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ANALYSIS OF METHODS FOR AUTOMATED RESEARCH OF DC VOLTAGE CONVERTERS OF MODULAR STRUCTURE

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ABSTRACT

Context. DC voltage converters (DCV) are part of modern power supply systems (PSS) and power supply ensuring the operation of electronic and radio devices, telecommunication systems and communication and to a large extent determine their power consumption, reliability, time of readiness for operation, weight, size and cost indicators. Even though there are a large number of different software packages used in engineering practice for the study and design of radio engineering devices, such computer-aided design (CAD) systems and virtual computer simulation of electronic circuits have some limitations that do not allow to quickly carry out the entire complex of studies of DCV required for the analysis of electrical processes in various operating modes.

Objective. In this section, the goal is to select the most suitable methods and algorithms that allow the development of software necessary for solving the problems of research and analysis of electrical processes for select energy parameters of the DCV of a modular structure in a separate power channel (PWC).

Method. The paper proposes a method that consists in using mathematical models describing electrical processes in DC voltage converters and creating, on the basis of the developed calculation algorithms, specialized software for the automated study of electrical processes in the DCV of a modular structure using a computer.

Results. The paper discusses the main methods of automated research of radio engineering devices, which can be used to analyze the electrical processes of pulsed DC voltage converters of a modular structure. Algorithms of calculation are given and, as an example, some results of automated research obtained using this method.

Conclusions. The analysis of the known methods of automated research of DC voltage converters of modular structure is carried out. Their advantages and disadvantages are given. It is shown that the most suitable method is based on the use of mathematical models describing electrical processes in DC voltage converters of this type. On the basis of the mathematical models presented in the second section of the work, algorithms and specialized software have been developed that allow them to be widely used in the automated research and design of modular-structured DC voltage converters.

KEYWORDS: modular voltage converters, power channel, converter operation modes, research algorithm for electrical processes.

ABBREVIATIONS

CAD is a computer-aided design system;
DCV is a DC voltage converter;
PWC is a power channel;
SPC is a single-phase pulse converter;
MPC is a multiphase pulse converter;
SP is a software package;
UHF is a ultra high frequency.

NOMENCLATURE

U_{out} is an output voltage (load);
I_{out} is an output current (load) DCV;
I_{outk} is an output current (load k-th PWC);
N is a number of power channels DCV;
f_a is an accumulation factor;
$L1$ is an inductance of the primary winding $W1$ of the power choke;
n_{21} is a transformation coefficient;

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N_{max} is a maximum number of power channels DCV;

C_{in} is a capacitance of the input filter capacitor;

C_{out} is a capacitance of the output filter capacitor;

$\bar{U}_{in}$ is a relative supply voltage;

R_r is an operating mode – stabilization (tracking);

R_p is a conversion mode – SPC (MPC);

P_{out} mode is a type of calculation: P_{out} = const, (P_{outk} = const);

R_{outk} is a load resistance k-th PWC;

P_{outk} is a load power k-th PWC;

f_{ak} is an accumulation factor k-th PWC;

f_{rk} is a return factor k-th PWC;

U_{ink} is an input voltage (power supply) k-th PWC;

f_{bk} is a boundary value of the converting frequency;

T_k is a converting period;

I_{m1k} is a choke current ripple PWC on the accumulation interval;

I_{m2k} is a choke current ripple PWC on the return interval;

I_{sk} is the average value of current consumption k-th PWC;

$\bar{U}_{ink}$ is a relative supply voltage k-th PWC;

$\bar{U}_{outk}$ is a relative load voltage k-th PWC;

I_{outk} is a load current k-th PWC;

$L1_k$ is an inductance of the primary winding $W1$ of the choke k-th PWC;

$L2_k$ is an inductance of the secondary winding $W2$ of the choke k-th PWC.

INTRODUCTION

Modern DCV of power supply and power supply systems, as a rule, use the high-frequency (pulse) principle of power conversion. This allows you to create devices and systems with higher power density and characteristics that are unattainable using other methods.

The modular structure of the construction of pulse DC voltage converters from N of the same type of interchangeable PWC simultaneously operating on a common load provides increased reliability, reduced manufacturing labor intensity, and increased level of unification and standardization of DCV. The use of the modular principle of construction of the DCV contributes to solving issues of redundancy, increasing the reliability of converters, increased manufacturability, adapting to changes in their operating modes, and saving energy.

In the study and computer-aided design of radio-technical devices, simulation of their operation on a computer is widely used today, when instead of expensive long-term experimental testing of electrical energy converters on breadboards, research using mathematical models describing the processes of the devices under study is used. Therefore, in the work are selected:

The object of study is the electrical processes in pulse DCV of modular structure.

The subject of study is automated methods for studying the electrical processes of modular DCV.

The purpose of the work is to develop the methods and algorithms that allow the development of software necessary for solving the problems of research and analysis of electrical processes for select of energy parameters of the DCV modular structure.

To achieve this, it is necessary to solve the following tasks – to analyze modern methods of automated research of radio engineering devices, using the selected mathematical model to develop algorithms and software for solving the problems of research and analysis of electrical processes DCV and to analyze the obtained results.

To carry out a set of necessary studies, the software must ensure the study of converters with SPC and MPC principles of converting electrical energy, the results of which are necessary in the design in order to improve the technical and economic indicators of the DCV.

1 PROBLEM STATEMENT

Mathematical models described in [1, 2, 3] describing electrical processes in a separate power channel and the converter as a whole, allow investigating the dependences: currents and voltages in the PWC elements, in its supply circuits and the load of the converter at a given operating mode. This makes it possible at any time to determine the magnitude of instantaneous currents, their maximum and minimum values, as well as the magnitude of the absolute and relative ripple of voltages and currents at the input and output of the DCV, respectively, with the SPC and MPC, as well as other electrical and energy parameters of the modular structure converters required to select the optimal parameters of the elements, operating modes of the power unit and control algorithms.

The indicated mathematical models also allow us to construct the dependences of the quality indicators of the electrical processes of DCV and energy parameters on the value of the values of the accumulation factors f_a and the transformation coefficient n_{21}, the numbers N of PWC and other parameters for different modes of operation [1].

These dependencies make it possible to identify the features of electrical processes (for example, under different operating modes) with other parameters unchanged (N, L_k, C_k) and to assess the degree of influence of one parameter or another on the nature of the dependence in the entire control range, both in any individual PWC, as well as and in the converter as a whole (Fig. 1).

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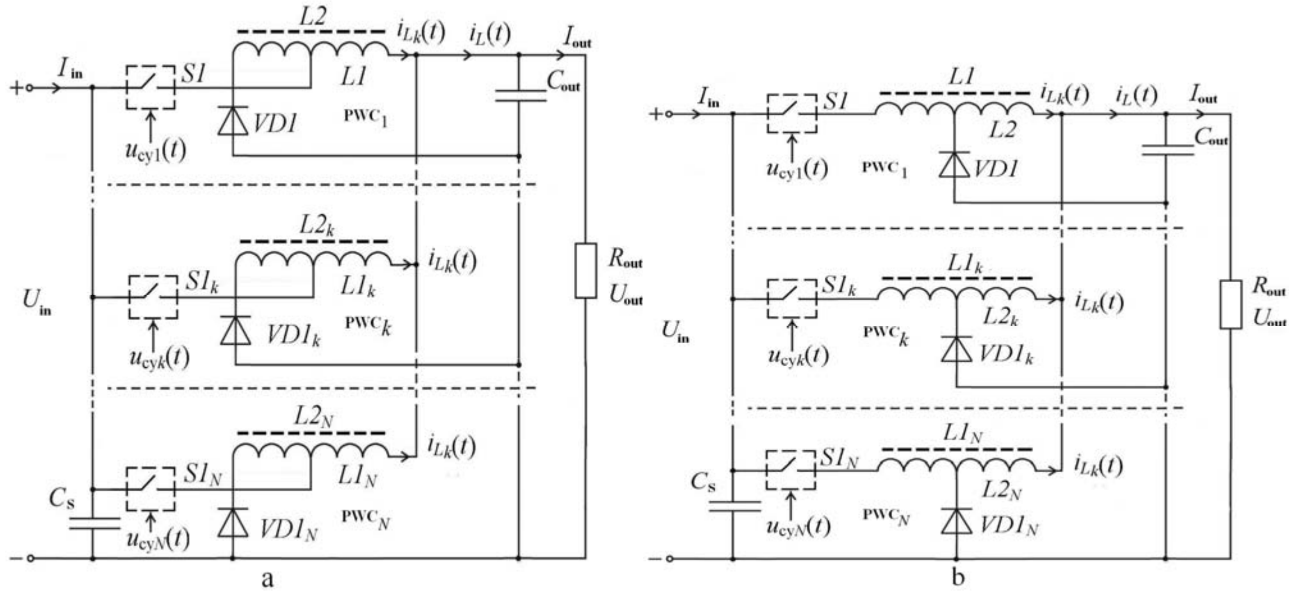

Figure 1 – Power section of the DCV of modular structure with parallel connection of a lower-type PWC with elements of transformation of chokes: a – $n_{21} > 1$; b – $n_{21} < 1$

Thus, the software package for the study of DCV should solve the following main tasks, which are presented in the form of an information model (Fig. 2):

1. Calculation of basic parameters;
2. Calculation of parameters in the time domain (timing diagrams of voltages and currents in the power section, as well as in the input and output circuits of the PWC and DCV);
3. Investigation of the parameters of electrical processes (values of voltages and currents on the elements of the power section of the DCV);
4. Study of quality indicators of electrical processes (absolute and relative values of voltage and current ripple in the input and output circuits of the DCV);
5. Investigation of energy parameters (values of operating currents, power losses on the elements of the power unit, efficiency factor of the DCV).

