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AUTOMATION OF STUDIES OF PULSED CURRENT GENERATORS BASED ON THE TOPOLOGICAL-ISOMORPHIC MODEL

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Purpose. *To evaluate the real usefulness of the topological-isomorphic model of powerful electromagnetic circuits on the example of the study of pulse current generators.*

Methodology. *Nodal potential method, Contour current method, Topologically isomorphic transformations.*

Findings. *The mathematical apparatus created and implemented as a program in MATLAB allows solving the problems of modeling and research of electromagnetic devices in parts (by types of stored energy).This makes it possible to simplify the research and optimization of such technical characteristics as efficiency, mass-dimensional indicators, etc. The magnetic circuit is depicted in the same detail as the electric circuit, and is described by a contour matrix. The mathematical description of electromagnetic devices determines the inductive parameters due to the geometric dimensions and characteristics of the magnetic conductors. The topology of the electrical circuit is represented by matrix blocks, which allows obtaining a mathematical description that simultaneously takes into account the distribution of currents and charges in the elements of the circuit. The system of equations is reduced to the Cauchy form and is composed taking into account the increments of magnetic fluxes and potentials on capacitors, which simplifies its solution by numerical methods on a computer. Thus, it is convenient to control the energy processes in the reactive energy-consuming elements of the circuit. The paper presents an example of research of a charger of a pulse current generator with an inductive-capacitive converter. In the research example, the expected qualitative characteristics were obtained.*

Originality. *The mathematical model of electromagnetic circuits does not provide for equivalent transformations associated with the geometric configuration of magnetic conductors. The topology of the electromagnetic circuit is presented in the form of separate matrices, which are connected by a matrix of coil connections.*

Practical value. *The implemented software in the MATLAB shell uses the parameters of magnetic conductors in the form of geometric dimensions of magnetic conductors and their technical characteristics. The results of modeling a powerful electromagnetic devices allows you to estimate the accumulated energy of the electric charge in capacitors and the magnetic field in magnetic circuits and to analyze the efficiency and pos-sible impact on the environment. The presented data preparation technology allows us to investigate processes in more complex magnetic structures, for example, in magnetic flux-controlled transformers.*

Keywords: electro-magnetic circuits; topological-isomorphic model; inductive-capacitive converters; pulse current generator; static electromagnetic devices; secondary power supplies, magnetic flux-controlled transformers.

I. INTRODUTION

Pulse current generators (PCG) are secondary power sources for various technological processes. They are distinguished by high output power, so it is important to study their energy performance and characteristics. Among the loads for PCG, capacitive energy storages (CES) are often used; they are widely used in physical experiments due to a number of advantages: low internal resistance ($< 10^{-3}$ Ohm); low inductance (up to 10^{-9} H). This makes it possible to ensure a short discharge time (10^{-4}–10^{-8} s), high efficient energy transfer to the load, and the possibility of achieving record values of power (up to 10^{13} W) and current rise rate (10^{13} A/s). In addition, CES have a number of operational conveniences: the absence of moving elements, ease of maintenance, a modular design principle that allows you to turn off and easily replace elements in case of accidental damage.

Computer modeling of electrical and electronic devices still plays a special role in the design of economical and technically efficient devices for various purposes. The main requirements for models should be the greatest degree of detail and ease of obtaining model parameters.

Design automation plays a special role in the power industry and, accordingly, in power electronics [1]. The development of automation in design tools is gaining momentum [2]. The derivation, modeling and control of power converter systems [3], a review of methods for verifying control algorithms in power electronics systems are considered in the works [4]. Attention is paid to the development of a model of converter losses that takes into account the physical dimensions of components, temperature dependence and parasitics of the circuit [5]. Research on the energy efficiency of powerful installations operating at industrial facilities and other

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uses of mathematical modeling in the power industry have become very common [6].

In autonomous power systems, all devices can be divided into three groups: power sources, converters (or secondary power sources) and power consumers.

Technological devices that use electric discharge in a liquid [7] are used for drilling, crushing rocks [8], in water treatment technology for the decomposition of micropollutants [9], [10], in electric discharge plasma technology for wastewater treatment [11]. With the growing demand for energy and the associated emissions of greenhouse gases that reduce the available fossil fuels, technologies for processing heavy hydrocarbon raw materials and renewable energy sources, such as biofuels, are developing [12].

