UDC 621.314.283 https://doi.org/10.20998/2074-272X.2022.3.05

K.M. Vasyliv

Method of dynamic parameters for mathematical modelling of switching processes of valves closing of semiconductor converters

A method has been developed for mathematical modeling of valve frequency converters (VFC) based on an analysis of the nature of the occurrence and patterns of the flow of inverse current of valves when they are locked using the dynamic parameters of valves, which are series-connected inductance and active resistance, changing in accordance with the pattern of concentration dynamics charges in semiconductor structures (bases, emitters and p-n junctions. Taking into account the presence of the inverse current of semiconductor valves significantly increases the level of adequacy of mathematical modeling of VFCs of arbitrary structure and purpose and in arbitrary modes of their operation, including asymmetric and emergency transient electromagnetic processes of electrotechnical complexes with VFCs, not only during the time interval of switching (closing) of valves, but throughout the entire time modeling. References 21, figures 9.

Key words: **valve, switching, inverse current, adequacy level, mathematical model, software code.**

Розроблено метод математичного моделювання вентильних перетворювачів частоти (ВПЧ) на підставі аналізу природи виникнення і закономірностей протікання інверсного струму вентилів під час їх запирання застосуванням динамічних параметрів вентилів, якими слугують послідовно з'єднані індуктивність та активний опір, що змінюються відповідно до закономірності динаміки концентрації носіїв електричних зарядів в структурах напівпровідників (базах, емітерах та p-n переходах). Врахування наявності інверсного струму напівпровідникових вентилів істотно підвищує рівень адекватності математичного моделювання ВПЧ довільної структури і призначення та в довільних режимах їх роботи включно з несиметричними та аварійними перехідними електромагнітними процесами електротехнічних комплексів з ВПЧ не лише на проміжку часу комутації (запирання) вентилів, але й в продовж всього часу моделювання. Бібл. 21, рис. 9.

Ключові слова: **вентиль, комутація, інверсний струм, рівень адекватності, математична модель, програмний код.**

Introduction. One of the research and practical directions of development of Electrical Engineering, called «Electronics», allowed to develop a number of electronic semiconductor devices, based on which a long list of various valve frequency converters (VFCs), which serve as switches for regulated electric drives based on electric [1], alternators [2], autonomous power supply systems [3] and even in multi-winding transformers for simultaneous connection of its secondary windings in the power supply circuit [4]. VFCs are also used in electrical equipment of many other types, for example, in discharge-pulse systems of special technological processes, in particular, the treatment of granular conductive media [5] and so on. The use of VFC as part of electrical equipment has made it possible to fundamentally increase its functionality.

The creation and improvement of valve converter technology is characterized by three main areas: the development of circuit solutions, the definition of static and dynamic characteristics and the study of basic energy relationships. The first direction is characterized by the development of hypothetical models, which are created on the basis of analytical methods using switching functions. A clear expression of this stage are the works [6, 7], which relate to direct frequency converters, but this also applies to other converters (rectifiers, inverters, frequency converters with a DC link, etc.).

Simultaneously with the development and implementation of VFCs, there is a need for mathematical modelling of electromagnetic processes occurring in these converters in order to improve both the systems they belong to and VFCs itself. It is fundamentally important to note that hypothetical models such as [6, 7] do not allow to model VFC processes.

Judging by the large number of research works aimed at solving the problem of mathematical modelling of VFCs, it turned out to be so complex that the problem of its solution remains relevant today, despite the fact that significant positive results have been clearly achieved.

Today, two approaches are used in the practice of mathematical modelling of VFCs. The first one involves the use of «ready-made» complexes and simulation environments. The MATLAB/Simulink software package has become so widely used, as evidenced by its use are in [8-11]. The same approach should include the use of special boards, for example, in [12] a developing board EPC9035 is used, which is a module of the half-bridge converter, and it was developed by Power Conversion. It is logical to include the software package MotorSolve [13]. It is important to note that in [13] it is emphasized that the models and algorithms embedded in the MotorSolve software are closed to the user, which significantly limits the ability to assess the level of adequacy of models. The same circumstance is typical for other software packages and simulation boards, including MATLAB/Simulink in the context of unavailability of comprehensive information on the used basic mathematical, electrical and other modelling methods, which confirms the need to develop methods and mathematical models of higher adequacy than in the available for modelling of electrical systems that contain VFCs, taking into account all the most important factors influencing the course of processes, among which is the switching of valves. Particular attention should be paid to insufficiently correct modelling in MATLAB/Simulink of valve locking, which does not take into account the occurrence and flow of inverse currents (currents of opposite direction, sign) during the recovery of valve properties for their closed state, and valves lock (in case of natural switching) immediately at the time of decay of their currents to zero.

The above-mentioned means of mathematical modelling of VFCs, including MATLAB/Simulink, are characterized by a high level of excellence in terms of their practical use. Because here the simulation is performed in the design mode by selecting and combining individual structural and functional elements into a single system, the formation of which automatically creates the appropriate program code (machine algorithm), which is also automatically generated using mathematical, electrical, mechanical or any other methods. Therefore, such modelling tools are often perceived by users as the absolute of perfection, which a priori eliminates the need to critically analyze and assess the level of adequacy of the results.

The second approach is characterized by personal development by researchers of mathematical models and even mathematical and electrical methods and on their basis algorithms and program codes. This requires a thorough knowledge of the whole spectrum from mathematical methods to physics of processes and programming and allows to understand the essence of modelling at the deepest level, and thus have information about the initial assumptions and opportunities to more accurately assess the adequacy of modelling. The position of the author of this article coincides with the second approach.

Based on the above, to substantiate the relevance of the problem to be solved by the article, and to formulate the task set in the article, we perform a brief analysis of the literature to determine the adequacy of mathematical modelling of VFCs in terms of abilities of mathematical and electrical methods used, including initial assumptions made during the development of mathematical models.

Literature analysis. From the point of view of modeling of VFC as a structural element of an arbitrary electrical (electrical power or electromechanical) system, the most effective are methods of two directions, the first of which describes electromagnetic processes by differential equations of electrical state with variable structure and constant parameters [14], and the second one is description of electromagnetic processes by differential equations of electrical state with constant structure and variable parameters.

The first group includes methods in which valves are modelled with ideal keys (S-models) [14]. A convincing advantage of S-models is that they do not need to operate with the parameters of the valves for the locked state, the value of which differs from the parameters for the conductivity state by 6-8 orders of magnitude. This avoids the scatter of parameters and, as a consequence, the rigidity of the system of differential equations and the difficulty of obtaining results in general. However, these methods have other significant drawbacks that limit the use of S-models of valves in the practice of VFC modelling. Thus, S-models provide a rupture of the valve branches for the closed state of the valves, which a priori means a change in the power circuit of the VFC, and therefore each specific state of the valves must correspond to its circuit power circuit and its corresponding differential equations system (DES). And here there are three problems. The first one is the need to form a large number of DES of electrical state (according to the full combination of all possible circuits of the VFC power circuit, based on each specific state of the valves). This problem entails a second complex problem, which is the need to form conversion functions that establish the connection of two adjacent in time limits of currents and voltages of reactive elements of the valve at the time of switching, i.e. the transition from the previous in time power circuit of the VFC to next one [14]. The process of formation of such functions is a separate task, which not only significantly complicates the mathematical model of the VFC, but also a priori reduces the level of its adequacy. The third problem is to correctly determine the timing of switching valves, because not for all VFCs, and the main for their modes of operation it is possible, for example, for dynamic and asymmetric ones.