2 REVIEW OF THE LITERATURE

In the process of automated research and design of electronic devices, as a rule, it is necessary to use a whole set of different software packages. Many sources provide descriptions and examples of modeling electrical processes of radio engineering devices using well-known CAD systems [7, 8, 9]. For example, at the stage of developing a structural diagram, programs such as SysCalc, System View, Simulink, LabView can be used. And when creating schematic diagrams – PSpice (as part of the DesignLab package), Micro-Cap, Electronics Workbench, and when designing UHF devices such specialized programs as Super Compact, Touchstone, Aplac and others [1, 2, 4, 8, 9].

These software products allow engineering studies to create, edit schematic diagrams and make a calculation of a number of parameters, calculate frequency characteristics and transients, perform a variety of device analyzes, and implement other service functions [3, 5, 6].

However, having some limitations, such software products do not allow to fully serve as a tool for researching voltage converters. All these programs are quite expensive and universal, and, as a rule, do not allow complex studies of several parameters at the same time. Also, the construction of dependencies in a relative form, for example, such as the ripple coefficients of voltages and currents, efficiency and other parameters, becomes much more complicated [3, 6, 7, 9]. Therefore, to study and analyze the specified parameters of various converter circuits under different operating modes, it is required to create specialized software – a software package (SP), which allows, using a mathematical model [2, 3, 8] describing electrical processes in the DCV, to carry out all the necessary calculations to solve the problems of automated research and design of converters of modular structure.

3 MATERIALS AND METHODS

When developing such a software package, the allocation of individual software modules – subroutines (SR) is used to calculate the parameters corresponding to the tasks being solved [2, 3, 5, 9]. This is due to the fact that the main computational procedures and operations that make up the individual stages of research should be interconnected and not be duplicated when solving various research problems, which contributes to the reduction of computational operations. Thus, a unified software algorithm can be represented as a set of software modules that will create the most clear and rational software structure.

As a result, the following basic requirements for a software package for studying converters of a modular structure can be distinguished:

1. The rational structure of the software information model, reflecting information links between individual SR when solving research problems, which helps to reduce time costs and resources for software development.

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2. The software must ensure the study of the DCV at various parameters of the PWC elements and the selected operating mode for the SPC and MPC.

3. Availability of a separate software module (control program) to control the operation of the software complex (selection of research tasks, change of initial data, providing information links between individual SR at a given stage of research), using the same initial data and calculated relationships of the used mathematical model.

In accordance with the tasks solved by the software package for the study of DCV (Fig. 1) [2, 3, 5], the following parameters are related to the simulation results:

1. To study time dependences – instantaneous values of currents and voltages in the input $i_{\text{in}k}(t)$, $u_{\text{in}k}(t)$ and output $i_{\text{out}k}(t)$, $u_{\text{out}k}(t)$ circuits of a single k-th PWC, their total values for the DCV $i_{\text{s.in}}(t)$, $u_{\text{s.in}}(t)$, $i_{\text{s.out}}(t)$, $u_{\text{s.out}}(t)$ at SPC and $i_{\text{M}sk}(t)$, $u_{\text{MS}}(t)$, $i_{\text{M.out}}(t)$, $u_{\text{M.out}}(t)$ MPC.

2. To study the dependencies of the quality indicators of the electrical processes of the DCV on the values of the accumulation and transformation coefficients, the value of the output power, the relative supply voltage and load, the number of power channels, and other parameters:

– absolute ripple of currents $\Delta I_{\text{in}k}$, $\Delta I_{\text{out}k}$, $\Delta I_{\text{s.in}}$, $\Delta I_{\text{s.out}}$, $\Delta I_{\text{M.in}}$, $\Delta I_{\text{M.out}}$ and voltages $\Delta U_{\text{in}k}$, $\Delta U_{\text{out}k}$, $\Delta U_{\text{s.in}}$, $\Delta U_{\text{s.out}}$, $\Delta U_{\text{M.in}}$, $\Delta U_{\text{M.out}}$, respectively, at the input and output to the PWC and DCV during SPC and MPC;

– the ripple coefficients of currents $\text{C}_{\text{rs.in}}$, $\text{C}_{\text{rs.out}}$, $\text{C}_{\text{rm.in}}$, $\text{C}_{\text{rm.out}}$ and voltages $\text{C}_{\text{rs.in}u}$, $\text{C}_{\text{rs.out}u}$, $\text{C}_{\text{rm.in}u}$, $\text{C}_{\text{rm.out}u}$ at the input and output of the DCV at the SPC and MPC, respectively;

– smoothing factor of the converter for current S_i and voltage S_u;

– smoothing coefficients of the structure at the input S_{in}, $S_{\text{in}u}$ and the output S_{out}, $S_{\text{out}u}$ in terms of current and voltage;

– adjusting characteristics ($U_{\text{in}}/U_{\text{out}}=f(f_{\text{a}})$ or $U_{\text{out}}/U_{\text{in}}=f(f_{\text{a}})$).

In this case, the smoothing coefficient is determined by the ratio $S_i=\text{C}_{\text{r.in}}/\text{C}_{\text{r.out}}$, $S_u=\text{C}_{\text{r.in}u}/\text{C}_{\text{r.out}}$ is used to characterize the efficiency of suppression of alternating currents or voltages in a device that has a filtering effect (for example, a rectifier, converter, filter), where $\text{C}_{\text{r.in}}$, $\text{C}_{\text{r.out}}$, $\text{C}_{\text{r.in}u}$, $\text{C}_{\text{r.out}u}$ – ripple coefficients, respectively, of the input and output current or voltage at the input and output of the DCV.

Smoothing coefficients of the structure of a modular converter in the power supply circuits S_{in}, $S_{\text{in}u}$ and loads S_{out}, $S_{\text{out}u}$ in terms of current and voltage characterize the efficiency of suppression of alternating components in the MPC, relative to the similar case of the SPC in the corresponding circuits of the converter. For SPC $S_{\text{in}}=S_{\text{out}}=1$, $S_{\text{in}u}=S_{\text{out}u}=1$ [7, 8]. For MPC S_{inM}, S_{outM} can be used as indicators characterizing the efficiency of smoothing the relative decrease in variable components in the MPC in comparison with the SPC made of the same number N PWC [6, 7].

3. To study the energy parameters of converters, which include:

– effective values of currents on PWC elements $I_{C\text{in}k\text{e}}$, $I_{S1k\text{e}}$, $I_{L1k\text{e}}$, $I_{VD1k\text{e}}$, $I_{L2k\text{e}}$, $I_{L12k\text{e}}$, $I_{C\text{out}k\text{e}}$, their total values for DCV $I_{S1\text{e}}$, $I_{L1\text{e}}$, $I_{VD1\text{e}}$, $I_{L2\text{e}}$, $I_{L12\text{e}}$, while the effective values of currents of capacitors of input and output smoothing filters during SPC and MPC will be different (in MPC, the maximum value of the corresponding currents is less) and $I_{C\text{inMe}} < I_{C\text{inse}}$ and $I_{C\text{outMe}} < I_{C\text{outse}}$.

– power losses on PWC elements $P_{C\text{in}k}$, P_{S1k}, P_{L1k}, P_{VD1k}, P_{L2k}, P_{L12k}, $P_{C\text{out}k}$, their total values for DCV P_{S1}, I_{VD1}, P_{L1}, P_{L2}, P_{L12}, while power losses on capacitors of input and output smoothing filters during SPC and MPC will be different and $(P_{C\text{M}} = P_{C\text{inM}} + P_{C\text{outM}}) < (P_{C\text{s}} = P_{C\text{ins}} + +P_{C\text{outs}})$.

– the coefficients of efficiency of the power channel $\eta_{\text{pwc}k}$ and the converter of modular structure at SPC η_{spc} and MPC η_{mps}.

Based on the foregoing, the tasks solved by the developed software will be a set of interconnected functional blocks, which are presented in the form of an information model, Fig. 2. With an automated study of converters of modular structure in accordance with the information model (Fig. 2), the software package allows you to:

1) study of the parameters of electrical processes in the time domain for various parameters of the elements, operating modes of both a single PWC, and the DCV as a whole;

2) a study of the influence of the magnitude of the values of the initial data and basic parameters on the quality indicators of electrical processes (on the absolute and relative pulsations of voltages and currents in the input and output circuits, and the smoothing coefficients) of the converter;

3) study of the influence of changing the number N of the PWC of the converter on the quality indicators of the electrical processes of the converter.

