PROCEDURE FOR THE SYNTHESIS OF MODELS OF ELECTRO-TECHNICAL COMPLEXES

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Розглянуто методику розробки візуальних математичних моделей складних багатоканальних електротехнічних комплексів, яка дозволяє скоротити час синтезу математичних моделей та зменшити ймовірність помилки. Методика складається з двох етапів: представлення електротехнічного комплексу у формі структури енергетичного тракту та перетворення її у візуально-блокову модель.

Представлення системи у вигляді структури енергетичних трактів засновано на запропонованому авторами принципі декомпозиції системи, який передбачає відокремлення у структурі перетворення потужності шістьох типів структурних елементів: джерела та приймача, розподільника та консолідатора, перетворювача енергії та накопичувача енергії.

Принцип декомпозиції дозволяє сформувати бібліотеку моделей субблоків-компонентів візуальної-блокової моделі та ввести уніфікацію позначень субблоків.

З метою ілюстрації запропонованої методики розглянуто приклад побудови візуальної моделі електропривода постійного струму валка прокатного стана та його реалізацію на персональному комп'ютері.

Приведено фрагмент бібліотеки компонентів візуально-блокової моделі з математичним описом компонентів, які входять до розглянутого прикладу.

Введена уніфікація створює умови для ефективної роботи розробника в напрямку розвитку даної методики синтезу моделей в частині формування бібліотеки субблоків. Крім того, уніфікація форми подання компонент бібліотеки створює умови для ефективної комунікації дослідників і розробників у рамках складних комплексних проектів.

Модель на стадії структури енергетичних трактів є вигідним інструментом візуалізації роботи системи та сприяє розумінню її функціонування.

Форма отриманої математичної моделі є зручною для подальшого перетворення її в модель у змінних стану, яка, в свою чергу, є відправною точкою при синтезі систем управління

Ключові слова: електротехнічний комплекс, принцип декомпозиції, енергетичний тракт, компонент системи, візуально-блокова модель

1. Introduction

Synthesis of a mathematical model of an electrotechnical complex is one of the important stages when creating it. Synthesis is used not only as a tool to verify effectiveness and operational capability of technical solutions for power equipment but also as a basis for the procedure of control system synthesis where electrical equipment acts as a control object. Regarding the latter case, it should be noted that according to experts [1], the procedure of synthesis of a mathematical model averages 80–90 % of the labor input in designing control systems.

The use of libraries of system components is the main means to reduce time spent for synthesis and refinement of a mathematical model as well as minimizing intensity of errors in mathematical modeling. A form of the created libraries of model components is influenced by the adopted principle of decomposition of the system for which a model must be synthesized.

However, not any system decomposition leads to a positive result in order to get subsystems more available for analysis. Rationality of decomposition is assessed from the point of view of integrity: if decomposition is unsuccessful, system and subsystem concepts cannot be interlinked and the consistency between them is lost. Decomposition should identify explicit subsystem properties and related concepts [2].

Conditionally speaking, aggregate principle is the widespread principle of decomposition. In accordance with this principle, a separate device being a component of electrotechnical complex and having certain design outlines is the element of the system as applied to the electrotechnical complex.

The aggregate approach to decomposition has an undoubted advantage since it reflects real structural units that the developer uses. However, this approach does not reflect the structure of energy paths and does not make it possible to analyze energy flows passing in electrotechnical complexes. The relevance of this problem becomes apparent when electrotechnical complex is a branched structure for conversion and transmission of energy.

2. Literature review and problem statement

Modeling of electrical systems can be referred to the so-called multidisciplinary modeling. An electrotechnical

complex may include subsystems of any physical nature. Methodological problems of multidisciplinary modeling were addressed in [3]. In particular, it is indicated that many modeling languages have been developed over the years, however not each of them is fully suitable for synthesis of multidisciplinary models. One of the requirements to a modeling language is expressiveness in describing physical processes under consideration. Another requirement implies creation of favorable conditions for re-employment of the previously created model. It is also indicated that it is necessary to develop a modeling paradigm that can be integrated into the project environment, even at minimal experience in analysis. An important aspect of model synthesis is also creation of conditions for joint teamwork of a group of specialists in various fields of knowledge.

It is indicated in [4] that development of complex systems is shifting towards the joint paradigm. Therefore, environment for building models should take into account collaboration within the project team and support multidisciplinary modeling. However, modern modeling tools do not fully meet this requirement since they were designed to solve specific problems from different disciplines.

