation of $SS1 = 0,\ SS2 = 0.$
47. $K_j, KZ1, SS1 = SS1 + AK;\ \ X_{KZ1}, SS2 = SS2 + BK_1;\ X_{KZ1}.$
48. Organization of the calculation cycle /47/, changing i from 1 to3 through 1.
49. Calculation of $PM = AO.$
50. Verification of the condition $MINDOS(3MELEM + IELEM) = 3,$ if it is fulfilled, then $AM = AMU \times AO.$
51. Calculation of $BX, BY, RKE.$
52. Printing the values $BX, BY, RKE.$
53. Organization of the calculation cycle /42-52/, changing $IELEM$ from 1 to $IELEN$ through 1.
54. Printing the values of $X_i.$
55. Organization of the calculation cycle /54/, changing i from 1 to $NPOIN$ through 1.
56. End.

II. CONCLUSION

According to the given block-diagram of calculation program by FEM we calculate flow distribution, magnetizing force, electrical parameters of the magnetic element of the power relay (Fig. 2) with the definition of error regarding the experimental data and calculation by the method of secondary sounces (MSS) (table 1 ... 4). As shows analysis, error of flow distribution calculation by FEM is not higher than 6% and sometimes it coincides with the error of calculation MSS. If each topological area is divided into 3 ... 5 additional areas in the form of rectangulars (finite elements), then the calculation error significantly decreases and composes 3% (by magnetic flux) and to 2.2% (by magnetizing force and electrical parameters). And it should be noted that with increase of the amount of calculated areas, the volume of calculations and the spent time significantly increases. There aries necessity in addition to on-line storage device (OSD) -to use the external memory of computer. This is especially concerns MSS. Therefore, comparing the given methods in error and laber intensity, great expediency and preference of FEM for calculatingrather complex magnetic elements and devices should be noted.

REFERENCES

[1]. Rozenblatt M.A. Magnetic elements of automatics and computer engineering.M.Nauka 1974.
[2]. Bardij V.V. Magnetic elements of digitial calculating machines. M.Energia 1974.
[3]. Demirchyan K.S., Chechurin V.A. Machine calculation of electromagnetic fields. M.Vysshaya shkola 1986.
[4]. ZenkevichO., MorganK. Finite elements and approximation.M.Mir 1975.
[5]. ZenkevichO. Finite elements method in engineering. M.Mir 1975.
[6]. Baston J.P., Jabion C., Ouichand G. Numerical modeling of field distribution in stacked iron sheets finite elements. Rev.Phys.Appl. v.15, 1990.
[7]. Gard V.K., Weiss J. Finite element solution of transient eddv-curent problems in multibiv-excited magnetic systems. IEEE Trans. Magn. 1996, v.22, №5.