The working body of these devices are pulsed current generators (PCG), which use the energy of a charged capacitance. To charge capacitor banks, special chargers (chargers) are used that convert mains energy into high voltage energy. The efficiency and economy of the PCG as a whole depend on the circuit diagram and parameters of the charger. Therefore, increasing the efficiency factor (EF) of storage devices is a paramount task in their design.

II. ANALYSIS OF LAST RESEARCHES

The group of secondary power sources includes electronic and electrical devices that provide the conversion, accumulation and transformation of electricity into a load. Despite the different weight and size characteristics, the specifics of the circuit design and the method of energy transfer, for all secondary power supplies there are indicators that are always sought to be improved during design - these are EF, stability of external characteristics, stability during disturbances, etc.

Calculation of EF of devices is impossible without accurate calculation of energy in all elements of the circuit. The mathematical model used in this work is focused on this class of problems and is described in the following publications. In the article [13], a mathematical model of electromagnetic circuits with the highest degree of detail of both the electric and magnetic circuits was developed. The magnetic circuit is presented in the same detail as the electric one, and is described by a contour matrix. A mathematical description of electromagnetic devices was obtained, in which the inductive parameters are determined by the geometric dimensions and characteristics of the magnetic cores. The topology of the electric circuit is represented by matrix blocks, which made it possible to obtain a mathematical description that simultaneously takes into account the distribution of currents and charges in the circuit elements. In the work [14], the system of equations was reduced to the Cauchy form, which simplifies its solution by numerical methods on electronic computers. A stable mathematical model of electromagnetic circuits with feedback in matrix form [15, 16], convenient for implementation on digital computers, has been developed. The model is constructed with respect to the increments of magnetic fluxes and potentials on capacitors.

The mathematical model of electromagnetic circuits (EMC), described in [16], is presented in the following form:

$$\begin{bmatrix} h^{-1}WY_{\rho}W^{t}+z^{-1}\Gamma_{m}R_{m}\Gamma_{m}^{t} & -z^{-1}WY_{\rho}A_{\varepsilon\rho}^{t} \\ -h^{-1}A_{\varepsilon\rho}Y_{\rho}W^{t} & h^{-1}A_{\varepsilon}CA_{\varepsilon}^{t}+z^{-1}A_{\varepsilon\rho}Y_{\rho}A_{\varepsilon\rho}^{t} \end{bmatrix}\times$$

$$\times\begin{bmatrix} \Delta\Phi \\ \Delta V_{\varepsilon} \end{bmatrix}=\begin{bmatrix} WY_{\rho}\left(A_{\varepsilon\rho}^{t}V_{\varepsilon}+E\right)-F(\Phi) \\ -A_{\varepsilon\rho}Y_{\rho}\left(A_{\varepsilon\rho}^{t}V_{\varepsilon}+E\right) \end{bmatrix}, \qquad (1)$$

where

$\varPhi$ - vector of magnetic fluxes in magnetic circuits;

V_{ε} - vector of electrical potentials on capacitors;

E - column vector of electromotive forces (EMF);

C - matrix of capacities of the electrical part of the circuit;

Y_{ρ} - conductance matrix of the electrical part of the circuit;

W - matrix of coiled engagements [13];

R_m - diagonal matrix of magnetic resistances;

$\varGamma_m$ - the incidence matrix of the magnetic part of the circuit;

$F(\varPhi)=\varGamma_{m}R_{m}\varGamma_{m}^{t}\varPhi$;

h - integration step.

Matrix A is represented by a set of blocks described in [16]:

$$A=\begin{vmatrix} A_{\varepsilon} & A_{\varepsilon r} \\ A_{o} & A_{r} \end{vmatrix},$$

where matrix blocks are:

A_{ε} – Incident Matrix of incoming branches of the graph of the capacitive part of the electronic circuit;

A_{o} – Incident Matrix of outgoing branches of the graph of the capacitive part of the electronic circuit;

A_{cr} – Incident Matrix, where the resistive branches are incident with the capacitive;

A_{r} – Incident Matrix, where the resistive branches are not incident with capacitive branches.