Solving the first problem requires significant costs even for VFCs with a simple electrical circuit and it is very difficult to solve this problem when we discuss modelling of transient electromagnetic processes, especially the modelling of asymmetric emergency modes, for which it is almost impossible to correctly predict all valve states. The third problem is solved by determining in advance the state of the valves, which is correct only in the case of artificial switching and only for symmetrical steady state.

Negative on the level of adequacy of key S-models of valves are also affected by ignoring the presence of reverse currents, because the concept of key models a priori excludes the presence of the electric branch of the valve in its closed state, and in terms of physics of process in semiconductor electronic devices such currents (reverse ones) are available.

Known mathematical models, which are based on the formation of a system of differential equations of the electrical state with a constant structure and variable parameters, allow to avoid defects of key models at fundamentally important points [15, 16].

Careful analysis of research literature sources, as well as practical experience in the field of mathematical modelling of VFCs indicates that significant theoretical and practical results in the context of mathematical modeling of electrical systems (ES) with valve frequency converters (according to the concept of their modelling using DES with constant structure and variable parameters) is achieved by combining the idea of modelling valves by separate active-inductive branches [16] with the modular principle of modelling of electrical-machine-valve systems (EMVS) [15] and inversion of DES [17]. This combination made it possible to describe the electromagnetic and electromechanical processes of arbitrary ES (with VFC of arbitrary structure and with arbitrary control system) by a single DES of electrical and mechanical equilibrium regardless of the state of the valves, which, in turn, allows to take into account mutual influences of EMVS structural elements as well as valve switching and operation of the automatic control system for arbitrary modes of operation of the EMVS (steady and dynamic ones, including symmetrical and asymmetrical, normal and emergency modes).

Let us analyze in more detail the mathematical model of the valve, in which the valve is represented by an active-inductive electric branch [15-17]. Therefore, the mathematical model of the valve as a basic structural element of VFC is developed on the basis of the following initial assumptions:

1) in the conductive state the valve is modelled by an active-inductive branch with small and as close as possible to the real values of inductance and active resistance for the conductive state of the valve;

2) in the locked state the valve is modelled by an active-inductive electric branch with high inductance and active resistance, which correspond as closely as possible to the locked state of the real valve;

3) the valves are switched instantly (the valve is opened according to the results of solving logical equations that describe the operation of the VFC control system), and the valves are closed at the time of transition through zero current of the switching valve (in case of natural switching).

The choice of the values of active resistance and inductance, which are modelled valves, in a sense is arbitrary, and the selection criterion is the highest possible level of adequacy of the model. Based on this, in the practice of VFC modeling for the conductive state we choose such small values of inductance L (L=0.1·10^{-4}) H and active resistance R (R=0.1·10^{-3}) Ω, which most closely correspond to the real the value of real valves in the conducting state, and for the closed state the values of inductance and active resistance of the valve branch are taken as those that most accurately correspond to the actual inductance and active resistance for the closed state of the valve L=0.1·10^{3} H and R=0.1·10^{4} Ω. It is critical to note that the L/R ratio (which determines the time constant) for both the conductive and closed states of the valve branch should be such that it is approximately 50 times greater than the integration step and at the same time not less than the minimum time constant of other sections of the electric circuit, the structural element of which is VFC [17].

At the time of transition of the valve to the locked state together with active resistance, also inductance increases by jump by 6-8 orders of magnitude. The consequence of such a change in inductance is the appearance of a rupture of the first current derivative due to a sudden (break type) strong change in the numerical value of the coefficient L at the current derivative in the equation of the electrical state of the valve written according to Kirchhoff second law

$$L \cdot \mathrm{p}i + R \cdot i + U = 0, \qquad (1)$$

where L, i, R, U are the inductance, current, active resistance and voltage of the valve branch, respectively; $p = \mathrm{d}/\mathrm{d}t$ is the differentiation operator in time t.

However, after switching the valves, the integral curves are smooth because the first derivative after switching is continuous, which eliminates one of the significant disadvantages of modelling valves with purely active resistance. Maintaining the time constant for the conductive and locked state of the valves constant ensures the stability of the numerical integration of the DES. Due to the sudden and large-scale change of parameters, the currents of closed valves are significantly distorted, but the values of these currents are small enough that at a certain stage of development of the theory of mathematical modeling of VFC, was considered correct to ignore them [15, 17].

Thus, the critical advantage of mathematical modelling of the valve by an active-inductive branch compared to the modelling by purely active resistance is the invariance of the valve time constant for the conducting and locked state [15-17], which provides numerical stability of DES integration that, in turn, is very important in the case of integration of long-term processes.

The necessary task of determining the time of transition of the valve current, which is locked, through zero at the switching step (moment of valve locking time) is determined by a simple procedure of DES inversion, which describes the processes (electromagnetic, electromechanical, mechanical and others) occurring in EMVS containing VFCs [17]. The essence of inversion is to integrate the entire DES at the switching step of the valve, according to its current, which becomes an independent variable, and the numerical value of the integration step is equal to the value of the switching current at the beginning of the switching step. The integration time here becomes an integral variable that is unknown and is the result of the solution of the DES. Therefore, the closing time of the valve is determined by only one step of integration during the inversion of the DES.

It should be noted that the inversion procedure is an indispensable tool for bypassing special points of integral variables, which are characterized by the presence of vertical sections of integral curves, in which the derivative is equal to infinity [17].

Despite the presence of the above rather effective methods of mathematical modelling of VFC, the method in which valves are modelled by active resistances is still used [18].

In the context of the analysis of research literature sources in general it should be noted that other known methods are still used, such as the method of adjustment [19] and the method of fundamental harmonics [20], characterized for which is the adoption of too simplistic (rough) initial assumptions with a focus on their use to calculate symmetric steady-state currents, which a priori does not allow to adequately model the course of electromagnetic processes occurring in ES with VFC in dynamic and asymmetric modes.

Problem definition. Many years of practice of mathematical modeling of EMVS on the basis of the theory described above [15-17] allowed to obtain results of a fairly high level of adequacy. But a careful analysis of the initial assumptions indicates that there is still a margin in terms of improving the adequacy of VFC mathematical models.