In [5], possibility of embedding an electric drive into a model as its component is not considered when building an electrical machine model.

Similarly, in [6], it is difficult to use the developed model as part of a power system model when developing a photoconverter model without transforming its structure.

The aggregate principle of decomposition was used in model synthesis together with combining levels of decomposition [7]. This approach has a disadvantage of not allowing introduction of unification of library elements. The likely goal of aggregation is a more compact record of the visional model.

A common approach in which several domains of the modeling language are combined is used in [8] when building a model. In this case, these are electrical circuit diagrams and structural equations. Combination of several domains in one model also makes unification difficult.

An accumulator battery model is formed in [9] as a component to be used in macromodels. However, similar to [8], the multi-domain principle is applied.

Characteristic features of the considered approaches include:
– sharing of different levels of system decomposition in one model;
– an impossibility to introduce unification of blocks;
– the absence of a formalized model synthesis procedure;
– a lack of a systematic approach to the synthesis procedure.

The above features of approaches to model synthesis do not create favorable conditions for communication of specialists involved in projects of development of electrotechnical complexes. This fact is particularly relevant for the projects that require participation of specialists in various knowledge areas and does not create conditions for knowledge accumulation.

It should be noted that the works cited above do not consider the issues of structure description for branched energy paths in which energy flow redistribution takes place.

It can be concluded from an analysis of the published data that there is an urgent problem to create more advanced procedures for synthesizing mathematical models of electrotechnical complexes. A number of actual requirements to development of these procedures can also be formulated:

– the necessity of unification of sub-block subsystems;
– availability of visualization of the model structure;
– creation of favorable conditions for formation of component libraries;
– creation of conditions for knowledge accumulation;
– creation of conditions for efficient communication between various experts involved in projects;
– maximum formalization of the synthesis procedure itself;
– creation of conditions for integration of descriptions in other design tools.

3. The aim and objectives of the study

The study objective was to develop a more advanced, as compared with the aggregate approach, procedure for synthesizing mathematical models of electrotechnical complexes, which would make it possible to reduce time for their creation, refinement and application.

To achieve the study objective, the following tasks were set forth:
– formulate the principle of decomposition of electrotechnical complex as a structure of energy path;
– introduce unification of the subsystem blocks of the visual-block model;
– develop the library components of the visual-block model for electrotechnical complexes;
– check operational capability of the proposed method by conducting a model experiment.

4. General principles of constructing a mathematical model

An approach to decomposition is considered in which electrotechnical complex is represented not as a set of interconnected units (devices) but as an energy path.

In general, structure of the energy path may be branched. Elements of this structure are functional units relative to the energy that is transmitted via the complex. In this case, energy approach is used in representation of an electrotechnical complex. This approach to building models was given in [10] for modeling multichannel electromechanical systems of wind power plants.

The considered principle of decomposition involves selection of a closed set of six elements [10] which have definite designation in the energy path circuit (EPC):
– $\triangleright$ for an energy source;
– $\triangleleft$ for an energy receiver;
– $\square$ for an energy converter;
– $\diamondsuit$ for energy storage;
– $\bigcirc$ for a distribution node (energy distributor);
– $\bigcirc$ for a consolidating node (energy consolidator).

For convenience, a mnemonic symbol indicating physical nature of this element is placed inside the structural element [10].

Electrical complex is represented as an energy object through which energy flows. Therefore, energy source and energy receiver are obligatory elements of this structure. The energy source is an element of the energy path that converts the energy flow coming from the external environment into the energy flow within the system. Similarly, the energy receiver converts energy flows inside the electrotechnical

complex into energy flows leaving the system for external environment. Both elements act as an intermediary between the electrotechnical complex and the external environment. The remaining elements can be either included in the system or absent.

The transformation element reflects function of changing form of the energy flow in which there is no branching of the energy flow.

The energy storage element reflects function of energy storage. For an electrotechnical complex, this element may be associated with the following processes in the system:

– energy accumulation in inertial masses;

– energy accumulation in elastic elements of the structure;

– energy accumulation in an electrical capacitance;

– energy accumulation in an inductance;

– accumulation of thermal energy due to heat capacity, etc.