Appendix

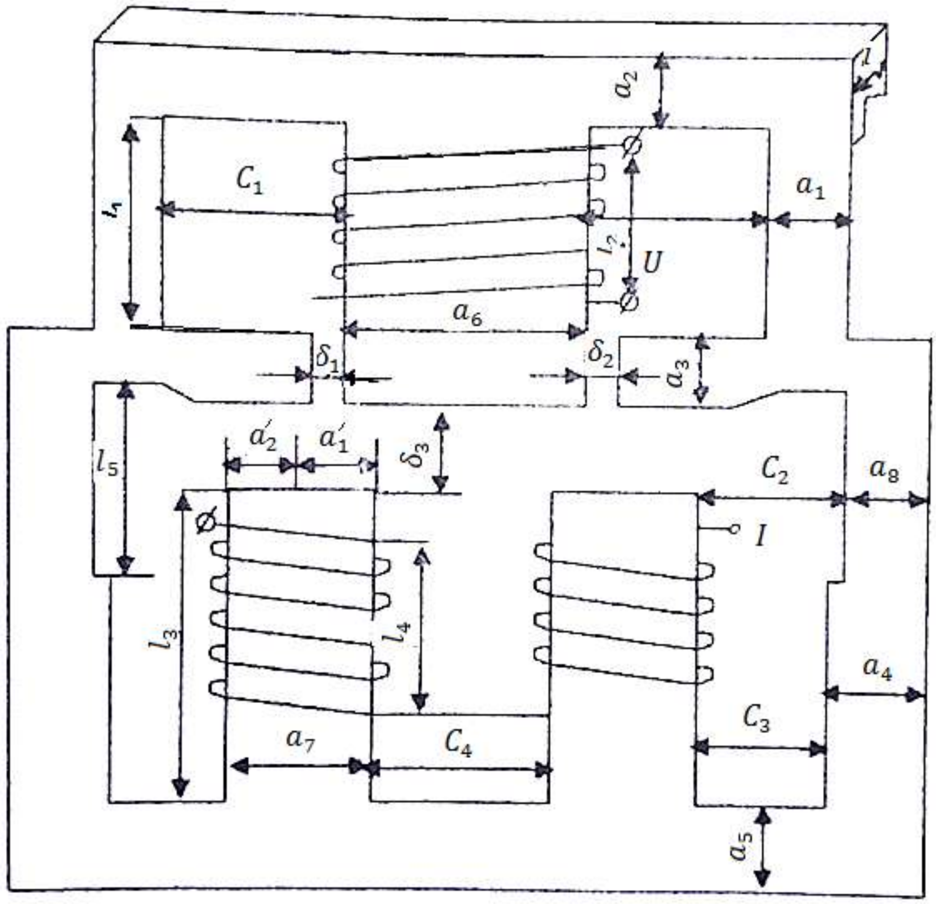


Figure 1. Block diagram of calculation of magnetic elements and devices by FEM:

$$a_1 = 1{,}2,\ a_2 = 1{,}3,\ a_3 = 1{,}1,\ a_4 = 1{,}4,\ a_5 = 1{,}2,\ a_6 = 2{,}4,\ a_7 = 1{,}5,$$
$$a_8 = 1{,}0,\ a_1' = 0{,}9,\ a_2' = 0{,}7,\ C_1 = 1{,}8,\ C_2 = 2{,}1,\ C_3 = 1{,}7,$$
$$C_4 = 1{,}8,\ l = 2{,}2,\ l_1 = 3{,}7,\ l_2 = 3{,}2,\ l_4 = 3{,}3,\ l_5 = 1{,}8,$$
$$\delta_1 = 0{,}02,\ \delta_2 = 0{,}03,\ \delta_1 = 0{,}6,$$ (sizes in cm.)

Table 1

Errors of flow distribution calculation in the areas of the power relay element (the number of areas 38).

Numberof topological areas	Experimental values of magnetic flux $\lvert\phi_i\rvert \cdot 10^{-5}, B\delta$	Calculation values of magnetic flux $\lvert\phi_i\rvert \cdot 10^{-5}, B\delta$		Calculation errors $\lvert\phi_{эксп}\rvert - \lvert\phi_{расч}\rvert / \lvert\phi_{эксп}\rvert, 100\%$	
		by MSS	by FEM	by MSS	by FEM
1	4,473	4,471	4,739	-5,992	-5,947
2	5.154	5,062	5,106	3,489	2,650
3	3,768	3,967	3,885	-5,281	-3,105
4	3,617	3,798	3,793	-5.004	-4,866
5	3,820	3,661	3,674	4,162	3,822
6	4,365	4,215	4.227	3,436	3,162
7	9,213	9,585	9,579	-4,038	-3,973
8	4,255	4,094	4,215	3,101	0,273
9	3,586	3,475	3,588	3,095	-0,056
10	3,652	3,871	3,850	-5,997	-5,422
11	3,661	3,784	2,777	-3.360	-3,169
12	4,905	4,665	4,689	4,893	4,404
13	4,663	4,396	4,415	5,115	4,705
14	1,509	1,607	1,599	-6,494	-5,964

15	2,483	2,667	2,355	5,783	3,404
16	2,235	2,380	2,369	-6,488	-5,996
17	2,007	2,137	2,073	-6,477	-3,288
18	3,983	3,725	3,475	6,478	5,975
19	1,184	1,260	1,255	-6,419	-5,997
20	0,906	0,855	0,858	5,529	5,298
21	2,122	2,249	2,247	-5,985	-5,291
22	3,755	3,612	3,638	3,808	3,116
23	0,959	0,905	0,907	5,631	5,442
24	1,114	1,051	1,078	5,655	3,232
25	1,817	1,927	1,926	-6,054	-5,999
26	2,135	2,065	2,070	3,279	3,044
27	2,208	1,065	2,077	6,476	5,933
28	1,626	1,539	1,547	5,251	4,859
29	0,251	0,235	0,239	6,375	4,781
30	0,254	0,238	0,240	6,299	5,512
31	0,220	0,206	0,212	6,364	3,536
32	0,218	0,204	0,211	6,422	3,211
33	0,202	0,195	0,194	3,435	3,960
34	0,179	0,172	0,173	3,911	3,352
35	0,262	0,273	0,271	-4,198	-3,435
36	0,280	0,269	0,270	3,929	3,571
37	0,177	0,185	0,184	-4,520	-3,955
38	0,175	0,168	0,169	4,000	3,429

Table2

Errors of calculation of magnetizing force and electric parameters of magnetic power relay element (the number of areas 38).