In real operating conditions of semiconductor frequency converters, the state of their valves (in particular, thyristors) and the course of electrical processes occurring in these valves is determined by the concentrations and gradients of positive (holes) and negative (electrons) charges in individual valve structures – emitters, collectors and p-n junctions. It is the concentration and gradients of charge carriers that change over time (restoring the properties of the thyristor for the locked state), ultimately cause a dynamic change in the resistance of the valves during their switching (e.g., locking), and hence the state of each valve.

To restore the properties of the thyristor for the locked state, it is necessary that after the passage of direct current part of the excess charges accumulated in the bases pass through the outer circuit by changing the polarity of the voltage (forward and reverse) at the thyristor electrodes under the action of which there is an inverse (reverse) current which speeds up the process of acquiring a thyristor locked state. Therefore, the state of the valve during the transition from conductive to closed ones changes under the action of reverse voltage and inverse current over a period of time, which is characterized by the presence of appropriate stages of charge concentration in the deep layers of emitters, bases and around *p-n* junctions which means that the valve current during its switching (inverse current) also changes over time according to the change in the concentration of charge carriers.

Based on this, it is obvious that the accepted initial assumption that the valve is locked at the time of transition of the current valve, which switches, to zero (instantaneous switching), is not correct enough.

The process of changing the concentration of charges in the thyristor layers during its locking, if we consider the thyristor as an element of an electric circuit according to the theory of electric circuits, manifests itself in changing (increasing) its resistance to a value equivalent to the resistance of the insulator.

The time of decline of the reverse current in the outer circuit to a certain fixed value does not mean complete restoration of the locked state of the thyristor, because in the deep layers of bases (mainly thick base) there are still excess electrons and holes, which continue to recombine. After the reverse current drops to a steady state, some more pause is required for the excess charges to disappear in the deep layers of the thick base. The total recovery time of the thyristor properties for the locked state t_V which starts from the moment of direct voltage drop across the thyristor to zero until the thyristor fully acquires the properties for the locked state, is equal to

$$t_V = t_S + t_P, \qquad (2)$$

where t_S is the time of decline of the inverse current to a fixed value; t_P is the time of disappearance of excess charges (pauses) in the deep layers of the thick base.

The pause time depends on the geometric dimensions of the thyristor layers, the lifetime of the charge carriers, as well as the rate of decline of the reverse voltage and the rate of increase of the next direct voltage applied to the thyristor. Recovery time t_V is one of the main catalog parameters of the thyristor, because of it its frequency properties depend. It is considered known.

Based on the above, **the goal of the article** is to develop a method of mathematical modelling of electrical processes occurring in valves during their locking, taking into account the restoration of their properties for the closed state, as well as the origin and regularity of inverse current in valves. The development of mathematical models of VFC based on this method will significantly increase the adequacy of mathematical models of both VFC and EMVS, which include VFC.

Substantive provisions. The above analysis of the processes occurring in the thyristor shows that when the valve is closed, first under the action of negative voltage there is an inverse current, and then due to changes in charge concentration in the bases this current decreases, which gives reason to interpret this as an equivalent increase in thyristor resistance if we consider the processes in the thyristor in terms of their external manifestations at the level of the anode-cathode electrical circuit part according to the laws of classical theory of electrical circuits. Based on the latter thesis, it seems logical and correct to consider and, accordingly, to model the switching process that occurs in the thyristor during its locking, based on the following provisions:

1) inductance and active resistance, which simulate the valve branch, dynamically increase according to a certain law, such as linear, parabolic or some other, which provides more accurate than in [16] determination of inverse valve current due to smooth change of inductance and active resistance of the valve and therefore smooth change of the first current derivative in contrast to the rapid one, as in the basic method [16];

2) as the time of the beginning of the dynamic increase of inductance and active resistance of the valve branch we take the moment at which the current of the switching valve is zero (it passes from plus to minus through zero, i.e. there is an inverse current);

3) the DES inversion procedure is performed only to determine the point in time that corresponds to the reference point of the thyristor switching process (occurrence of inverse current), and not for complete locking of the valve;

4) the time of complete recovery of the thyristor for the locked state is considered known and regulated by the technical data of the thyristor;

5) assignment of inductance and active resistance of the valve branch to a value corresponding to the locked state of the thyristor (its final locking) is performed at the time of completion of the process of restoring the properties of the valve for the locked state.

These provisions, together with those adopted in [15-17] in parts 1) and 2) and partly 3) regarding instantaneous valve opening and given above, form the theoretical basis of the method of dynamic parameters of mathematical modelling of valve frequency converters proposed here.

The need to take into account the time of locking valves is obvious not only in terms of patterns of electrophysical processes occurring in valves, but also based on the possibility of operation of a fundamentally certain type of electrical equipment based on VFC which is emphasized in the literature, in particular in [4, 10].

In one of variants, the idea proposed here was implemented in [21] during mathematical modelling of electromagnetic processes occurring in an autonomous power supply system based on an asynchronized generator with a contactless cascade modulator exciter without describing the basic theoretical positions set forth here.

The practical verification of the proposed method is performed on the example of mathematical modelling of N_F-phase AC rectification system (ACRS), a generalized diagram of the power electric circuit of which is shown in Fig. 1, where the letters A, K denote the anode and cathode N_F-phase thyristor groups; the letter M – N_F-phase of the AC network; the letters H, D – the load (rectified current link) and diode, respectively, which serve as structural elements of the ACRS. Other designations are as follows: E, i, R, L, φ – electromotive force, current, active resistance, inductance and electrical potentials of nodes. The letters A, K, M, H, D in the lower indices indicate that the coordinates belong to the structural elements corresponding to the accepted designation, and the letter T – to the thyristors. The numbers in the lower indices indicate the ordinal numbers of the coordinates within the structural elements, and the numbers in the lower indices at the potentials φ – the ordinal numbers of the potentials of the electrical circuit; N_F – the number of phases, the maximum value of which in the program code is limited to 24 (N_F = 24).

It is important to note that in the diagram of Fig. 1 (in both the mathematical model and the corresponding program code) provides a choice of either a bridge circuit (when both valve groups are operating and the diode is closed), or a star connection circuit (when the anode group is closed and the diode is constantly in conductive state). Permanently closed diode or valves of the anode group functionally means the rupture of their electrical branches, which changes the generalized circuit to the selected one. The choice of one of these variants of the circuit is performed only during the operation of the program code at the level of numerical values of the state indicators of the thyristors and the diode vector (24).