It should be noted that the element function is set in accordance with the purpose of the element specified by the developer. In this case, processes that are not related to this function may take place in it. For example, ohmic losses associated with the conversion function may take place in inductive storage device since the energy changes from electrical form to thermal one. In addition, a branching function may be present in the element because of power loss. In this case, division into main and loss streams occurs in the element. If necessary, this branching may be reflected in the path structure. However, it is inappropriate from the point of view of the chosen concept. It is expedient to reflect the energy functions relating to the main purpose of the electrotechnical complex elements in the structure only. Secondary functions (losses, parasitic capacitances, inductances, etc.) must be included inside the structural element in this case.

Distributor and consolidator make it possible to describe multi-channel structures in a form of an energy path. In this case, attention should be paid to peculiarity of structure of cause-and-effect relationships of these elements. As a result of analysis of various schemes of electrotechnical complexes, a fundamental pattern was revealed which can be expressed in a form of the following dual rules:

– in the distribution unit being an element of the structure of the cause-and-effect relationships, direct cause-and-effect relationship passes to the nod outputs and feedback is subjected to summation;

– in the consolidating unit being an element of the structure of the cause-and-effect relationships, on the contrary, direct cause-and-effect relationship is subjected to summation and feedback is transmitted to the nod inputs.

5. An example of synthesis of a mathematical model

To illustrate the method, consider an example of constructing a relatively simple mathematical model of electrical equipment constituting an electric drive for a sheet metal rolling roll. Its functional diagram is shown in Fig. 1. The roll is driven for rotation with the help of two DC motors (M1 and M2), rigidly fixed at the roll ends. The motors are connected to the power source through DC voltage pulse converters. Their filling factor is formed by the Controller control circuit through the Dr drivers. The control circuit generates control signals according to the feedback signals from the rotor current sensors (CS1 and CS2), the roll angular velocity sensor (SpS) and the signal of targeted rotation speed, ω_{targ}.

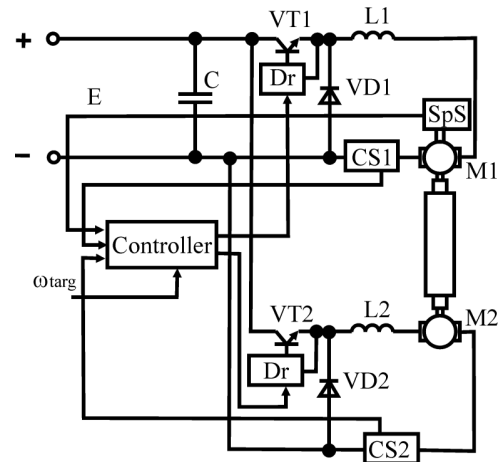The drive is controlled by slave regulation.

Fig. 1. A drive functional diagram

The energy path diagram corresponding to the functional diagram is shown in Fig. 2. The energy path is a two-channel structure. A DC main is the energy source and the roll mechanism itself is the energy receiver.
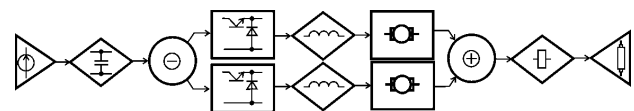

Fig. 2. An energy path diagram

The scheme contains two common energy storage devices: input capacitance and flyweights. Branching of energy flows is described using a distributor and a consolidator, respectively.

At the next stage, the energy path elements are replaced by the corresponding elements from the library of elements of the visual-block model (VBM) (Fig. 3). The VBM elements are placed in the same positions as the EPC elements. After placement of the VBM elements, they are connected in a form of directed segments as shown in Fig. 3. First, direct cause-and-effect relations are introduced and then feedbacks are closed.

Completeness of the model is formally determined by absence of "open" inputs of all VBM elements. Besides, input values are present in the VBM structure. In the case under consideration, these are the filling factors, γ, of the direct-voltage transducers.
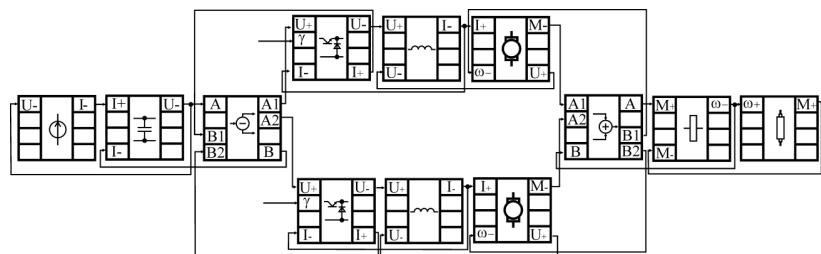