Name of quantities	Experimental data	Calculation data		Calculation errors, %	
		by MSS	by FEM	by MSS	by FEM
Stress coil					
Magnetizing of force F_{ku}, A	165,6	157,2	157,4	5,072	4,952
Magnetizing current $I_u, 10^{-3}, A$	27,6	29,1	28,9	-5,435	-4,710
Consumed power P_{rU}, B_T	3,5	3,309	3,315	5,457	5,286
Phase shift between current and stress $\varphi(0)$, degree	$79^0 15'$	$76^0 11'$	$76^0 45'$	3,870	3,155
Current coil					
Stresses in clamps of coil U_1, B	0,186	0,197	0,195	-5,819	-4,839
Consumed power P_{rU}, B_T	0,506	0,489	0,483	5,336	4,545
Phase shift between current and stress $\varphi(1)$, degree	$57^0 5$	$55^0 10'$	$55^0 20'$	4,611	4,323

Tale 3

Errors of calculation of flow distribution in areas of the magnetic power relay element (the number of areas 142).

Numberof topological areas	Experimental values of magnetic flux $\lvert\phi_i\rvert \cdot 10^{-5}, B\delta$	Calculation values of magnetic flux $\lvert\phi_i\rvert \cdot 10^{-5}, B\delta$		Calculation errors $\lvert\phi_{exp}\rvert - \lvert\phi_{cal.}\rvert / \lvert\phi_{exp}\rvert, 100\%$	
		by MSS	by FEM	by MSS	by FEM
1	4,473	4,542	4,538	-1,543	-1,453
2	5,254	5,147	5,205	1,868	0,763
3	3,768	3,866	3,851	-2,601	-2,203
4	3,617	3,697	3,692	-2,212	-2,074
5	3,820	3,873	3,860	-1,387	-1,047
6	4,365	4,248	4,259	2,680	0,428
7	9,213	9,477	9,471	-2,866	-2,800
8	4,255	4,132	4,414	2,201	-2,627
9	3,586	3,487	3,478	3,649	2,761
10	3,652	3,549	3,570	2,320	2,245
11	3,661	3,726	3,714	-1,775	-1,448
12	4,905	4,764	4,788	2,875	2,385
13	4,663	4,514	4,595	2.569	0,820
14	1,509	1,537	1,531	-1,856	-1,458
15	2,483	2,365	2,379	2,994	2,420
16	2,235	2,280	2,263	-2,013	-1,253
17	2,007	2,046	2,041	-1,943	-1,694
18	3,983	3,868	3,876	2,887	2,686
19	1,184	1,152	1,167	2,703	1,436
20	0,906	0,080	0,881	2,870	2,759
21	2,122	2,174	2,162	02,451	-1,885
22	3,755	3,669	3,669	2,743	2,290
23	0,959	0,934	0,938	2,607	2,190
24	1,114	1,083	1,096	2,783	1,616
25	1,817	1,869	1,867	-2,862	-2,752
26	2,135	2,088	2,093	2,201	1,967
27	2,208	2,251	2,146	2,582	2,208
28	1,626	1,581	1,586	2,768	2,460
29	0,251	0,247	0,244	2,789	1,954
30	0,254	0,247	0,250	2,756	1,575
31	0,220	0,215	0,216	2,273	1,818
32	0,218	0,212	0,214	2,752	1,835
33	0,202	0,197	0,198	1,980	1,980
34	0,179	0,174	0,175	2,793	2,235
35	0,262	0,267	0,269	-1,908	-2,672
36	0,280	0,273	0,273	2,857	2,500
37	0,177	0,182	0,181	-4,825	-2,260
38	0,175	0,172	0,172	2,286	1,714

Table 4.

Error of the calculation of magnetizing force and electric parameters of magnetic power relay element (the number of areas 142).

Name of quantities	Experimental data	Calculation values		Calculation errors, %	
		by MSS	by FEM	by MSS	by FEM
Stress coil					
Magnetizing force F_{ku}, A	165,6	151,6	161,9	2,415	2,234
Magnetizing current $I_u, 10^{-3}, A$	27,6	28,24	28,11	-2,319	-1,848
Consumed power P_{rU}, B_T	3,5	3,401	3,428	2,829	2,057
Phase shift between current and stress $\varphi(0)$, degree	$79^0 15^/$	$77^0 15^/$	$77^0 45^/$	2,524	1,893
Current coil					
Stresses in coil clamps U_1, B	0,186	0,189	0,188	-1,613	-1,075
Consumed power	0,506	0,489	0,499	1,581	1,383

P_{rU}, B_T					
Phase shift between current and stress $\varphi(1)$, degree	$57^0 15'$	$56^0 30'$	$56^0 40'$	2,305	2,017

R.E. Ismibeyli" Algorithm of a numerical-analytical method for calculating magnetic devices of information control systems" American Journal of Engineering Research (AJER), vol.8, no.07, 2019, pp.01-13