4) study of the influence of changes in these parameters on the energy performance of the DCV in different modes of operation.

In accordance with the tasks of the study of the DCV, the following functions of the investigated parameters have been identified, which are necessary to assess the quality of electrical processes, energy parameters in the PWC elements, as well as in the input and output circuits of the converter (Fig. 2):

1. Functions of time – $f(t)$.

2. Not being functions of time, for example, the accumulation factor – $f(f_{\text{a}})$, functions of the transformation ratio – $f(n_{21})$ or functions of the number of power channels – $f(N)$, functions of value relative supply voltage – $f(\overline{U}_{\text{п}})$.

To solve each of the tasks of the automated research, the "Control program" [4] is used, which controls the computational process, as well as the input of the initial data, the output of the calculation results, including the construction of graphs of the selected dependencies.

The control program carries out the required research using separate functional (depending on the tasks to be solved) program modules, implemented in the form of dynamically linked libraries [4]. During research, the con-

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trol program uses a set of software modules in the form of dynamic libraries containing a set of tools necessary for solving a particular problem.

4 EXPERIMENTS

To perform these studies using a computer, it is advisable, on the basis of an analysis of all the calculated ratios and the formulated research tasks, to divide the entire process of calculating the processes and parameters of the converter into a number of independent tasks. Next, distribute them (Fig. 3) by type of research and for each problem to be solved, compose a calculation algorithm, on the basis of which the software should be implemented in the form of appropriate subroutines. After that, it is necessary to combine all the subprograms into a single software complex for the study of DCV, consisting of software modules with various tasks to be solved.

Let us consider in more detail, taking into account the adopted approach – separation into a separate software module – a module for calculating basic parameters that are common for any type of research.

Let's select separate subroutines (SR), which are part of the algorithm for studying the DCV (Fig. 3), implemented in the form of a dynamically connected library:

1) SR "Calculation of basic parameters" serves for preliminary calculation of parameters and their preparation as initial data for calculating the investigated quantities (block (bl.) 3, Fig. 3);

2) SR "Time dependencies" for calculating timing diagrams (bl. 11, Fig. 3) both in the circuits of a separate power channel, and at the input and output of the converter as a whole (Fig. 1);

3) SR "Quality indicators" (bl. 10, Fig. 3) for calculating the dependences on the accumulation coefficient (with the possibility of changing the number N of PWC, bl. 5, Fig. 3 and the transformation ratio n_{21} – bl. 6, Fig. 3) quality indicators (Fig. 3) of the electrical processes of the DCV (absolute pulsations, pulsation coefficients, smoothing coefficients);

4) SR "Energy parameters" (bl. 9, Fig. 3) for calculating the effective values of currents in the elements of the PWC, the converter, as well as the efficiency at different values of the accumulation coefficients f_a and transformation n_{21}, values, output power P_{out} and various the number N of power channels of the DCV.

The algorithm of the software complex for the study of DCV contains the following blocks and subroutines:

After the start of the program (bl. 1) of the algorithm (Fig. 3), in bl. 2, the initial data are entered: the parameters of the elements, the required type of research, the required type of dependence that needs to be obtained. Depending on the selected type of study, the type of dependence in the subroutine (bl. 3), the basic parameters

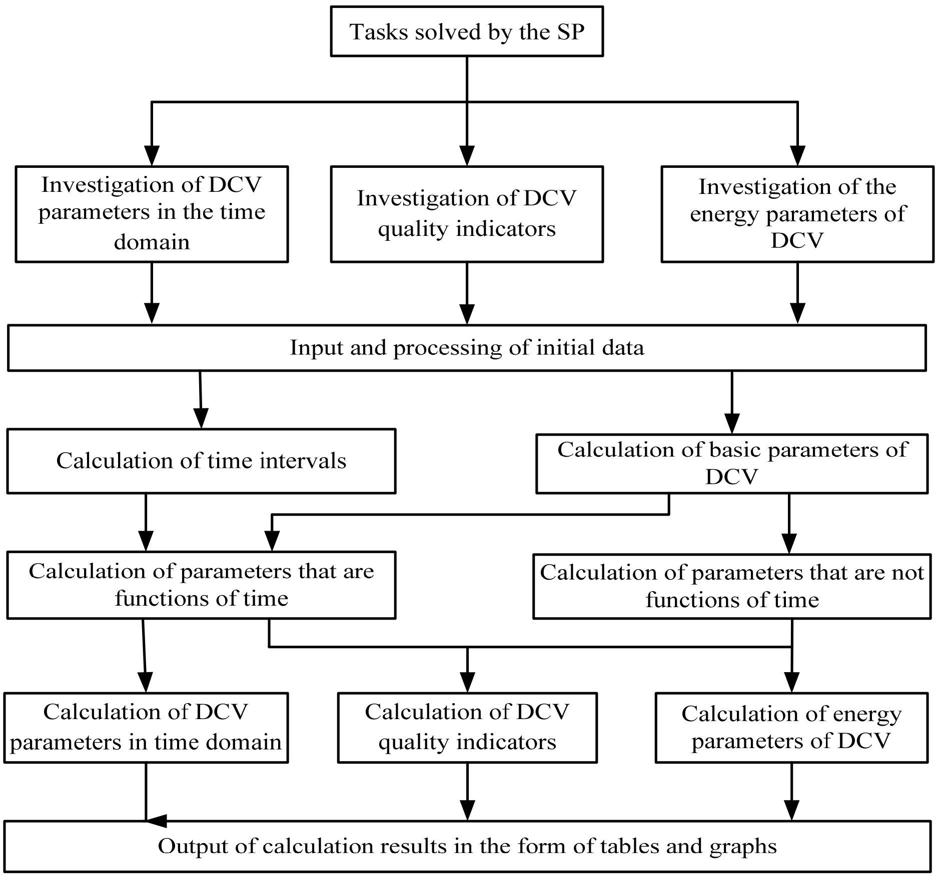

Figure 2 – Software Information Model

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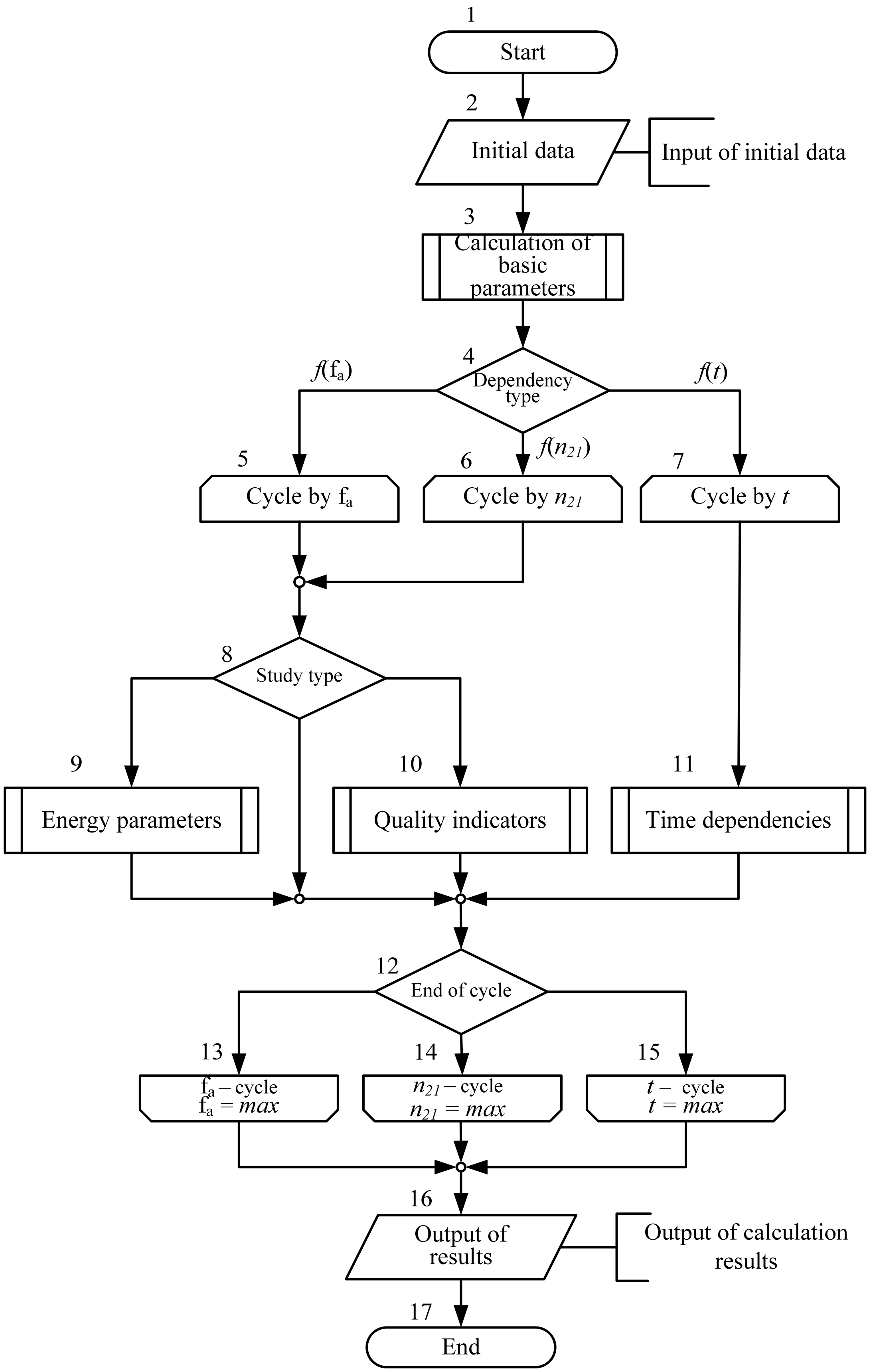