Fig. 3. A visual-block model diagram

6. The library of the visual-block model elements

Next, consider a fragment of the library for constructing the VBM under consideration. A DC voltage source is shown in Fig. 4. Rectification circuit is not considered in this presentation. Moreover, the R_{int} parameter determines slope of the current-voltage characteristics of the DC voltage source.
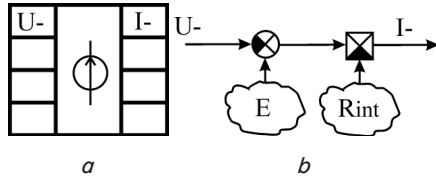

Fig. 4. A direct voltage source: designation (*a*); visual model (*b*)

Capacitive energy storage is shown in Fig. 5. The model is presented in an integral form taking into account initial voltage on the capacitor. This assumption does not include capacitance losses. Input values include the capacitor charge current, I+, and the discharge current, I−, respectively. Voltage on the capacitor, U−, is output value.
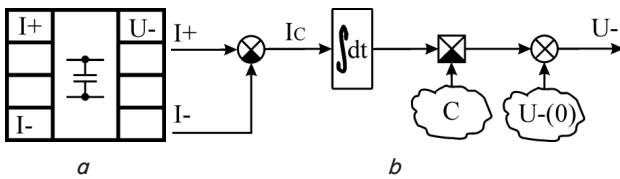

Fig. 5. A capacitive energy storage: designation (*a*); visual model (*b*)

A two-channel distributor is shown in Fig. 6. When energy is directed from left to right, the direct cause-and-effect relationship "A" is represented by a simple node. The summing node corresponds to the feedback "B" passing through the energy distributor (as mentioned above).
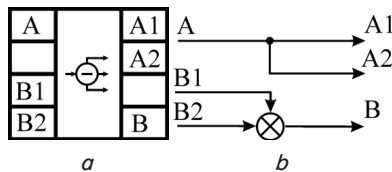

Fig. 6. A simple two-channel distribution node: designation (*a*); visual model (*b*)

A pulse converter of DC voltage of step-down type is shown in Fig. 7. This model describes a pulsed source in values which are mean for the period of key operation. Such description significantly reduces time of modeling the electrotechnical complex which includes a pulsed source of DC voltage.

It should be noted that with the accepted decomposition method and the approach to formation of a library of VBM elements, this element does not describe the entire device but only a part of the scheme with key elements. Voltage at the source input, U+, current at the source output, I−, and the coefficient of filling of the transistor key, γ, are the input values from the point of view of the system of cause-and-effect relationships. Voltage at the source output, U−, and current at the source input, I+, are the output parameters of the model. In this assumption, the model does not describe

a discontinuous current mode. The model takes into account losses in the semiconductor keys of the circuit in the form of direct voltage drops on the transistor, U_{on_VT}, and the diode, U_{on_VD}, taking into account differential resistances, R_{on_VT}, R_{on_VD}, on the keys respectively.
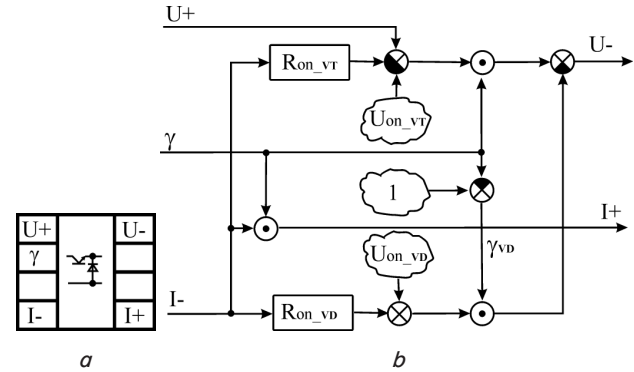

Fig. 7. The pulsed source of DC voltage of step-down type: designation (*a*); visual model (*b*)