Relatively $\Delta\Phi$ and ΔV_{ε} system (1) can be solved by any numerical method. Varying the value z, we can change the methods of numerical integration [16].

III. FORMULATION OF THE WORK PURPOSE

The main purpose of this work is to demonstrate the application of the matrix-topological model (1), described in [13]-[16], to the study of pulsed current generators containing massive magnetic parts of the circuit.

IV. EXPOUNDING THE MAIN MATERIAL AND RESULTS ANALYSIS

Among all types of chargers, circuits with inductive-capacitive converters (ICCs) make it possible to obtain the maximum efficiency and, in the case of high ohmic resistance of the charging circuit, are optimal [7].

Let's consider the scheme of the charger with the ICC, shown in Fig.1.

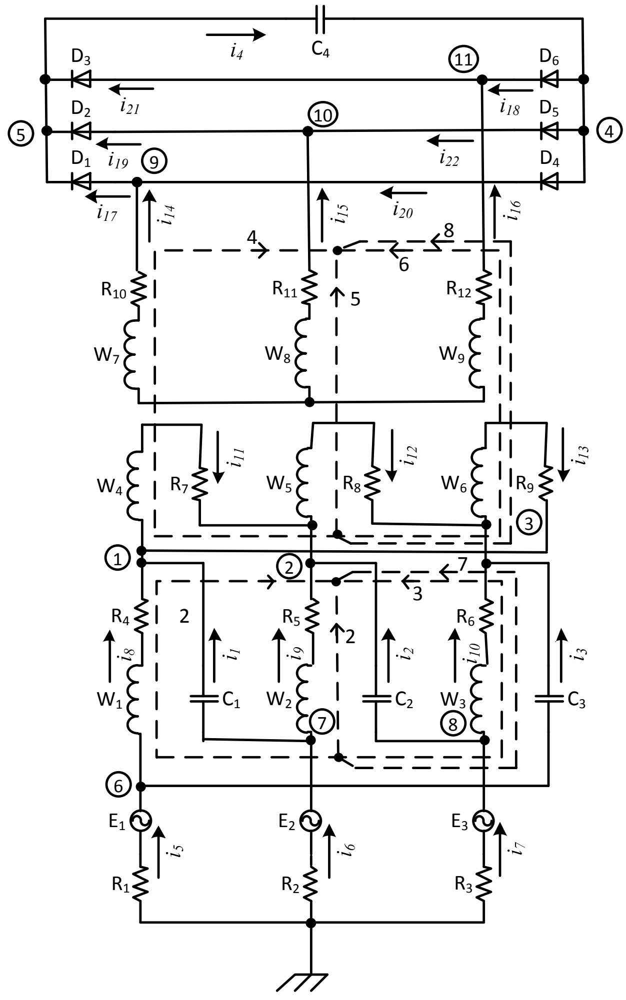
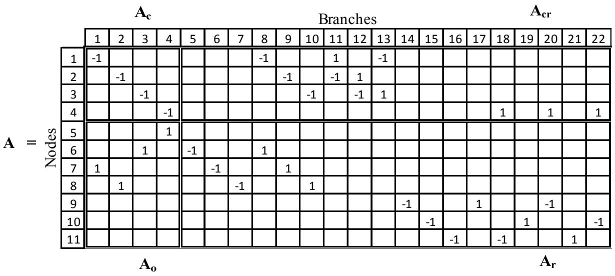


Figure 1. Electrical schematic diagram of the charger with ICC. The dotted line shows the graph of the magnetic circuit

To a three-phase alternating current network, represented by ideal sources of electromotive forces (EMF) $E_1 - E_3$ and active resistors $R_1 - R_3$, an ICC is connected, consisting of capacitors $C_1 - C_3$ and a three-phase choke. Structurally, the choke consists of a magnetic core with air gaps $\delta_1 - \delta_3$, on which windings with a number of turns $W_1 - W_3$ and active resistances $R_4 - R_6$ are mounted. A step-up transformer is connected to the output of the ICC, where - low voltage windings (LVW) and - high voltage windings (HVW). The active resistance of the LVW in the diagram (Fig.1) is $R_7 - R_9$, HVW, respectively, $R_{10} - R_{12}$. The leakage magnetic fluxes of the inductor and transformer can be taken into account by introducing additional magnetic branches (branches 7 and 8 in Fig.1).