Figure 3 – DCV research algorithm

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are calculated, which are used in the corresponding calculations (time dependences, quality indicators or energy parameters) in the PWC or DCV. In bl. 4, depending on the given type of the investigated dependence, the computational process branches out: bl. 5, if the selected dependence on the accumulation coefficient – $f(f_a)$, or bl. 6, dependence on the transformation ratio – n_{21} or bl. 7, if the study of time dependences $f(t)$ is selected. The specified bl. 5, bl. 6, bl. 7 are the beginning of the corresponding cycles for the selected type of dependence. For example, for dependence on the accumulation coefficient – $f(f_a)$, in bl. 5, its minimum f_{amin} and maximum f_{amax} values are determined, as well as the step Δf_a, with which the accumulation coefficient will change. The accuracy of the calculation depends on the size of the step interval Δf_a. With an increase in Δf_a, the error increases. A decrease in Δf_a in order to increase the calculation accuracy leads to an increase in the calculation time.

In addition to calculating the parameters of elements and plotting dependencies, it is important to study the characteristics of the device under various operating modes and when changing the parameters of the elements.

To create the software, the calculation method was used [4], while the study of electrical processes is implemented in the form of an array of input data elements and the corresponding array of elements of the calculation results, that is, in the form of a function $Y_m=f(X_n)$ where Y is an array of calculation results, X is an array initial data, m – element number in the array of calculation results, n – element number in the initial data array. This makes it possible at the program level to separate the study that operates with the values of m and n from the mathematical model using the corresponding arrays of initial data – X and calculation results – Y. In this case, the control program is universal, and the change in the applied purpose of the study can be carried out by replacing the mathematical model and arrays X and Y, which are implemented using a separate dynamically linking libraries (DLL) program module. Therefore, to carry out any research using a universal control program, it is sufficient to create additional DLL [4].

The principle of operation of a specialized program for research is to calculate the array of results in the main function using the appropriate subroutines (the required set of DLL) based on the array of initial data and basic parameters (Fig. 4) [4].

To carry out automated studies of the DCV, a program was used that allows you to work with DLL [4]. At the same time, the program itself is not tied to a specific mathematical model and can be used to study a wide range of technical devices. Changing the application purpose of the program is done by replacing the dynamic library file (mathematical model).

The algorithm of the program for the research is described in detail in [4]. This control program, being a universal one, allows to carry out a wide range of automated studies of DCV in accordance with the mathematical model implemented in the DLL. When studying converters in the time domain, as well as the influence of the value of the accumulation coefficient – f_a, the transformation ratio – n_{21} and other parameters on the quality indicators and energy parameters of the DCV of the modular structure of construction, several directions can be distinguished:

1) Investigation of the influence of these parameters on the quality indicators of the DCV at a constant load power, when the load power P_{out}=const, and the consumption and load current of the k-th power channel is N times less than the total current of the DCV $P_{out}=I_{out}U_{out}$, $P_{outk}=P_{out}/N=(U_{out}I_{outk}/N)U_{out}$, $I_{outk}=I_{out}/N$. Such a construction of converters allows you to build converters from low-power (low-current) and, accordingly, cheaper element base with better dynamic characteristics. Here, the output voltage and load current of the converter are taken as the initial data, and the load resistance will be determined as $R_{out}=U_{out}/I_{out}$, and in the k-th power channel it will be $R_{outk}=U_{out}/I_{outk}$ or $R_{outk}=R_{out}\cdot N$.

2) Investigation of the influence of the above parameters on the quality indicators of the DCV with a constant power P_{outk}=const of the k-th power channel. Then the load power will increase with an increase in the number of power channels $P_{out}=NP_{outk}=(I_{outk}U_{out})N$. Such a construction of converters allows unifying the converter modules and increasing its power by connecting additional modules. Here, as the initial data, the voltage U_{out} and the current I_{outk} of the load of the k-th power channel are taken, and the load resistance of the k-th power channel will be determined, as shown in Table 1, and in the DCV it will be $R_{out}=R_{outk}\cdot N$.

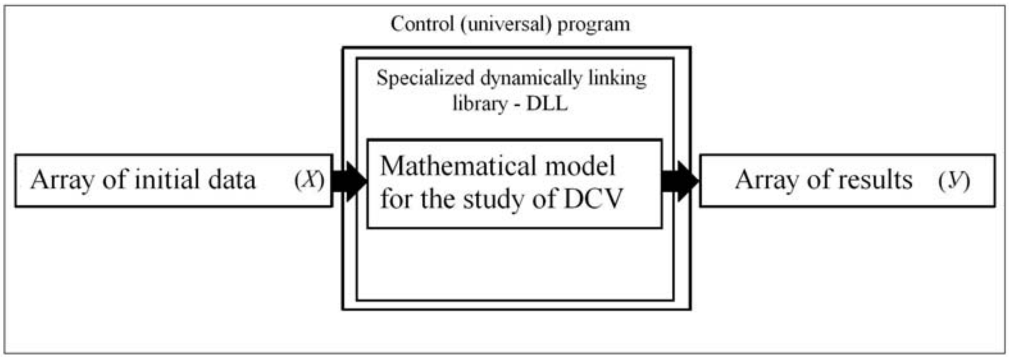

Figure 4 – The structure of an automated study using a specialized program and DLL

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For both single-phase and multiphase converters at the boundary mode of operation [5, 6], the regulation (stabilization) of the output parameters occurs by changing the frequency and duration of the control pulses, which compensate for the change in the parameters of the input voltage and load resistance. But at the same time, the frequency in individual power channels remains the same.

When researching converters of a modular structure (when the number N of power channels is increased, connecting them in parallel to each other, their equivalent inductance changes, and therefore the conversion frequency f_b, therefore the results obtained in this way are incorrect. conversion f_b it is necessary to ensure a constant value of the equivalent inductance of the choke.

When the power channels are connected in parallel to the total load, the resistance R_{out} (current I_{out}) of the load will be evenly distributed between the k-th power channels at a constant load power, when the load power P_{out}=const, ($R_{outk} = R_{out}N$) and, accordingly ($I_{outk} = I_{out}/N$).

The frequency of converting the DCV is determined by the parameters of the inductances of the chokes $L1_k$ and the load resistances R_{outk} in separate power channels. However, from [5] it follows that with a change (power P_{out}), resistance R_{outk}, at the same value of the inductance of the choke $L1_k$, the conversion frequency f_a will change accordingly.

So, the increase in the number N of power channels connected in parallel with each other at a constant value of the load power (P_{out} = const) of the converter will not cause a change in the conversion frequency (f_b), since the frequency is proportional to the value $R_{outk}/(2 \cdot L1_{kN})$, where $L1_{kN}$ – the equivalent inductance of the choke $L1_{kN} = L1_{kNmax} /N$, which is obtained when forming the equivalent circuit of the DCV from, for example, N_{max} = 8 the number of power converter modules of the same type containing N equivalent power channels with the same parameters of the elements of the power channels (Fig. 5).

In order to conduct research on converters of modular structure at a constant value of the conversion frequency f_b, it is necessary to change the inductance $L1_k$ of the chokes in proportion to the change in the resistance R_{outk} (power P_{outk}) of the load [5].

At the same time, to study converters of modular structure with single-phase and multiphase principles of transformation in the boundary mode of operation, an algorithm (Fig. 9) and a technique for calculating the basic parameters are used [5].

Let us take the following assumptions: with a single-phase conversion principle, the PWC of the converter operate synchronously and in phase, and all chokes, as connected in parallel, can be replaced with an equivalent choke $L1=L1_k/N$. Thus, a single-phase pulse converter of N modules connected in parallel with each other – PWC (Fig. 5a, 6a, 7a) can be considered as one power module (Fig. 5b, 6b, 7b), with an equivalent inductance $L1$ with the corresponding total currents in its circuits.

It should be taken into account that the distribution of the load resistance and inductance of the choke will be carried out in the SPC and MPC differently.

Depending on the direction of research, the inductance of the choke, the load resistance and, accordingly, the currents in the circuits (equivalent – Fig. 5b), 6b), 7b) of the converter will be redistributed in different ways.