An inductive storage is shown in Fig. 8. The model is presented in an integral form taking into account the initial current passing through the inductance, L, and losses which are taken into account with the help of the R_L parameter. Voltage at the input, U+, and voltage at the output, U−, respectively, are input values. Current passing through the inductance, I−, is the output value.
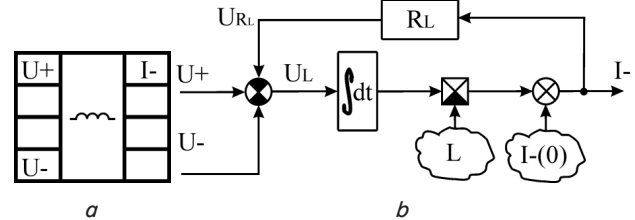

Fig. 8. An inductive energy storage: designation (*a*); visual model (*b*)

A DC motor is shown in Fig. 9. The model does not take into account non-linear relationships in an electric machine. Magnetic flux in the motor magnetic system is assumed to be constant. Therefore, there is a direct proportionality between the rotor current and the electromagnetic moment as well as between the motor EMF and the angular velocity of the shaft rotation with coefficients K_m and K_e, respectively. Electrical and mechanical losses in the machine are taken into account with the help of resistance R_{int} and coefficient $K_{mechloss}$, respectively.
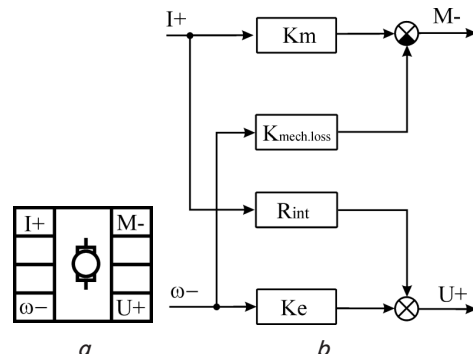

Fig. 9. A DC motor: designation (*a*); visual model (*b*)

A two-channel consolidator is shown in Fig. 10. When energy is directed from left to right, the direct cause-and-effect relationship "A" is represented by an adder. A simple node corresponds to feedback "B" passing through the energy consolidator.
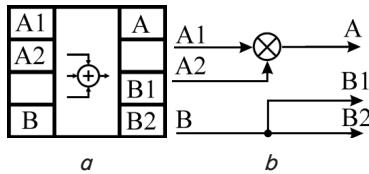

Fig. 10. A simple two-channel consolidating node: designation (*a*); visual model (*b*)

An inertial element with the moment of inertia, *J*, is shown in Fig. 11. The model is presented in an integral form taking into account initial angular velocity of rotation. The moment of the mechanical power source, M+, and the moment of the mechanical power receiver, M−, are the input values. The angular velocity of the system rotation, ω−, is the output value.
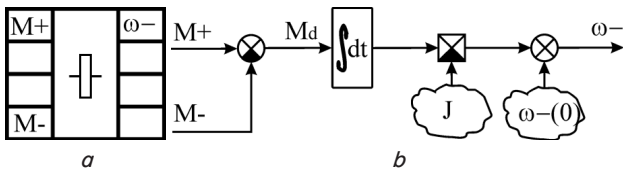

Fig. 11. The inertial element: designation (*a*); visual model (*b*)

The actuating mechanism is shown in Fig. 12. The model is presented in an integral form. The angular velocity of rotation of the system, ω+, is the input value. The moment of resistance, M+, is the output value. The subsystem is covered by a non-linear, fairly rigid negative shaft moment feedback thereby providing an absolutely soft static mechanical characteristics with a constant torque, M_{max}.

The model describes operation of the rolling stand for any angles of shaft rotation, ϑ_V, including reversing. It has been assumed that when reversing, work of a mechanical load is considered idling.
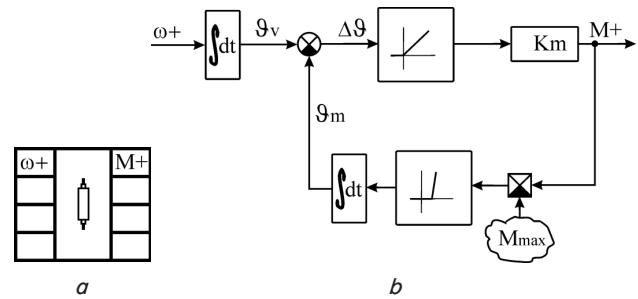

Fig. 12. An executive mechanism: designation (*a*); visual model (*b*)

7. Implementation of a simulation model on a PC

The above VBM was implemented on a personal computer in the package of visual modeling in a form of a simulation model. A version of this implementation in the Matlab Simulink environment is presented in Fig. 13. The PID-control element of control which performs functions of the PID controller was added to the original VBM structure.