The alternating current at the output of the transformer is rectified by semiconductor diodes $D_1 - D_6$ and used to charge the capacitive energy storage C_4.

The graph of the electric circuit of the charger (Fig. 1) consists of 11 nodes and 22 branches and is represented by a topological matrix A (see Fig. 2).



Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	-1							-1			1		-1									
2		-1							-1		-1	1										
3			-1							-1		-1	1									
4				-1														1		1		1
5				1																		
6			1		-1			1														
7	1					-1			1													
8		1					-1			1												
9														-1			1			-1		
10															-1				1			-1
11																-1		-1			1	

Branches

Figure 2. Incident matrix for a charger circuit with an ICC

According to the number of capacities, 5 branches and 5 nodes belonging to the capacity subgraph are separated into a separate block A_ε. The remaining branches and nodes make up a resistive subgraph (block A_ρ).

The graph of the magnetic circuit is shown in Fig. 3. The branches are numbered in accordance with Fig. 1.

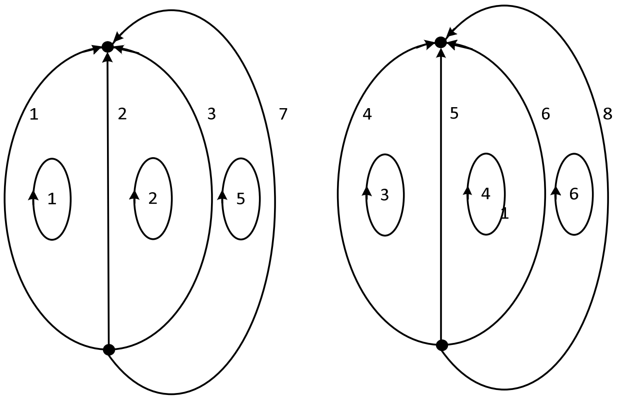


Figure 3. Graph of the contour matrix of the magnetic circuit

The directions of the contours of the magnetic circuit were chosen and the contour matrix G_m was compiled (Fig. 4).

The magnetic connection between the electric and magnetic graphs is provided by a matrix W (Fig. 5).

We begin the work of the charger model under the following initial conditions: the voltage on all capacitors, the currents and magnetic fluxes in all branches are equal to zero.

$$\mathbf{G_m} = \begin{array}{cc|cccccccc} & & \multicolumn{8}{c}{\text{Magnetic branches}} \\ & & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ \hline \text{Magnetic circuits} & 1 & 1 & -1 & & & & & & \\ & 2 & & 1 & -1 & & & & & \\ & 3 & & & & 1 & -1 & & & \\ & 4 & & & & & 1 & -1 & & \\ & 5 & & & 1 & & & & -1 & \\ & 6 & & & & & & 1 & & -1 \end{array}$$

Figure 4. Contour matrix of the magnetic circuit

$$\mathbf{W} = \begin{array}{cc|cccccccccccccccccc} & & \multicolumn{18}{c}{\text{Resistor branches}} \\ & & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 & 18 \\ \hline \text{Resistor nodes} & 1 & & & & W_1 & -W_2 & & & & & & & & & & & & & \\ & 2 & & & & & W_2 & -W_3 & & & & & & & & & & & & \\ & 3 & & & & & & & W_4 & -W_5 & & W_7 & -W_8 & & & & & & & \\ & 4 & & & & & & & & W_5 & -W_6 & & W_8 & -W_9 & & & & & & \\ & 5 & & & & & & W_3 & & & & & & & & & & & & \\ & 6 & & & & & & & & & W_6 & & & W_9 & & & & & & \end{array}$$

Figure 5. Matrix of mutual contours

During the operation of the charger, the charging current is parametrically stabilized by the phenomenon of voltage resonance in the ICC, and is independent of the capacitor bank voltages C_4. To ensure that the voltage on the capacitance C_4 grows linearly (Fig. 6) due to the constant charge current (Fig. 7), the ICC must allocate linearly increasing energy to the load.