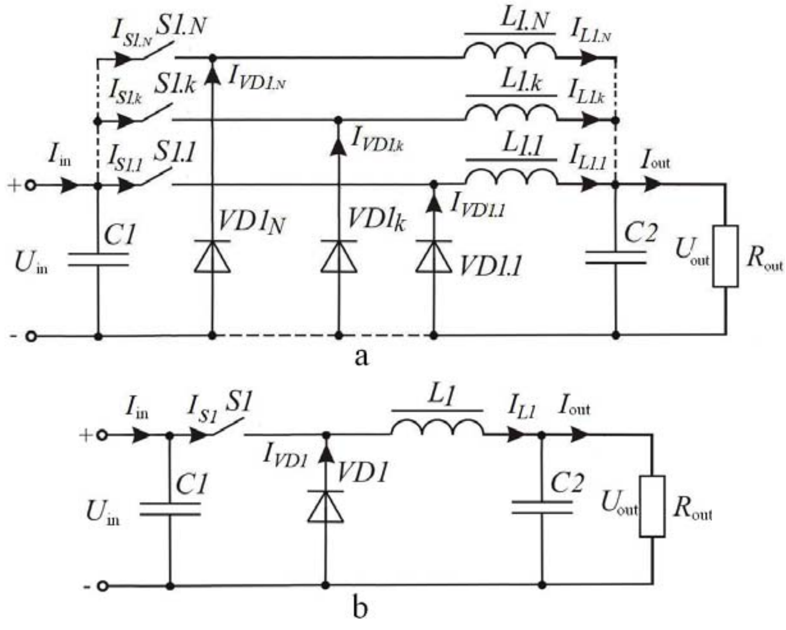

Figure 5 – Converter of modular structure of N parallel-connected PWC (a), and its equivalent circuit (b) with n_{21} = 1

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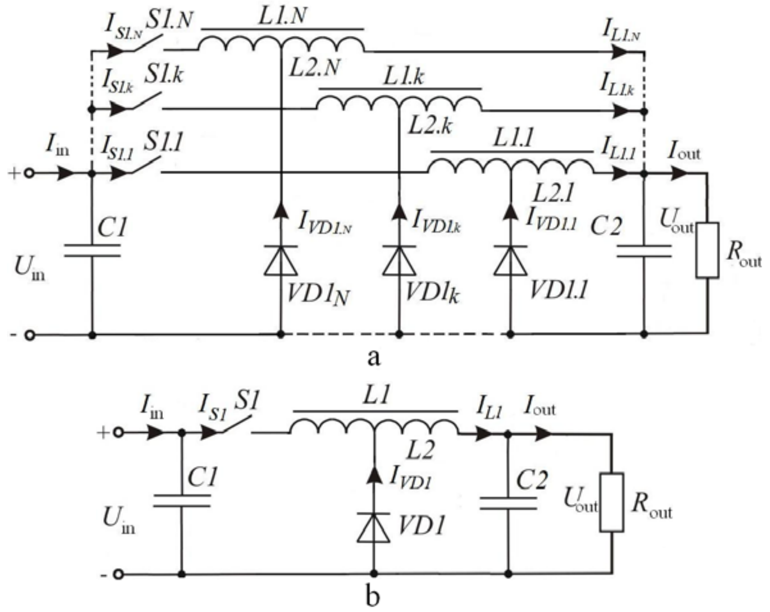

Figure 6 – Converter of modular structure of *N* parallel-connected PWC (a), and its equivalent circuit (b) with $n_{21} < 1$

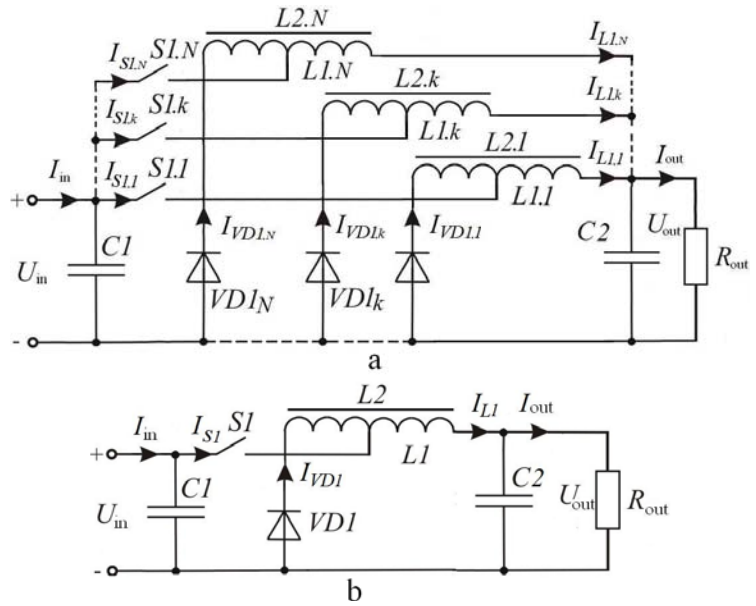

Figure 7 – Converter of modular structure of *N* parallel-connected PWC (a), and its equivalent circuit (b) with $n_{21} > 1$

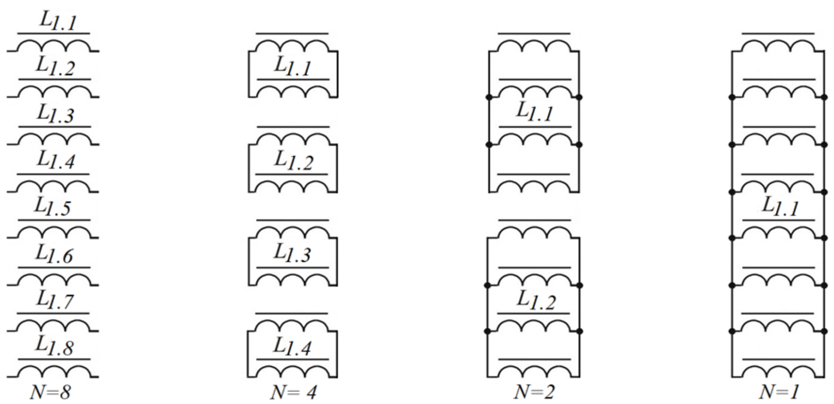

Figure 8 – Equivalent inductances $L1_{kN}$ obtained with a different number *N* of power channels connected in parallel to each other on the basis (N_{max} = 8) of eight PWC

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In this case, it should also be taken into account that if the research is carried out at a constant value of the load power P_{out} = const, regardless of other conditions, then with an increase in the number N of parallel-connected power channels, the value of the total currents in the consumption circuit I_{in} and load I_{out}, as well as their average values will not change. And the currents in the circuits of a separate k-th power channel will be N times less than the value of the indicated total currents of the DCV.

In this case, the inductance of the choke will be distributed to N power channels $L1=L1_k/N$. For example, in a single-phase converter of a modular structure of 8 parallel-connected PWC with inductance of chokes in separate power channels $L1_k$ = 100 μH, the equivalent choke $L1$ will have inductance $L1$ = 100/8 = 12.5 μH.

When forming, for example, N_{max} = 8, the number of power converter modules of the same type containing N equivalent power channels with the same parameters of elements, their equivalent circuits can be considered as a converter with N equivalent chokes $L1_{kN} = L1_{kN\max}/N$ and resistances $R_{outkN} = R_{outkN\max} \cdot /N$ k–x equivalent PWC.

If we replace the chokes $L1.1$, $L1.2$, …$L1_k$, …$L1_N$ of the converter of N power channels with equivalent L_{1kN}, for example, for N_{max} = 8, it can be seen that it is possible by combining them to form a converter with the number of N equivalent power channels ($1 \le N \le 8$) – 8-channel, 4-channel, 2-channel and SPC of 8 PWC. This approach is illustrated in Figure 8, where it is shown how, on the basis of the DCV of 8 PWC N_{max} = 8, an equivalent DCV is formed with parallel connection of the chokes, while ensuring the constancy of the conversion frequency f_b.

Table 1 shows how the equivalent resistances $R_{\text{н}kN}$ and inductances $L1_{kN}$ will be determined when forming N channel converters of eight (N_{max} = 8) identical k-th PWC.

Table 1 – Equivalent resistances and inductances of the SPC at N_{max} = 8

N	1	2	4	8
R_{outkN}	$R_{outk}/8$	$R_{outk}/4$	$R_{outk}/2$	R_{outk}
$L1_{kN}$	$L1_k/8$	$L1_k/4$	$L1_k/2$	$L1_k$

Carrying out research for SPC and MPC in different modes of operation with a different number of N PWC, provided that (P_{out}=const, I_{out}=const, R_{out}=const) and in order to ensure the constancy of the conversion frequency, the calculations must be carried out as follows:

The initial data in this case will be the parameters of the DCV – the output voltage U_{out}, the load current I_{out}, the number N PWC and the inductance of the choke $L1$.