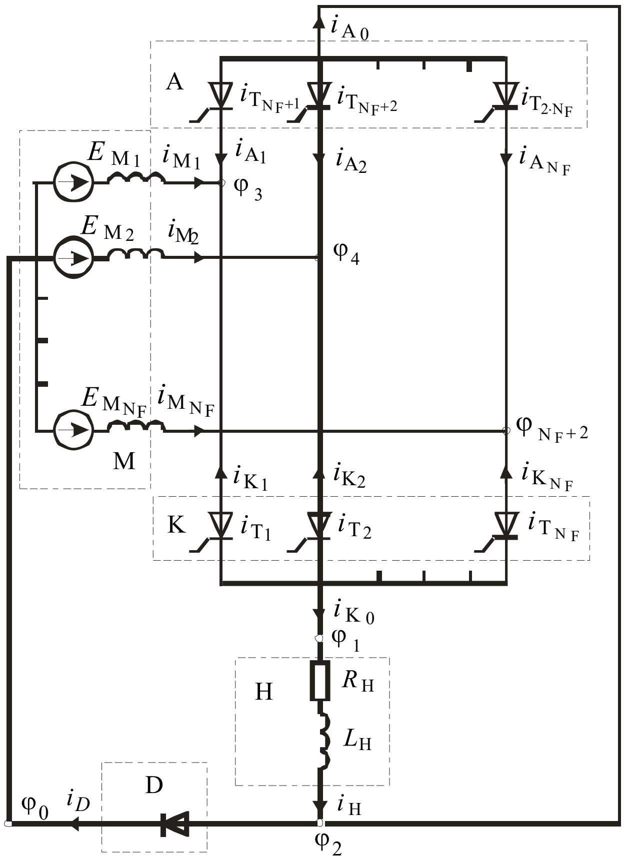

Fig. 1. Diagram of power electric circuit of the N_F-phase AC rectification system

The mathematical model of the N_F-phase ACRS is the DES of the electrical state and the system of logical equations, which simulates the operation of the rectifier control system.

The mathematical model of the N_F-phase system of rectification of electric currents will be developed on the basis of the theory of mathematical modelling of electrical-machine-valve systems [15], according to which mathematical models of arbitrary EMVS are developed on a modular basis, i.e. they are built from «ready» mathematical models of separate structural elements of the diagram of a power electric circuit. As can be seen from Fig. 1, here the following structural elements are: N_F-phase electrical network, N_F-phase cathode and anode thyristor groups, as well as active-inductive load and diode. Consider the mathematical models of each of the structural elements.

Mathematical model of N_F-phase electrical network. We represent the electric network with a $2{\cdot}N_F$-polar, and we describe the electric equilibrium by the vector equation of the outer branches, which has the following form:

$$\mathrm{p}\, i_M + G_M \cdot \varphi_M + T_M = 0, \qquad (3)$$

where the vector of currents of external branches:

$$i_M = (i_{M1},\ldots,\ i_{MN_F},\ \ -i_{M1},\ldots,\ -i_{MN_F})\,; \qquad (4)$$

coefficient matrix:

$$G_M = \begin{bmatrix} G_e & -G_e \\ -G_e & G_e \end{bmatrix}, \qquad (5)$$

in which the diagonal matrix of inverse inductances of the phases of the network:

$$G_e = \mathrm{diag}\left(\frac{1}{L_{M_1}}, ..., \frac{1}{L_{M_{N_F}}}\right); \qquad (6)$$

vector of potentials of external network nodes in which $\varphi_{0_j} = \varphi_0 = 0$ (j = 1, ..., N_F):

$$\varphi_M = (\varphi_3,\ \varphi_4, ...,\ \varphi_{N_F+2},\ \varphi_{0_1}, ...,\ \varphi_{0_{N_F}}); \qquad (7)$$

vector of free terms:

$$T_M = (T_e, -T_e), \qquad (8)$$

in which

$$T_e = \left(\frac{i_{M_1} \cdot R_{M_1} - e_{M_1}}{L_{M_1}}, ..., \frac{i_{M_{N_F}} \cdot R_{M_{N_F}} - e_{M_{N_F}}}{L_{M_{N_F}}}\right). \qquad (9)$$

In (6), (9) we indicate L_{M_j}, R_{M_j}, i_{M_j}, e_{M_j} are the inductance, active resistance and instantaneous values of current and electromotive force of the j-th phase of the network.

Mathematical model of N_F-phase cathode thyristor group. The cathode thyristor group is represented by the N_F+1-polar, and the electrical equilibrium is described by the vector equation of the outer branches, which, according to [15] and the proposed method, has the following form:

$$\mathrm{p} i_K + G_K \cdot \varphi_K + T_K = 0\,, \qquad (10)$$

where the vector of currents of external branches:

$$i_K = (i_{K_1}, i_{K_2}, ..., i_{K_{N_F}}, i_{K_0}) = (-i_{T_1}, -i_{T_2}, ..., -i_{T_{N_F}}, i_{K_0}), \qquad (11)$$

in which

$$i_{K_0} = i_H = \sum_{j=1}^{N_F} i_{T_j}, \qquad (12)$$

where i_{T_j} is the current of the j-th thyristor (j = 1,…, N_F);

where the coefficient matrix:

$$G_K = \begin{bmatrix} G_{T_1} & 0 & \cdots & 0 & -G_{T_1} \\ 0 & G_{T_2} & \cdots & 0 & -G_{T_2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & G_{T_{N_F}} & -G_{T_{N_F}} \\ -G_{T_1} & -G_{T_2} & \cdots & -G_{T_{N_F}} & \sum_{j=1}^{N_F} G_{T_j} \end{bmatrix}; \qquad (13)$$

vector of external potentials (poles) of the cathode thyristor group:

$$\varphi_K = (\varphi_3, \varphi_4, ..., \varphi_{2+N_F}, \varphi_1); \qquad (14)$$

vector of free terms:

$$T_K = \begin{bmatrix} G_{T_1} \cdot R_{T_1} \cdot i_{T_1} \\ G_{T_2} \cdot R_{T_2} \cdot i_{T_2} \\ \vdots \\ G_{T_{N_F}} \cdot R_{T_{N_F}} i_{T_{N_F}} \\ -\sum_{j=1}^{N_F} G_{T_0} \cdot R_{T_0} \cdot i_{T_0} \end{bmatrix}. \qquad (15)$$

The components of the matrix of coefficients G_K and the vector of free terms T_K are: inverse inductance

$$G_{T_j} = 1/L_{T_j}; \qquad (16)$$

where L_{T_j} is the inductance of the j-th thyristor; R_{T_j}, i_{T_j} are the active resistance and current of the j-th thyristor branch of the cathode valve group.

Mathematical model of N_F-phase anode thyristor group. The electrical equilibrium equation of the anode thyristor group is written based on similar considerations as for the cathode.

Mathematical model of the diode. The diode model is represented by a bipolar, and the electrical equilibrium equations are written on the basis of similar considerations as for thyristor groups.

Mathematical model of active-inductive loading. The static load is represented by a bipolar, and the electric equilibrium is described by the vector equation of the outer branches, which is obtained similarly to the equations of the electric network.