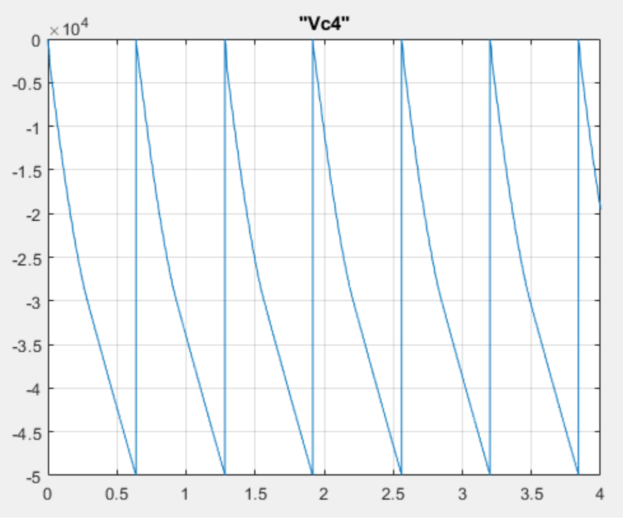


Figure 6. Voltage on the capacitance grows linearly

This is provided by a ramping current at the input of the ICC (Figure 8) and a ramping voltage at the output of the ICC (Figure 9).

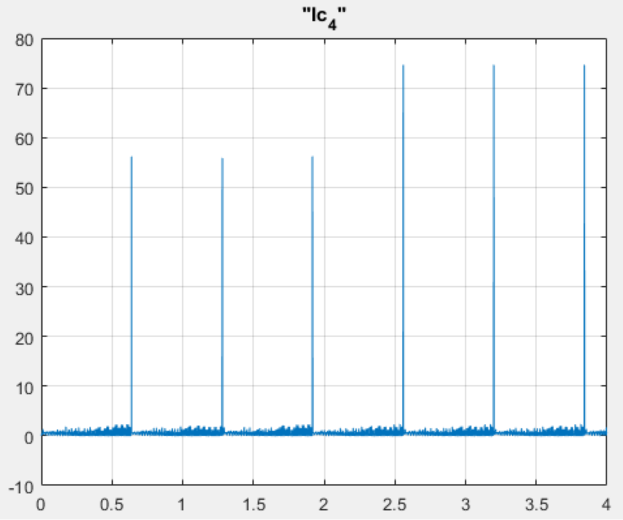


Figure 7. The constant charge current

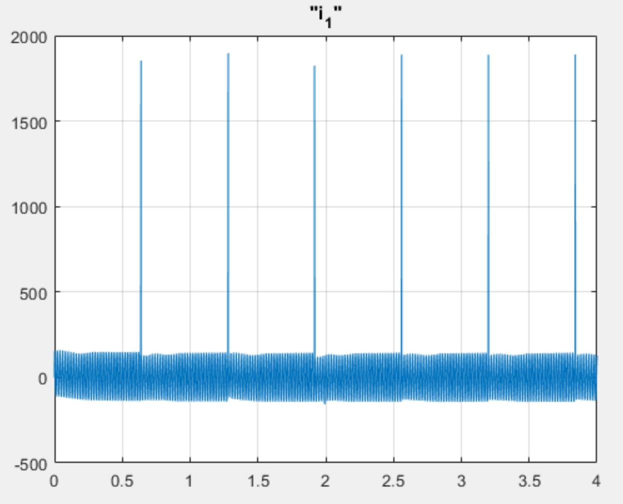


Figure 8. A ramping current at the input of the ICC

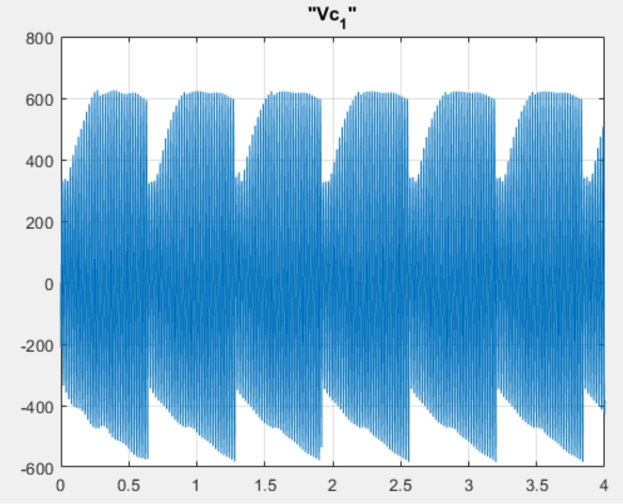


Figure 9. A ramping voltage at the output of the ICC

At the same time, the constancy of the amplitude value of the current is ensured at the output of the ICC (Fig. 10).