Calculation results:

– DCV output power – $P_{out} = I_{out} \cdot U_{out}$;

– Load resistance DCV – $R_{out} = U_{out}/I_{out}$;

– Output power of the k-th PWC – $P_{outk} = P_{out}/N$;

– Load resistance of the k-th PWC – $R_{outk}=(P_{out} \cdot N)/N_{max}$;

– Load current of the k-th PWC – $I_{outk} = U_{out}/R_{outk}$;

The inductance of the choke of the k-th PWC $L1_k=(L1 \cdot N)/N_{max}$, where N_{max} is the (basic) maximum number of PWC from which the DCV is formed. For example, as shown in Figure 8, N_{max} = 8.

Further in Table 2, the main (basic) parameters of inductance, resistance, power and current of the k-th power channel corresponding to the indicated type of research are given, with P_{out}=const.

Table 2 – Main (basic) parameters of DCV at P_{out} = const

	N	$L1_k$	R_{outk}	P_{outk}	I_{outk}
P_{out} = const I_{out} = const R_{out} = const f_b = const	8	$L1$	R_{out}	$P_{out}/8$	$I_{out}/8$
	4	$L1/2$	$R_{out}/2$	$P_{out}/4$	$I_{out}/4$
	2	$L1/4$	$R_{out}/4$	$P_{out}/2$	$I_{out}/2$
	1	$L1/8$	$R_{out}/8$	P_{out}	I_{out}

When conducting a study of the dependences of quality indicators on the parameters of the elements of the power channels in various modes of operation with a different number N of PWC, provided that (P_{outk}=const, I_{outk}=const, R_{outk}=const) with the same constant frequency as in the previous case conversion f_b, calculations must be carried out in accordance with Table 3.

The initial data in this case will be the output voltage U_{out}, the load current I_{outk} of the k-th PWC, the number N of power channels and the inductance of the choke $L1$.

Calculation results:

– Output power of the k-th PWC – $P_{outk} = U_{out} \cdot I_{outk}$;

– DCV output power – $P_{out} = P_{outk} \cdot N$;

– Load current DCV – $I_{out} = I_{outk} \cdot N$;

– Load resistance of the k-th PWC – $R_{outk} = U_{out}/I_{outk}$;

– Load resistance DCV – $R_{out} = U_{out}/I_{out}$;

– The inductance of the k-th PWC choke $L1_k=L1$.

Taking into account the foregoing, the following algorithm for analyzing the electrical processes of the DCV with increasing N number of power channels with a constant power of the k-th PWC P_{outk} = const (proportional increase in the output power of the DCV and at a constant load power P_{out} = const (implementation of the DCV from a larger number N of power channels of lower power). Thus, the equivalent inductance $L1_{kN}$ and the resistance R_{outkN} of the k-th power channels will be determined differently (Tables 2, 3).

Table 3 – Main (basic) parameters of DCV at P_{outk} = const

	N	R_{out}	P_{out}	I_{out}
P_{outk} = const I_{outk} = const R_{outk} = const f_b = const $L1_k$ = const	8	$R_{out}/8$	$8P_{out}$	$8I_{outk}$
	4	$R_{out}/4$	$4P_{out}$	$4I_{outk}$
	2	$R_{out}/2$	$2P_{out}$	$2I_{outk}$
	1	R_{out}	P_{out}	I_{outk}

To obtain correct results, it is necessary to take into account the indicated features of calculating the parameters of the DCV when studying the electrical processes of the converter, both in the time domain and the dependences on the accumulation coefficients (f_a), transformation (n_{21}), the value of the relative supply voltage ($\bar{U}_{in}$), the number N of power channels and value of output power (P_{out}) of the DCV.

For all the specified studies of the DCV, the basic parameters U_{in}, T, f_b, $L2_k$, R_{outk}, R_{out}, I_{in}, P_{in}, P_{out}, I_{m1}, I_{m2} necessary for carrying out the necessary studies will be calculated in the SR, the conditional name of which is “Basic parameters” The initial data in the SP for calculations will use the parameters presented in Table 4.

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Table 4 – Initial data for calculating electrical processes

№	Designation	Name
1	U_{out}	Output voltage (load)
2	I_{out}	Output current (load) DCV
3	I_{outk}	Output current (load of the *k*-th PWC)
4	N	The number of power channels DCV
5	f_b	Accumulation factor
6	$L1$	Primary winding inductance of the choke *W*1
7	n_{21}	Transformation coefficient
8	N_{max}	Maximum number of power channels DCV
9	C_{in}	Capacitance of the input filter capacitor
10	C_{out}	Capacitance of the output filter capacitor
11	$\bar{U}_{in}$	Relative supply voltage
12	R_r	Operating mode – stabilization (tracking)
13	R_p	Conversion mode – SPC (MPC)
14	$P_{out}mode$	Type of calculation: P_{out}=const, (P_{outk}=const)

The main basic parameters of the *k*-th power channel PWC (coefficients of accumulation f_{ak} and return f_{rk}, power supply voltage U_{ink}, load resistance R_{outk}, conversion frequency $f_{bk}=1/T_{bk}$, accumulation time t_{ak} and return time t_{rk} of energy by a power choke, current ripple ranges I_{m1k}, I_{m2k} of the choke, average values of current consumption I_{ink} and load I_{outk}, out power P_{outk}) are presented in Table 5.

In the case under consideration, with the symmetry of the electrical processes and the identity of the parameters of the elements in the *k*-th PWC DCV $U_{ink}=U_{in}$, $U_{outk}=U_{out}$, $f_{bk}=f_b$, $T_{bk}=T_b=1/f_b$, $f_{ak}=f_a$, $f_{rk}=f_r$, $W_{1k}= W_1$, $W_{2k}= W_2$, $t_{ak}=t_a$, $t_{rk}=t_r$, $I_{ink}=I_{in}/N$, $I_{outk}=I_{out}/N$, $I_{m1k}=I_{m1}$, $I_{m2k}=I_{m2}$.

In this case, the indicated intermediate (basic parameters) will be preliminarily calculated, which are the initial data for subsequent calculations and studies using the ratios that are presented in Table 5.

Table 5 – Basic parameters of electrical processes of *k*-th PWC

№	Designation	Name
1	R_{outk}	Load resistance *k*-th PWC
2	P_{outk}	Load power *k*-th PWC
3	f_{ak}	Accumulation factor *k*-th PWC
4	f_{rk}	Return factor *k*-th PWC
5	U_{ink}	Input voltage (power supply) *k*-th PWC
6	f_{bk}	The boundary value of the conversion frequency
7	T_k	Conversion period
8	I_{m1k}	choke current ripple on accumulation interval
9	I_{m2k}	Choke current ripple on return interval
10	I_{ink}	Average current consumption *k*-th PWC
11	$\bar{U}_{ink}$	Relative supply voltage *k*-th PWC
12	$\bar{U}_{outk}$	Relative load voltage *k*-th PWC
13	I_{outk}	Load current *k*-th PWC
14	$L1_k$	Inductance of winding *W*1 of the inductor *k*-th PWC
15	$L2_k$	Inductance of winding *W*2 of the inductor *k*-th PWC

Using a mathematical model [2, 3] and algorithms (Fig. 3, 9), software has been developed for the automated study of DC voltage converters [6, 7].

5 RESULTS

Using the specified software, the dependences of the energy parameters were obtained (Fig. 10 – Fig. 12). The dependences of the relative effective values of the currents of the switch $S1_k$ and the diode $VD1_k$ are shown in Fig. 10. The first study (Fig. 10 a) was carried out at a fixed load voltage and a variable input voltage (the input voltage was set in such a way that at a given accumulation factor f_a the output voltage remained constant. The second study was carried out at a fixed ratio of input and output voltages $\bar{U}_{in}$ of the converter (Fig. 10 b).

The analysis of the conducted studies shows that the influence of the transformation ratio of the choke on the relative effective values of the currents of the keys $S1_k$ (I_{eS1k}/I_{outk}) and $VD1_k$ (I_{eVD1k}/I_{outk}) (where I_{outk} is the load current of the power channel) is quantitatively and qualitatively the same as for a fixed power of the power P_{outk}=const (when the power of the converter is proportional to the number of power channels $P_{out}= NP_{outk}$), and for a fixed power of the converter P_{out}=const (when the power of PWC is inversely proportional to the number of power channels $P_{outk} = P_{out}/N$).

From the graphs (Fig. 10) it can be seen that by choosing the transformation ratio of the choke, it is possible to increase or decrease the relative currents of the power switching elements. In this case, the degree of influence of the transformation ratio of the choke depends both on the value of the accumulation coefficient and on the value of the relative supply voltage.

With the accumulation coefficient f_a = 0.5 and the transformation ratio of the choke n_{21} = 1, the relative effective current of the key $S1_k$ is equal to the relative effective current of the diode $VD1_k$ (Fig. 10 a). This is due to the equality of both the relative durations of the open state of these power switching elements (f_a = f_r) and the range of their pulsations ($I_{m1} = I_{m2}$) (Fig. 11 a). This feature of the operation of the power section of the converters is useful in practice, since it allows the use of power elements $S1_k$ and $VD1_k$ with the same installed power or, in the case when a transistor is used instead of the diode $VD1_k$, the same elements. The operation of the converter at a different value of *kn* leads to a redistribution of the effective values of the currents of the power switching elements. With an increase in f_a, the relative effective current of the transistor $S1_k$ increases, the diode $VD1_k$ decreases (Fig. 10 a). A decrease in kn leads to the opposite phenomenon: a decrease in the relative effective current of the transistor S1k and an increase in the relative effective current of the diode $VD1_k$.