Nodal system of equations of electrical state of N_F -phase current rectification system. The nodal system of equations of electric state is written in the basis of electric potentials of independent nodes of the diagram of a power electric circuit (Fig. 1) and has the following form:

$$A \cdot \varphi + B = 0, \qquad (17)$$

where the coefficient matrix:

$$A = \sum_{j=M}^{H} \Pi_j \cdot G_j \cdot \Pi_j^t; \qquad (18)$$

vector of potentials of independent circuit nodes:

$$\varphi = (\varphi_1, \varphi_2, ..., \varphi_{N_F+2}); \qquad (19)$$

vector of free terms:

$$B = \sum_{j=M}^{H} \Pi_j^t \cdot T_j; \qquad (20)$$

and Π_j, G_j, T_j, Π_j^t are the incidence matrices, coefficient matrices, free terms vectors and matrices transposed to Π_j matrices for the j-th structural element of the circuit (j = M, K, A, D, H).

Logical equations of the N_F-phase rectifier control system. The operation of the thyristor rectifier control system will be described by logical equations, which have the following form:

$$Z_j = Z_{U_j} \wedge Z_{\alpha_j} \wedge Z_{K_j} = \text{true } j = (1,\dots, 2\cdot N_F), \quad (21)$$

where Z_j is the condition for opening the j-th thyristor (the j-th thyristor is opened at the true value of Z_j); Z_{U_j} is the condition of opening of thyristors on voltage (Z_{U_j} accepts true value at positive voltage on the j-th thyristor when $U_{T_j} \geq 0$); Z_{α_j} accepts true value when the current angle of the j-th thyristor is in the set range taking into account an ignition angle; Z_{K_j} accepts true value when the j-th thyristor locked, the symbol «^» indicates the operation of logical multiplication (conjunction).

For a diode, the logical equation has the form

$$Z_D = Z_{D_U} \wedge Z_{D_K}, \quad (22)$$

where Z_{D_U} is the condition of opening the diode by voltage (Z_{D_U} has true value at positive voltage on the diode $Z_{D_U} \geq 0$); Z_{D_K} has true value when the diode is locked.

The state of the diode remains constant (locked) for the bridge circuit and conductive – for the circuit with a star connection, when all the thyristors of the anode valve group are locked, i.e. in the electrical circuit and the equation system the anode thyristor group remains but is out of operation (this applies to the program code, which implements the mathematical model of the AC rectification system and the algorithm for calculating electromagnetic processes).

The second-order numerical Runge-Kutta method was used to integrate the DES in the mathematical model of the EMVS, which successfully combines a sufficient level of accuracy with the optimal cost of machine time, and the Gauss method was used to solve the linear system of algebraic equations of electrical state (17).

Algorithm for calculating electromagnetic processes. The input data for the calculation of electromagnetic processes of the system (Fig. 1) is divided into three groups. E_M, L_M, R_M, f_M, N_F – amplitude of electromotive force, inductance and active resistance of phase branches of the network, frequency and number of phases of the network; L_W, R_W – inductance and active resistance for the conducting state of thyristors and diodes; L_Z, R_Z – inductance and active resistance for the closed state of thyristors and diodes; R_H, L_H – active resistance and inductance of active-inductive load; t_V – recovery time of thyristors properties for their locked state.

The second group of input data includes the initial conditions, which are combined into a vector of integrated variables V and a vector K_Π of the state of the valves. These vectors have the following structure:

$$V = (i_H, i_D, i_{T_1}, \dots, i_{T_{2N_F}}, i_{M_1}, \dots, i_{M_{N_F}}, t), \quad (23)$$

where t is the integration time;

$$K_\Pi = (K_{T_1}, K_{T_2}, K_{T_3}, \dots, K_{T_{2N_F}}, K_D). \quad (24)$$

The elements of the vector K_Π (24) have the values:

- 1 – for the conductive state of the valves;
- 0 – for locked state in the case of controlled valves;
- 2 – for locked and uncontrolled valves.

The third group includes the following input data that relate directly to the operation of program code: t_K – final integration time; Δt – step of DES integration in non-switching time intervals; Δt_K –step of integration within the time interval of restoration of thyristor properties for their locked state.

The calculation of electromagnetic processes occurring in the EMVS is performed in the following sequence.

1. Based on the initial conditions: (vector V(23)), the array of states of the valves K_Π (24) and the input data of the first group matrices of coefficients and vectors of free terms of the structural elements of the rectification system according to the diagram (Fig. 1) are formed: (5), (8); cathode thyristor group – (13), (15) and all other structural elements.

2. On the basis of matrices of coefficients and vectors of free terms of structural elements the matrix of coefficients and vector of free terms of system of equations (17) by (18), (20), accordingly, is formed.

3. The system of equations of electrical state (17) with respect to the vector of potentials of independent nodes φ (19) is solved and the integration vector pV is formed, which is equal to the time derivative of the vector of integrated variables V (23) and has the following structure:

$$pV = (pi_H, pi_D, pi_{T_1}, \dots, pi_{T_{2N_F}}, pi_{M_1}, \dots, pi_{M_{N_f}}, 1). \quad (25)$$

4. Logical equations (21) are solved and the state of thyristors is determined. If the state of the thyristors has changed (at least one of them has opened), then the integration vector pV (25) is redefined.

5. One of the explicit numerical methods is integrating the DES with a given integration step Δt, resulting in its solution (new value of the vector V (23)) at the current integration step.

6. A check is performed regarding the change the value to negative current of any of the open thyristors in the current integration step. If the current of an arbitrary open thyristor has changed from a positive value to a negative one, the DES is inverted, which determines the time at which the open thyristor current is zero (passes from zero from plus to minus). From this point in time, at time interval t_V, and until the time when the j-th thyristor restores its properties for the closed state, the thyristor parameters (its inverse inductance G_{T_j} and active resistance R_{T_j} from (13), (15) for the cathode and similarly for anode thyristor group) changes (the resistance increases and the inverse inductance decreases) according to a given law (linear, parabolic, exponential, or arbitrary others). During the switching time t_V, it is reasonable to reduce the integration step Δt_K by at least one or even two orders of magnitude (Δt_K=Δt/100) compared to the set integration step Δt for the off-

switching period. In the first integration step after the end of the switching period, the thyristor parameters are assigned a value for the locked state, the state indicator of the thyristor K_{T_j} is set to 0 ($K_{\mathrm{T}_j} = 0$), and the integration step returns a value that corresponds outside the switching period.

7. With a certain multiplicity of integration steps, the results of process calculations are output to information files. These results are all the coordinates included in the vector of integrated variables V (23) and the potentials of independent nodes of the diagram (Fig. 1) (19) and their difference in any combination, as well as the results of harmonic analysis of selected coordinates.

8. At each integration step, a check is performed regarding the current integration time t outside its set final value t_K. If the current value of the integration time t is equal to or exceeds the set final $_K$ $(t \geq t_K)$ value, the DES integration procedure is terminated, and otherwise, when $t < t_K$ – continues.