It should be noted that the resulting model does not contain any structural elements except for the VBM elements. Thus, the model is built at the same hierarchical level which significantly improves the degree of formalization and convenience of the synthesis procedure.

As the practice of repeated use of the considered procedure shows, the chosen design of the unified blocks of the VBM library is quite convenient at the analytical stage of model creation although it contains design redundancy.

The results of simulation of electromechanical processes in the considered system are shown in Fig. 14. In simulation, the input signal for setting angular velocity of roll rotation is an input to the system in a form of a step function of time, $\omega_{targ}(t)$. The graphs (Fig. 14) show variation of the rotor currents I1(t), I2(t) depending on time and actual angular velocity of roll rotation, ω(t).

Comparative analysis was carried out by means of a parallel model experiment using the VBM model and the model built in Sim Power Systems. Identical input actions were sent to the input of the models in a form of a time-dependent angular velocity instruction. The output time functions of the rotor currents and the angular velocity were compared.
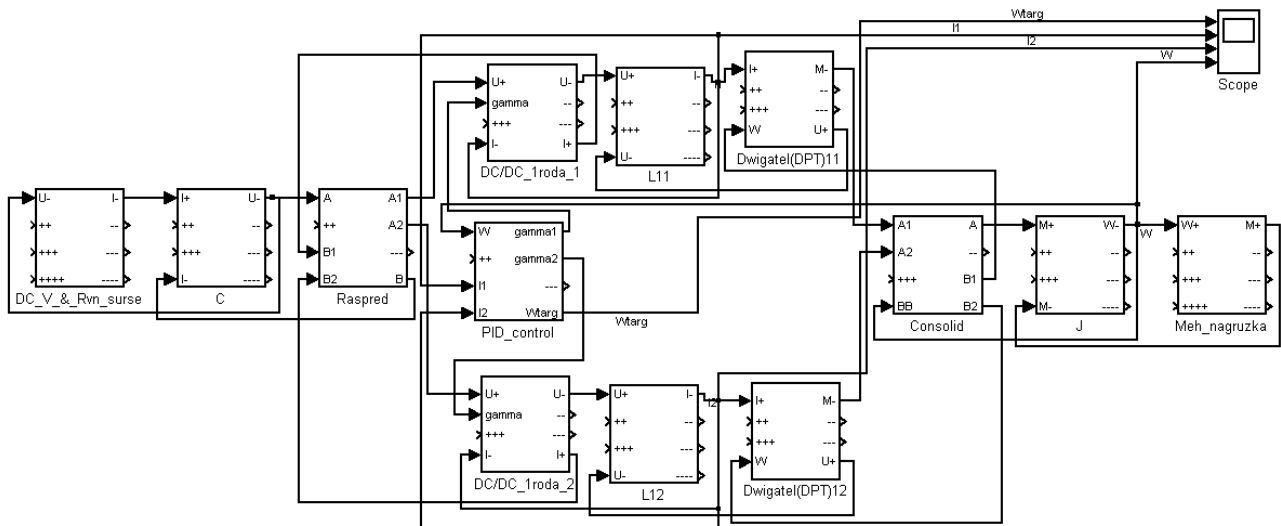

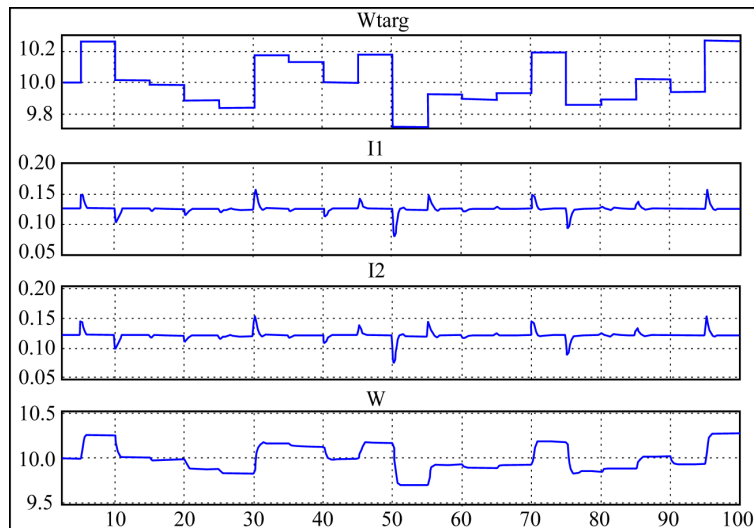Fig. 13. Implementation of a simulation model on a PC