Choosing the transformation ratio of the choke allows you to align the relative effective values of the currents of the power switching elements. So, for example, with the accumulation coefficient f_a = 0.2, the equality of the relative effective values of the currents $\bar{I}_{eS1k} = \bar{I}_{eVD1k}$ occurs when using a choke with a transformation ratio n_{21} = 2, and for f_a = 0.8 – at n_{21} = 0.5 (Fig. 6, but). The diagrams of the choke currents for this case are illustrated in the figure in 11, b, c.

The dependence of the relative operating currents of the switches $S1_k$ and $VD1_k$ on the value of the transformation ratio n_{21} at various values of the relative supply voltage $\bar{U}_{in}$ is shown in Fig. 12.

It can be seen from the graphs that an increase in the transformation ratio n_{21} leads to an increase in the relative effective current of the switch $S1_k$, and a decrease in the

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relative current of the diode $VD1_k$ at any values of the relative supply voltage $\bar{U}_{\text{in}}$.

However, the degree of influence of the transformation ratio of the choke on the values of the relative effective currents of the power elements is different. Thus, in the range $1 < n_{21} < 5$, the relative effective value of the diode current decreases by 0.75 times, while the relative effective value of the current increases by 1.5 times (Fig. 12).

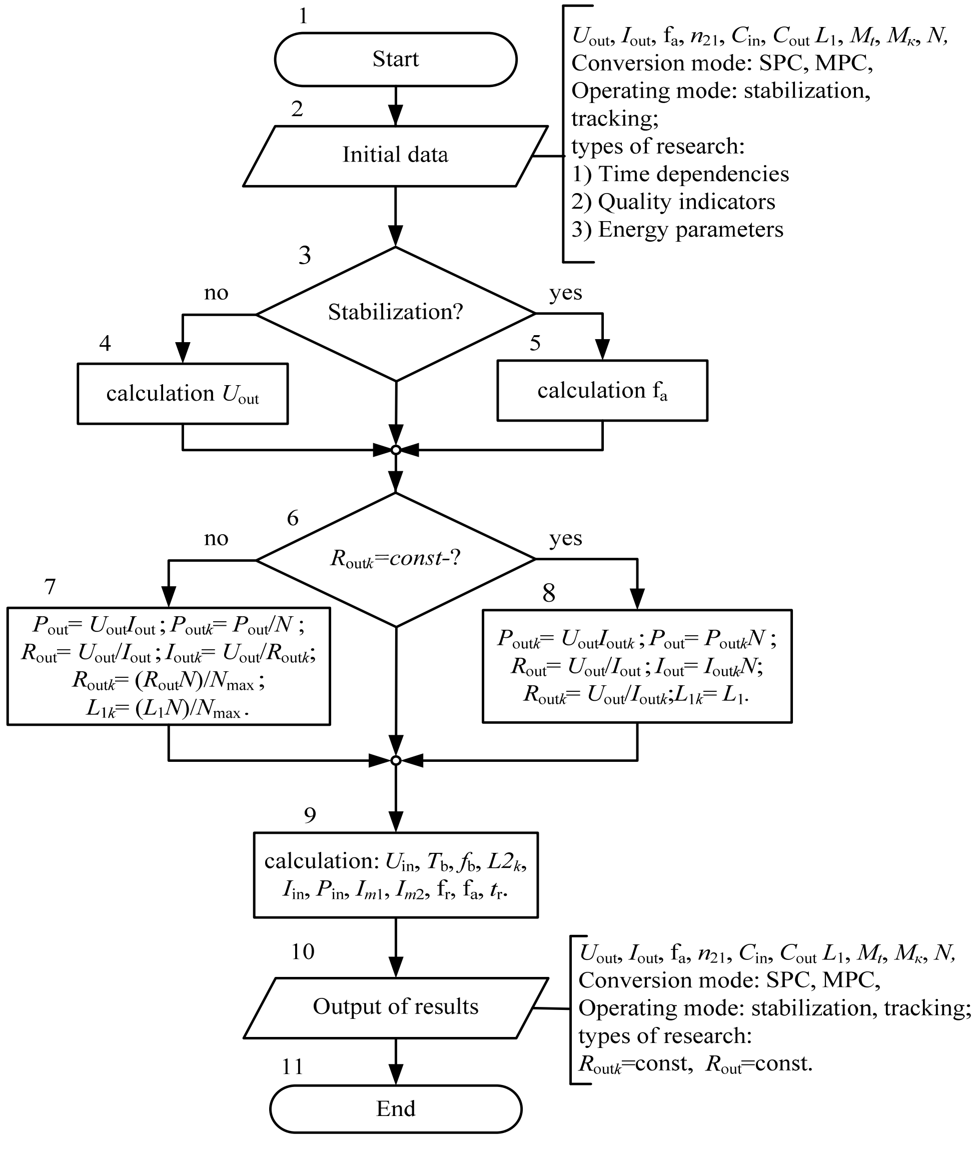

Figure 9 – Algorithm for calculating basic parameters

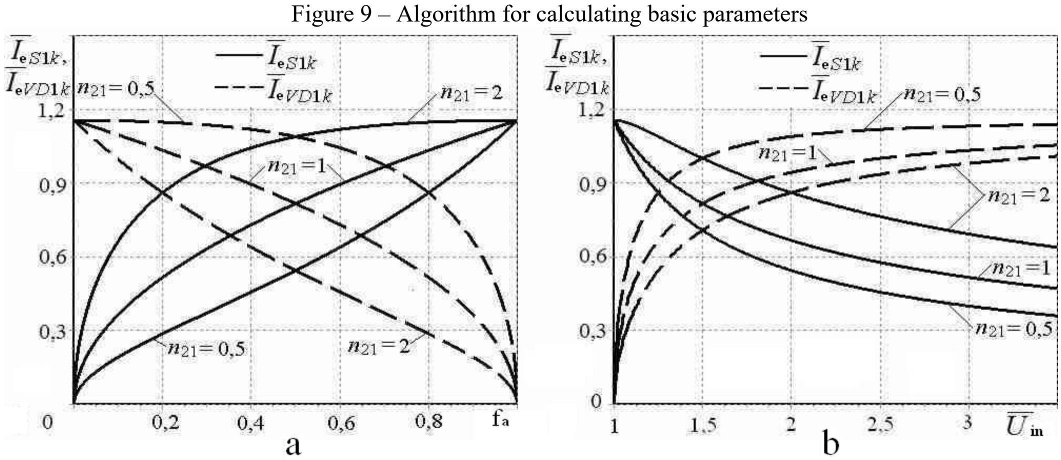

Figure 10 – Dependences of the effective currents value of switches $S1_k$ and $VD1_k$ on f_a (a), and on $\bar{U}_{\text{in}}$ (b) for different values n_{21}

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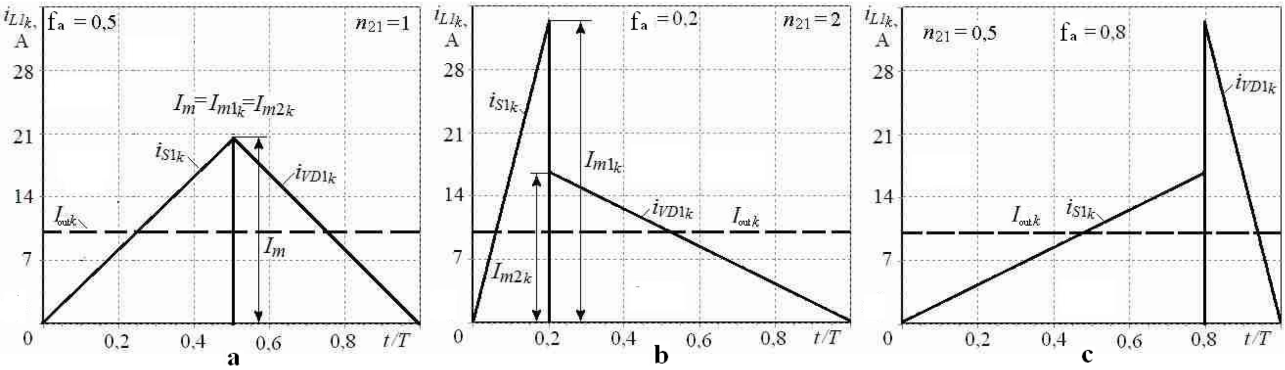
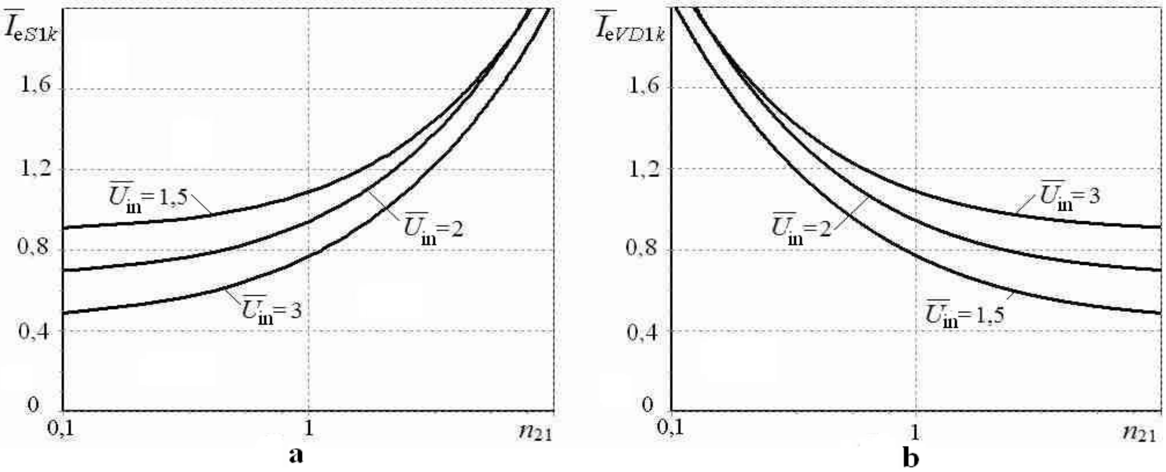