Based on the above mathematical model and the corresponding algorithm, the program code was developed in the FORTRAN programming language for computer modelling of electromagnetic processes occurring in the rectification system of the N_F-phase current (Fig. 1). To test the proposed method for the correctness of its theoretical provisions and suitability for practical application, with the help of the developed software code computer simulation of electromagnetic processes occurring in EMVS is performed (Fig. 1) on several diagrams of the electrical power circuit (the bridge circuit of the rectifier and the star rectifier circuit) with the number of phases N_F = 1, 2, 3, 6 and 12 (of 24 possible). The following are the results of computer simulation of electromagnetic processes for a three-phase bridge EMVS.

The input data of the first group are selected with such numerical values that the main coordinates, which are rectified voltage and current i_H, u_H correlated with the values of rectified current and voltage of the valve excitation system of turbogenerators TGV series 500 and 800 MW. Therefore, the main input data of the first group have the following numerical values: for 3-phase electrical network E_M = 800 V, $L_M = 0.1\cdot10^{-6}$ H, $R_M = 0.1\cdot10^{-5}$ Ω, f = 50 Hz – amplitude of electromotive force, inductance and resistance of phase electric branches of the network, as well as the frequency of its voltage and current; for rectifier and diode: $L_W = 0.1\cdot10^{-3}$ H, $L_Z = 0.1\cdot10^{3}$ H – inductance of thyristor (and diode) branches in conductive and closed states, respectively; R_W = 0.001 Ω, R_Z = 1000 Ω – active resistance of thyristor (and diode) branches in the conductive and closed states, respectively; α_r = 0° – thyristor control angle; for load: L_H = 0.075 H, R_H=1.5 Ω – inductance and active resistance; Δt = 10 μs – integration step; Δt_K = 0.1 μs – integration step on the switching interval (locking) of valves; t_K = 0.65 s – final integration time; t_V = 50 μs – full recovery time of the thyristor properties for the locked state.

The task of modelling is to study the patterns of electrical processes that occur in the thyristors of the rectifier with an emphasis on the study of switching processes that occur during the locking of thyristors, taking into account the presence of inverse (reverse) current. It is noted above that the proposed method and, accordingly, the mathematical model provide the ability to choose the law of change of thyristor parameters during their switching. In this context, at the first stage of the study we consider the linear law of change of parameters of thyristors that switch during their locking.

Figure 2 shows the calculated dependencies of the instantaneous phase currents of the cathode thyristor group.

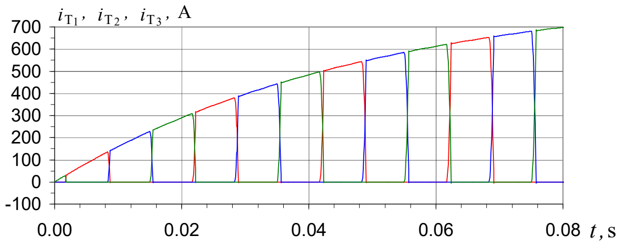

Fig. 2. i_{T_1}, i_{T_2}, i_{T_3} – phase currents of the cathode group

It is obvious that the instantaneous currents of the anode thyristor group have a similar character to the currents of the cathode group, but are shifted by 180°.

An important coordinate in terms of analysis of electromagnetic processes in the EMVS is the rectified current, the curve of which is shown in Fig. 3.

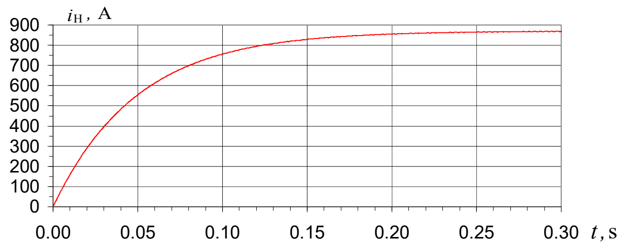

Fig. 3. i_H – rectified current

Figure 3 shows that the curve of the rectified current encircles the curves of the valve currents of the cathode thyristor group in the upper circuit, which corresponds to the physics of electromagnetic processes occurring in the EMVS. In general, the curves of the calculated dependencies of the phase currents of the cathode thyristor group and the rectified current shown in Fig. 2, 3, reflect the course of the transient in EMVS from zero initial conditions and provide information about the functioning of the mathematical model and the corresponding program code on the physics of processes occurring in this system, and, to some extent, the level of adequacy of the real physical system at the level of the nature of the curves qualitatively and at the level of their numerical values quantitatively. From Fig. 3 it is seen that the rectified current acquires a steady-state value according to the time constant, the value of which is determined by the load parameters, i.e. their ratio L_H/R_H.

From the point of view of the method declared above, it is fundamentally important to obtain information on the presence and regularity of changes in the inverse current of thyristors that switch during their locking, as well as the nature of changes in thyristor parameters at the stage of their locking (during the restoration time of the properties of thyristors for the locked state). Such information is provided by the curves of current, inverse inductance and active resistance of the thyristor, which is locked. For thyristor No. 1 these curves are shown in Fig. 4-6.

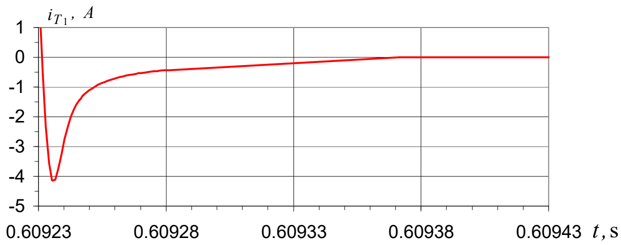

Fig. 4. i_{T_1} – inverse current of the first thyristor (linear law)

The nature of the curve in Fig. 4 clearly indicates not only the presence of the inverse current of the first thyristor (transition of thyristor current to the negative region), but also the pattern of its change, according to which it increases to a certain maximum value (here it is i_{T_1} = –4.19 A), and then – its decrease to the steady-state value, which is equal to i_{T_1} = –0.2 A.

The presence of inverse current and the regularity of its change are quite expected and are perceived as those that generally correspond to the process of restoring the properties of thyristors for the closed state during their switching. Obviously, here the maximum value of the inverse current is determined by the pattern of changes in the parameters of the switching thyristors. We remind that in this variant of calculations the linear law of change of parameters of the switching thyristors is accepted.

The nature of the curves of inverse inductance (Fig. 5) and active resistance (Fig. 6) is absolutely obvious, because the value of these coordinates varies according to the linear law within given limits according to the initial assumptions and basic provisions of the proposed method.