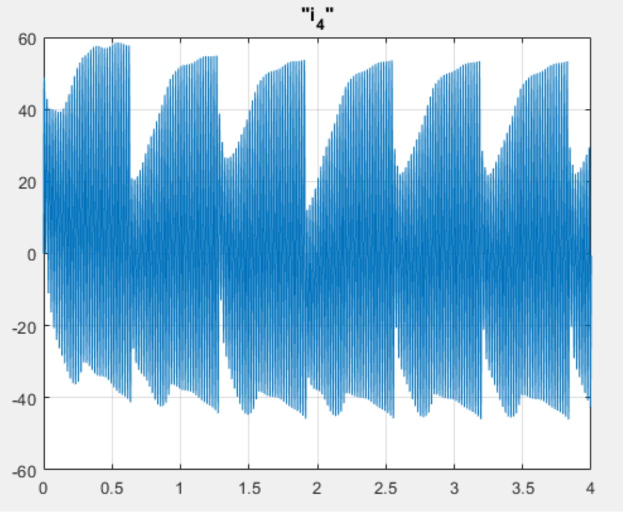


Figure 10. The current at the output of the ICC

Figure 11 shows the magnetic fluxes in the three cores of the ICC and separately the magnetic flux of leakage on it.

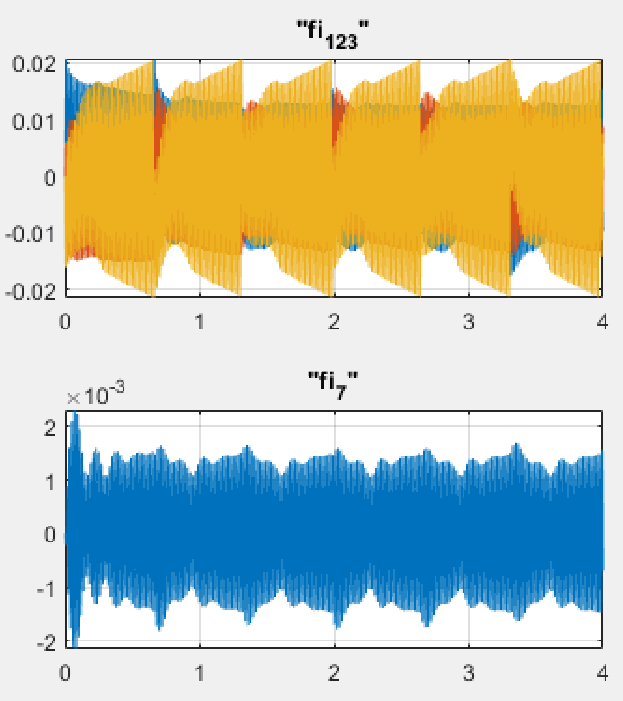


Figure 11. Magnetic fluxes acting in the magnetic cores of the ICC (fi_{123}) and in external space (fi_7)

Efficiency calculation. The efficiency is calculated as follows:

$$\eta = \frac{W_{C4}}{W_\rho},$$

where W_{C4} is the energy accumulated in the capacitor C_4 for the entire charge time (t_z); W_ρ - active energy consumed from the network during the time t_z.

The simulation results of the ICC charger (Figure 1) can be explored with experimental tests. The efficiency of the model is 92%, according to the experiment - 90%. The result turned out to be overestimated due to the fact that the model did not take into account the hysteresis losses in the magnetic cores.

In this paper, some graphs of the process of charging the load capacity are given, however, diagrams of currents, voltages and magnetic fluxes can be obtained in all branches and nodes of the circuit. The high information content of the software makes it possible to increase the efficiency of the study of chargers, for example: to check the reliability of the simulation, to identify resonant circuits and evaluate their frequency, to investigate the effect of nonlinearities of magnetic components, etc. Modern computing tools enable the developer of complex technological devices to increase the share of creative work and improve the quality of the products being developed.

V. CONCLUSION

1. The developed software (software), compiled according to the mathematical model (1), successfully implements calculations for powerful technological devices with electromagnetic circuits.