Figure 11 – Timing diagrams of choke currents of the PWC $i_{outk}(t)$ at, U_{out} = const, f_{ak} = 0.5 and n_{21} =1 (a), f_{ak} = 0.2 and n_{21} = 2 (b), f_{ak} = 0.8 and n_{21} = 0.5



(c).

Figure 12 – Dependence of the effective value of the currents of the keys $S1_k$ (a) and $VD1_k$ (b), on n_{21} at different values of the relative supply voltage $\bar{U}_{in}$

6 DISCUSSION

Thus, to equalize the effective values of the currents in the power switching elements in the tracking mode with the accumulation ratio f_a < 0.5, it is necessary to use a choke with a transformation ratio $n_{21} < 1$, with an accumulation ratio f_a > 0.5, it is necessary to use an inductor with a transformation ratio $n_{21} > 1$. In the stabilization mode, to equalize the effective value of the current between the power switching elements with a supply voltage to load ratio $\bar{U}_{in} > 2$, it is necessary to use a choke with a transformation ratio $n_{21} > 1$, with $\bar{U}_{in}$ <2, the transformation ratio of the choke should be less than one $n_{21} < 1$. It should also be noted, that when the effective values of the currents in the power switching elements are equal, the relative effective value of the current in them is 50% of the load current ($\bar{I}_{eS1k} = \bar{I}_{eVD1k}$=0.5).

CONCLUSIONS

Based on the results of this article, the following conclusions can be drawn:

The paper discusses the main methods of automated research and design of radio engineering devices that can be used to analyze the electrical processes of pulsed DC voltage converters of a modular structure.

The main tasks to be solved by the developed software are formulated; the basic requirements for the software for the study of pulsed DCV are given; with the help of the information model of the software complex, the connection of the research tasks to be solved with individual software modules is shown.

Algorithms of calculations are given, the analysis of research results obtained using the proposed method is given.

The scientific novelty of obtained results is that the algorithms and software modules have been firstly developed that constitute the computational basis for the analysis and study of electrical processes and energy parameters of converters of modular structure.

The practical significance of obtained results is that the developed calculation algorithms and software can be used to solve the problems of analysis and research of DCV, which have increased functional capabilities in comparison with the existing CAD systems of radio engineering devices.

Prospects for further research – the proposed approach is the basis for solving the problems of research and design of DCV of modular structure, plays an important role in identifying the features of functioning, choosing the optimal modes of its functioning and the option of circuit design.

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АНАЛІЗ МЕТОДІВ АВТОМАТИЗОВАНОГО ДОСЛІДЖЕННЯ ПЕРЕТВОРЮВАЧІВ ПОСТІЙНОЇ НАПРУГИ МОДУЛЬНОЇ СТРУКТУРИ

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АНОТАЦІЯ

Актуальність. Перетворювачі постійної напруги (ППН) входять до складу сучасних систем електроживлення (СЕЖ) та електропостачання, забезпечуючи роботу електронних та радіотехнічних пристроїв, телекомунікаційних систем та апаратури зв'язку, значною мірою визначаючи їх енергоспоживання, надійність, час готовності до роботи, масо-габаритні та вартісні показники. Незважаючи на те, що в інженерній практиці використовується велика кількість різних пакетів програм для дослідження та проектування радіотехнічних пристроїв, такі системи автоматизованого проектування (САПР) та віртуального комп'ютерного моделювання електронних схем мають деякі обмеження, що не дозволяють швидко провести весь комплекс досліджень ППН, необхідний для аналізу електричних процесів за різних режимів роботи апаратури.

Ціль. В даному розділі метою є вибір найбільш підходящих методів та алгоритмів, що дозволять розробити програмне забезпечення, необхідне для вирішення завдань дослідження та аналізу електричних процесів та енергетичних параметрів ППН модульної структури в окремо взятому силовому каналі (СК).

Метод. В роботі запропонований метод, який полягає у використанні математичних моделей, що описують електричні процеси в перетворювачах постійної напруги і створенні на базі розроблених алгоритмів розрахунку, спеціалізованого програмного забезпечення для автоматизованого дослідження електричних процесів в ППН модульної структури за допомогою ЕОМ.

Результати. В роботі розглянуті основні методи автоматизованого дослідження радіотехнічних пристроїв, які можна використовувати для аналізу електричних процесів імпульсних перетворювачів постійної напруги модульної структури. Наведено алгоритми розрахунку і, як приклад, деякі результати автоматизованого дослідження, отримані при використанні даного методу.

Висновки. Проведено аналіз відомих методів автоматизованого дослідження перетворювачів постійної напруги модульної структури. Наведено їх переваги та недоліки. Показано, що найбільш підходящим є метод, заснований на використанні математичних моделей, що описують електричні процеси в перетворювачах постійної напруги даного типу. На основі наведених у другому розділі роботи математичних моделей, були розроблені алгоритми і спеціалізоване програмне забезпечення, які дозволяють широко їх використовувати при автоматизованому дослідженні і проектуванні перетворювачів постійної напруги модульної структури.

КЛЮЧОВІ СЛОВА: модульні перетворювачі напруги, силовий канал, режими роботи перетворювача, алгоритм дослідження електричних процесів.

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АНАЛИЗ МЕТОДОВ АВТОМАТИЗИРОВАННОГО ИССЛЕДОВАНИЯ ПРЕОБРАЗОВАТЕЛЕЙ ПОСТОЯННОГО НАПРЯЖЕНИЯ МОДУЛЬНОЙ СТРУКТУРЫ

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АННОТАЦИЯ

Актуальность. Преобразователи постоянного напряжения (ПНН) входят в состав современных систем электропитания (СЭП) и электроснабжения, обеспечивая работу электронных и радиотехнических устройств, телекоммуникационных систем и аппаратуры связи, в значительной степени определяя их энергопотребление, надежность, время готовности к работе, массогабаритные и стоимостные показатели. Несмотря на то, что в инженерной практике используется большое количество различных пакетов программ для исследования и проектирования радиотехнических устройств, такие системы автоматизированного проектирования (САПР) и виртуального компьютерного моделирования электронных схем имеют некоторые ограничения, не позволяющие быстро провести весь комплекс исследований ППН, необходимый для анализа электрических процессов при различных режимах работы аппаратуры.

Цель. В данном разделе целью является выбор наиболее подходящих методов и алгоритмов, что позволят разработать программное обеспечение, необходимое для решения задач исследования и анализа электрических процессов и энергетических параметров ППН модульной структуры в отдельно взятом силовом канале (СК).

Метод. В работе предложен метод, который заключается в использовании математических моделей, описывающих электрические процессы в преобразователях постоянного напряжения и создании на базе разработанных алгоритмов расчета, специализированного программного обеспечения для автоматизированного исследования электрических процессов в ППН модульной структуры при помощи ЭВМ.

Результаты. В работе рассмотрены основные методы автоматизированного исследования радиотехнических устройств, которые можно использовать для анализа электрических процессов импульсных преобразователей постоянного напряжения модульной структуры. Приведены алгоритмы расчета и, в качестве примера, некоторые результаты автоматизированного исследования, полученные при использовании данного метода.

Выводы. Проведен анализ известных методов автоматизированного исследования преобразователей постоянного напряжения модульной структуры. Приведены их преимущества и недостатки. Показано, что наиболее подходящим является метод, основанный на использовании математических моделей, описывающих электрические процессы в преобразователях постоянного напряжения данного типа. На основе приведенных во втором разделе работы математических моделях были разработаны алгоритмы и специализированное программное обеспечение, которые позволяют широко их использовать при автоматизированном исследовании и проектировании преобразователей постоянного напряжения модульной структуры.

КЛЮЧЕВЫЕ СЛОВА: модульные преобразователи напряжения, силовой канал, режимы работы преобразователя, алгоритм исследования электрических процессов.

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