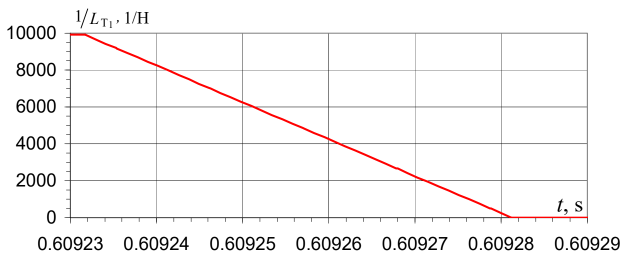

Fig. 5. $1/L_{T_1}$ – inverse inductance of the first thyristor (linear law)

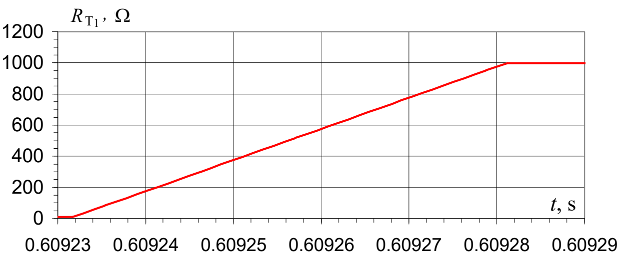

Fig. 6. R_{T_1} – active resistance of the first thyristor (linear law)

In order to determine the effect on the laws of change of the inverse current of thyristors during their locking, we consider similar calculation dependencies obtained on the basis of the parabolic law of change of parameters of thyristors that switch. As for the linear law, Fig. 7–9 show the calculated dependencies of the inverse current, inverse inductance and active resistance of the first thyristor.

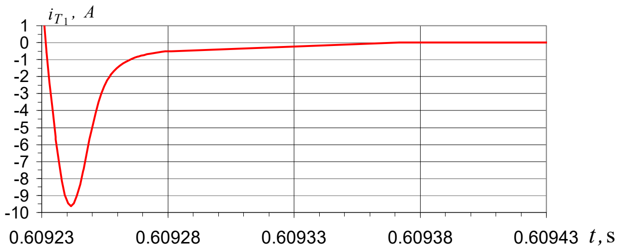

Fig. 7. i_{T_1} – inverse current of the first thyristor (parabolic law)

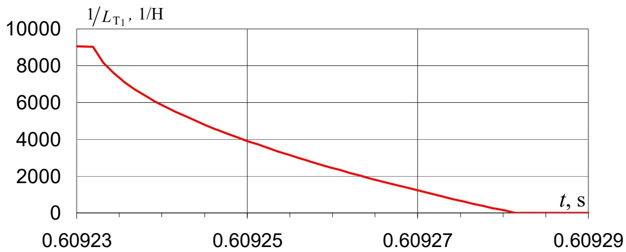

Fig. 8. $1/L_{T_1}$ – inverse inductance of the first thyristor (parabolic law)

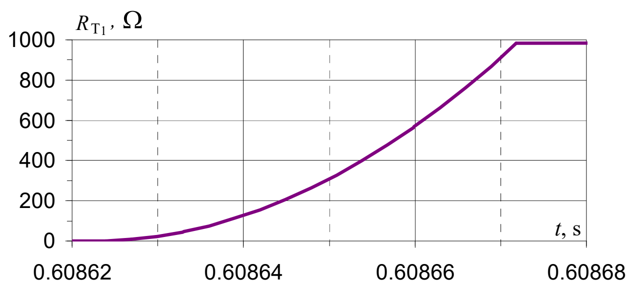

Fig. 9. R_{T_1} – active resistance of the first thyristor (parabolic law)

Figure 7 shows that in general the nature of the current of the first thyristor is similar to the nature of the current in Fig. 4, and the current curve in Fig. 7 differs from the current in Fig. 4 by larger maximum value of inverse current, which is equal to i_{T_1} = –9.63 A. This difference is explained by the lower value of active resistance and inductance of the thyristor at the beginning of the recovery period of thyristor properties for the locked state, which is clearly seen in Fig. 8, 9, in which the corresponding curves have a parabolic shape at the stage of changing the parameters of thyristors.

The fact that the values of the inverse current maximum for the linear and parabolic laws of change of parameters of the thyristor which switches are different (which is a priori obvious) means the problem of choosing the law variant during computer simulation. On the one hand, the linear law on average should describe the change of parameters quite accurately, but, on the other hand, in real conditions such physical processes are almost rarely linear, so there is reason to believe that we should apply some other low – nonlinear (e.g. parabolic) law. Just as the recovery time of thyristor properties for the locked state is different depending on the size and type of thyristors and their individual structures (emitters and bases), it is logical in each case to select the law of change of thyristor parameters. At this stage of the study this is only about methods of accounting for inverse current at a fundamentally higher level of adequacy, than proposed by other currently known methods and, as a consequence, more accurate consideration of thyristor switching processes that occur during their locking.

Thus, the results of mathematical modeling of EMVS taking into account the presence of inverse current in thyristors that switch during their locking, obtained using the proposed method, give grounds to argue that in principle this approach is sufficiently substantiated in terms of accepted correct initial assumptions and consistent real processes that occur in the thyristor at the stage of its locking and restoration of properties for the locked state, at the level of concentration of electric charge carriers in real thyristors, which ultimately manifests itself in changes in thyristor resistance and its function as a semiconductor. The concentration of charges in the structures of the thyristor and its resistance are causally related, which means that if it is reasonable and rational to choose the necessary law of change of thyristor parameters for the recovery phase for the locked state, such a law will correspond to real concentrations of electric charges, which justifies their consideration.

Conclusions and prospects of research.

1. In the current large number of methods of mathematical modelling of VFCs, too little attention is paid to the consideration of inverse currents that occur during closing valves and which actually exist in closed valves and have some impact on both VFC processes and their functioning in general. Correct consideration of inverse currents of valves (especially during their locking) remains an urgent problem, the solution of which would significantly increase the level of adequacy of mathematical modelling of VFCs.

2. In some methods, inverse valve currents are not taken into account at all, for example, in key S-models [14] either obtained incorrectly due to the instantaneous switching of valves accepted in the initial assumptions and, as a consequence, a sudden change in the first derivative of the valve current that switches during its locking, and therefore inverse currents are ignored [15-17] based on the smallness of their values.

3. It is proposed to simulate the process of locking valves, taking into account the restoration of their properties for the locked state, by changing (according to the determined law) the parameters of inverse inductance and active resistance, for a known locking time. The final locking of the valves should be performed after the time of restoration of the properties of the valves for the locked state. This method, on the one hand, provides a smooth change in the parameters of the valves during their locking and, consequently, the correct values of the inverse current, and, on the other hand, takes into account the occurrence and dynamics of changes in inverse current at the stage of closing the valves during the restoration of their properties for the closed state, which significantly increases the adequacy of mathematical modelling of VFCs and electrical systems containing VFCs.

4. The results of computer simulation of VFCs, obtained using the proposed method in the mathematical model, suggest that the presence and regularity of changes in inverse currents corresponds to the processes occurring in VFCs at the level of concentration of electric charge carriers in terms of the value and the nature of the inverse current, which, in turn, indicates an increase in the adequacy of mathematical modelling of VFCs.