Fig. 14. Time dependent variations of the signal for targeting angular velocity of roll rotation, $\omega_{targ}(t)$, the rotor currents, $I1(t)$, $I2(t)$ and the actual angular velocity of roll rotation, $\omega(t)$

For a correct comparison of the current simulation results, difference in the instantaneous current values was filtered by a low-pass filter. This procedure was performed because of presence of current ripple in the model built at the circuit level.

Maximum instantaneous deviation of the output parameters in certain parts of the transition process was 2–3 %, which is acceptable accuracy for most engineering calculations.

The simulation results were consistent with the results of the model experiment obtained in the Sim Power Systems simulation environment which confirms operational capability of the proposed synthesis method.

8. Discussion of the results obtained in studying the development of the method of visual-block modeling of electrotechnical complexes

The developed method makes it possible to present a mathematical model in a single basis in which relations between the elements are identical to the cause-and-effect relations and completely abstracted from their physical nature. This gives grounds for calling the obtained method a universal tool for studying system properties using simulation modeling.

The considered principle of system decomposition allows one to create a closed library of components. This, in turn, several times reduces the time spent on synthesis and refinement of the mathematical model. In particular, in the presence of an already formed library of components, it took no more than one hour to obtain the simulation model discussed above. Synthesis of the same model in the classical way, including refinement usually takes several hours depending on the experience and qualifications of the developer.

The form of the obtained mathematical model is convenient for its further transformation into a model in state variables [11, 12] which, in turn, is the starting point for synthesis of control systems [13].

The method obtained in the study, in contrast to the common aggregate approach to visual modeling, makes it possible to visualize energy flows within the system contributing to a better system understanding.

With further development of the method for narrow classes of systems, a VBM library can be formed as a closed set containing a finite number of elements.

Availability of closed libraries opens up the possibility of development of formal methods for synthesis and optimization of electrotechnical complexes.

Disadvantages of the considered method include greater number of elements in the model structure as compared with the aggregate approach as well as some redundancy in the design of VBM elements.

It should also be noted that at this stage of development of a modeling method, the VBM library is not yet completed and mathematical descriptions of the elements have essential assumptions. In this regard, further study of the method development is supposed to be carried out in a direction of expanding the library and increasing adequacy of the component models.

9. Conclusions

1. A procedure for synthesis of mathematical models of electrotechnical complexes has been developed. Its essence lies in the fact that the electrotechnical complex is represented as a structure of the energy path. The procedure is based on the method of system decomposition and the energy paths based on it. The proposed language allows one to visualize power flows in the electrotechnical complex which contributes to understanding of the system operation. Besides, the proposed method of decomposition makes it possible to create a library of components of the visual-block model. Availability of the component library enables reduces time for model synthesis and refinement. For example, for synthesis of the example considered in this paper, time reduction was dozens of times depending on the experience of the model developer.

2. Unification of the form of representation of library components of the visual-block model elements has been introduced which creates conditions for effective work of developers in the direction of elaboration of this procedure in terms of formation of the library of components. In addition, unification of the form of representation of the library of components creates condition for effective communication within the group of researchers engaged in development of a complex project.

3. A part of the library of elements for synthesis of the visual-block model of an electrotechnical complex has been developed. As a result of analysis of the features of structural elements of the model, rules of formation of structure of the cause-and-effect relationships of the distribution and consolidating nodes were formulated. The above rules should be understood as the revealed pattern which manifests itself in a certain class of systems. Introduction of a distribution and consolidation nodes as the language elements enables building of visual models of branched energy paths at the same hierarchical level. This, in turn, significantly increases

the model visibility, creates conditions for unification when forming the library of components.

4. All stages of synthesis of a mathematical model were considered in detail on the example of a DC drive: analysis of the block diagram, representation in a form of the energy path structure, its conversion into a visual-block model and implementation on a personal computer. The results obtained in studying behavior of the system with the help of the obtained simulation model in comparison with the simulation results using the model built in Sim Power Systems were also presented. A comparative analysis of the simulation results allows us to conclude that the proposed procedure is operable.

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