2. The software simplifies the preparation of data for the model by not using preliminary calculations of the parameters of the magnetic part of the circuit.

3. The software allows you to obtain graphs of instantaneous values of voltages and currents of the transient process in all elements of the electrical part.

4. The software allows you to obtain graphs of instantaneous values of magnetic fluxes in the metal cores of electromagnetic converters and magnetic fluxes of dissipation.

5. The result of modeling a powerful electromagnetic device allows you to estimate the accumulated energy of the electric charge in capacitors and the magnetic field in magnetic circuits and to analyze the efficiency and possible impact on the environment.

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АВТОМАТИЗАЦІЯ ДОСЛІДЖЕНЬ ГЕНЕРАТОРІВ ІМПУЛЬСНОГО СТРУМУ НА ОСНОВІ ТОПОЛОГІЧНО-ІЗОМОРФНОЇ МОДЕЛІ

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Мета роботи. *Оцінити реальну корисність топологічно-ізоморфної моделі потужних електромагнітних кіл на прикладі дослідження генераторів імпульсного струму.*

Методи дослідження. *Метод вузлових потенціалів, Метод контурних струмів, Топологічно-ізоморфні перетворення.*

Отримані результати. *Створений і програмно реалізований математичний апарат у MATLAB дозволяє* *вирішувати задачі моделювання та дослідження електромагнітних пристроїв по частинах (за видами накопиченої енергії). Це дає змогу спростити дослідження та оптимізацію таких технічних характеристик, як коефіцієнт корисної дії, масогабаритні покажчики тощо. Магнітопровід зображується так само детально, як і електрична схема, і описується контурною матрицею. Математичний опис електромагнітних пристроїв визначає індуктивні параметри, обумовлені геометричними розмірами, характеристиками магнітопроводів та обмоточними даними. Топологія електричного кола представлена матричними блоками, що дозволяє отримати математичний опис, який одночасно враховує розподіл струмів і зарядів в елементах електричного кола. Система рівнянь приведена до форми Коші та складена з урахуванням приростів магнітних потоків і потенціалів на конденсаторах, що спрощує її розв'язування чисельними методами на електрообчислювальних машинах. Таким чином, зручно контролювати енергетичні процеси в реактивних енергоспоживаючих елементах схеми. Розроблене програмне забезпечення (ПЗ) за представленою математичною моделлю, успішно реалізує розрахунки для потужних технологічних пристроїв з електромагнітними ланцюгами. ПЗ спрощує підготовку даних до моделі за рахунок не використання попередніх розрахунків параметрів магнітної частини кола, дозволяє отримати графіки миттєвих значень напруг і струмів перехідного процесу в усіх елементах електричної частини, дозволяє отримати графіки миттєвих значень магнітних потоків в металевих сердечниках електромагнітних перетворювачів та магнітних потоків розсіювання. У роботі наведений приклад дослідження зарядного пристрою генератора імпульсного струму з індуктивно-ємнісним перетворювачем. У прикладі дослідження були отримані очікувані якісні характеристики.*

Наукова новизна. *Математична модель електромагнітних кіл не передбачає еквівалентних перетворень, пов'язаних з геометричною конфігурацією магнітопроводів. Топологія електромагнітного кола представлена у вигляді окремих матриць, які з'єднані матрицею з'єднань котушок.*

Практична цінність. *Реалізоване програмне забезпечення в оболонці MATLAB використовує параметри магнітопроводів у вигляді геометричних розмірів магнітопроводів та їх технічних характеристик. Результати моделювання потужних електромагнітних пристроїв дозволяють оцінити накопичену енергію електричного заряду в конденсаторах і магнітне поле в магнітопроводах, проаналізувати коефіцієнт корисної дії і можливий вплив на навколишнє середовище. Представлена технологія підготовки даних дозволяє досліджувати процеси в більш складних магнітних конструкціях, наприклад, як в трансформаторах, що керуються магнітним потоком.*

Ключові слова: електромагнітні кола; топологічно-ізоморфна модель; індуктивно-ємнісні перетворювачі; генератор імпульсного струму; статичні електромагнітні пристрої; вторинні джерела живлення; трансформатори з керуванням магнітним потоком.