5. The subject of further research is to determine the laws of change of dynamic parameters of valves in accordance with the laws of change in the concentration of charge carriers in their design and at the same time functional structures (bases and emitters).

Conflict of interest. The author declares no conflict of interest.

REFERENCES

1. Shapoval I.A., Mykhalskyi V.M., Doroshenko A L. Speed control of the doubly-fed induction machine with controlled converters in the stator and rotor circuits. *Technical Electrodynamics*, 2017, no. 6, pp. 18-25. (Ukr). doi: https://doi.org/10.15407/techned2017.06.018.

2. Mazurenko L.I., Lishchenko A.I. *Asinkhronnye generatory s ventil'nym i ventil'no-emkostnym vozbuzhdeniem dlia avtonomnykh energoustanovok* [Asynchronous generators with valve and valve-capacitive excitation for autonomous power plants]. Kyiv, Naukova Dumka Publ., 2011. 272 p. (Rus).

3. Mazurenko L.I., Vasyliv K.M., Dzhura O.V., Kotsiuruba A.V. Simulation model and control algorithm for isolated hydro-wind power system. *Technical Electrodynamics*, 2020, no. 1, pp. 17-26. (Ukr). doi: https://doi.org/10.15407/techned2020.01.017.

4. Novikov M.A., Panfilov Zh.I., Remizevich T.V., Rashitov P.A. Analysis of the processes of simultaneous switching of thyristor bridges in converters with multi-winding transformers. *Elektrichestvo*, 2013, no. 6, pp. 29-35. (Rus).

5. Shydlovska N.A., Zakharchenko S.M. Progress of semiconductor discharge-pulse systems for processing granular conductive media. *Technical Electrodynamics*, 2020, no. 3, pp. 69-78. (Ukr). doi: https://doi.org/10.15407/techned2020.03.069.

6. Dzhiudzhi L., Pelli B. *Silovye poluprovodnikovye preobrazovateli chastity* [Power semiconductor frequency converters]. Moscow, Energoatomizdat Publ., 1983. 400 p. (Rus).
7. Zhemerov G.G. *Tiristornye preobrazovateli chastoty s neposredstvennoi sviaz'iu* [Thyristor frequency converters with direct connection]. Moscow, Energiia Publ., 1977. 280 p. (Rus).
8. Zhemerov G.G., Krylov D.S., Mashura A.V. Energy efficiency of the subway electrical supply system with electrical energy recovery at braking. *Electrical Engineering & Electromechanics*, 2019, no. 5, pp. 25-30. doi: https://doi.org/10.20998/2074-272X.2019.5.04.
9. Khlopenko N.J. Calculation and design of a robust speed controller of a frequency-controlled induction electric drive. *Electrical Engineering & Electromechanics*, 2020, no. 3, pp. 31-36. doi: https://doi.org/10.20998/2074-272X.2020.3.05.
10. Butkevych O.F., Chyzhenko O.I., Popovych O.M., Trach I.V. An influence of the facts upon an electrical network's mode during direct start-up of an asynchronous machine in the complex load's composition. *Technical Electrodynamics*, 2018, no. 6, pp. 62-68. (Ukr). doi: https://doi.org/10.15407/techned2018.06.062.
11. Bibik O.V., Mazurenko L.I., Shykhnenko M.O. Formation of characteristics of operating modes of switched reluctance motors with periodic load. *Electrical Engineering & Electromechanics*, 2019, no. 4, pp. 12-16. doi: https://doi.org/10.20998/2074-272X.2019.4.02.
12. Onikienko Y.O., Pilinsky V.V., Popovych P.V., Lazebnyi V.S., Smolenska O.I., Baran V.S. Modelling of operation modes and electromagnetic interferences of gan-transistor converters. *Electrical Engineering & Electromechanics*, 2020, no. 3, pp. 37-42. doi: https://doi.org/10.20998/2074-272X.2020.3.06.
13. Rymsha V.V., Radimov I.N., Gulyy M.V., Merkulov I.V. Motorsolve software package: verification of parameters and characteristics of the brushless permanent magnet motor. *Electrical Engineering & Electromechanics*, 2019, no. 5, pp. 20-24. https://doi.org/10.20998/2074-272X.2019.5.03.
14. Tonkal' V.E., Rudenko V.S., Zhuikov V.Ia. *Ventil'nye preobrazovateli peremennoi struktury* [Valve converters of variable structure]. Kyiv, Naukova Dumka Publ., 1989. 336 p. (Rus).
15. Plakhtyna E.G. *Matematicheskoe modelirovanie elektromashinno-ventil'nykh system* [Mathematical modeling of electromachine-valve systems]. Lvov, Vishcha Shkola Publ., 1986. 164 p. (Rus).
16. Dizhur D.P. Method of simulation on a digital computer of valve converter circuits. *Izvestia of the Research Institute of Direct Current*, 1970, no. 16, pp. 7-9. (Rus).
17. Fil'ts R.V. *Matematicheskie osnovy teorii elektromekhanicheskikh preobrazovatelei* [Mathematical foundations of the theory of electromechanical converters]. Kyiv, Naukova Dumka Publ., 1979. 208 p. (Rus).
18. Hutsaliuk V.Y., Yurchenko O.M., Zubkov I.S., Pazenko V.P. Serial connecting of resonant voltage inverters for high-frequency induction heating equipment. *Technical Electrodynamics*, 2018, no. 4, pp. 70-73. (Ukr). doi: https://doi.org/10.15407/techned2018.04.070.
19. Belov G.A., Serebriannikov A.V., Garanin S.G. Calculation and analysis of processes in reversible pulse converters with two-way differential pulse-width modulation. *Elektrichestvo*, 2013, no. 2, pp. 42-63. (Rus).
20. Goriakin D.V., Mytsyk G.S. Study of the operating modes of a three-phase bridge inverter circuit. *Elektrichestvo*, 2012, no. 5, pp. 23-31. (Rus).
21. Mazurenko L.I., Vasyliv K.M. The law of the electric magnetic processes of the security exercise systems of the autonomous asynchronized generator on the case of the cascade three-phase three-flexible voltage modulator. *Technical Electrodynamics*, 2018, no. 6, pp. 46-49. (Ukr). doi: https://doi.org/10.15407/techned2018.06.046.

Received 03.02.2022
Accepted 25.03.2022
Published 01.06.2022

K.M. Vasyliv [1], *Doctor of Technical Science, Professor,*
[1] Lviv Polytechnic National University,
12, Bandera Str., Lviv, 79013, Ukraine,
e-mail: karl.vasyliv@gmail.com (Corresponding author)

How to cite this article:
Vasyliv K.M. Method of dynamic parameters for mathematical modelling of switching processes of valves closing of semiconductor converters. *Electrical Engineering & Electromechanics*, 2022, no. 3, pp. 28-38. doi: https://doi.org/10.20998/2074-272X.2022.3.05