Optimization of Model Structure of Induction Motor Control System

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Abstract: - This paper considers the principles of mathematical description of model elements in variable-frequency induction motor control systems for determining their component and structural composition and analyzing data conversion processes in the interaction between all the subsystems of a microprocessor-based control system and in the process of its structure optimization. The authors propose a method of formalizing operation processes of the control system elements, such as a transformer, a rectifier, a passive filter, an inverter, an induction motor, a microprocessor-based control system, and instruments for measuring and displaying information. A structural and functional model of a microprocessor-based variable-frequency control system of an induction motor has been developed. The rules for describing functional structures at various levels of decomposition of the variable-frequency induction motor control system have been determined. The approach proposed in this paper enables moving from various structural and principal diagrams to their mathematical models for the following analysis and optimization. Analytical expressions describing the structure and signals conversion processes in certain subsystems of the induction motor control system became available. The analysis of these expressions allows drawing the conclusion that it is possible to structurally optimize the reference model by means of replacing a variety of separate blocks by a single microcontroller, in which the control algorithm is programmatically implemented. On the basis of analysis of analytical expressions describing the control system model elements, the composition of feedback signals necessary for implementation of the function of induction motor control was determined.

Key-Words: - Induction motor, modeling, variable-frequency control, optimization, analytical description

1 Introduction

The cage rotor induction machine is widely used in industrial applications. It has quite a low cost compared to the cost of other machines. The relative simplicity of conception of the machine hides quite a great functional complexity, as soon as it is aimed at controlling the performed electromechanical conversion.

Currently several options are known of a formalized record of logical-dynamic processes of signals conversion in the control systems. On the one hand, they include structural and principal diagrams, and on the other hand – Matlab-models, which have been realized on two levels of presentation of signals conversion logical-dynamic processes. If the first level of presentation of signals conversion logical-dynamic processes is created for the developers of various functional structures and realized as structural and principal diagrams, then the second one is intended for the functional structure of microcontroller compute core (CoreMK), and it is realized as computer-oriented mathematical models with the input and converted arguments.

One of the tasks in the modern theory of automatic control is the development of new methods of formalized recording of various logical and dynamic processes for converting analog and digital signals in control systems for asynchronous motors. This formalized recording of signal conversion processes should be performed in the form of analytical symbols, which should form a functionally complete mathematical model. And this model, in turn, would make it possible to make available its informational content. At the same time, the main quality of the functionally complete mathematical model of the logical-dynamic process of signal conversion process should be the minimization of the verbal description of their content. This will make it possible to use formal methods in optimizing the structure of the microprocessor control system of an asynchronous motor.

The Matlab Simulink modeling environment is used for studying variable-frequency induction motor control processes. For this purpose, a system model is developed. It consists of a set of blocks, performing certain functional transformations, and relationships between them. The main aim of this research is, firstly, to analyze the model for studying induction motor control processes, and secondly, to optimize the model structure and eliminate its redundancy by composing specific subsystems that are capable of converting an external action to data signals and reproducing the processes at data level. The criterion of induction motor control system optimization is its structural minimization – reduction of a number of model elements by substitution thereof for a microcontroller, in which the control system operation algorithms are programmatically implemented. In such a case, the optimized model part operation algorithm remains intact. The use of a microcontroller will permit expanding a set of functions to be performed by the control system. One of such function may be a diagnostics of the induction motor. Induction motors are subject to many different types of faults, such as bearing related faults, stator winding turn faults, rotor related fault and other faults. The fault does not affect the normal operation in the early stage, it will induce irreversible damage to the core when the fault becomes severe. Therefore, early diagnosis of the stator winding turn faults in operation is important to avoid losing production time and expensive cost for maintenance and repair. It is important to emphasize that software implementation of these functions will not affect the control system structure or require for modifications to be introduced into the diagram provided that control system structural minimization has been properly fulfilled, and microcontroller receives all the necessary feedback signals.

2 Problem Formulation

The models described in [1-6] contain the structure of the induction motor control system in a generalized form, where the fundamental concepts of the electromechanical conversion have been recalled and applied to the modeling of an elementary machine, composed of a stator coil and a rotor coil. The model of inductor motor is clarified in the three-axe frame linked to its supply, making the most of the matrix formalism. Then, several mathematical transformations are presented and used so as to substitute components from electrical quantity [4]. Such models are illustrative and contain information on a large number of system structural properties. Each block of the system can also be represented as a set of separate blocks, can be refined and instantiated if necessary. In these studies it was noted that one of the problems in optimizing systems is to limit the applicability of a particular method due to the characteristics of processes occurring in systems of different physical nature. The absence of a unified mathematical apparatus for describing processes in systems that are of a different physical nature preconditions the necessity of further research in this direction.

In such a case, there is no need to change the whole scheme. It is sufficient to replace specific elements with block diagram models containing several interacting blocks. Modern variable-frequency control systems of induction motors, such as Altivar, ABB, Siemens and others, process feedback signals for generating control actions. In this case, the analog-to-digital conversion of feedback signals takes place, and then the signals are fed to a microprocessor. The microprocessor in turn may comprise a mathematical motor model [5,7] and makes use of the measured values of parameters for calculating control actions. Modeling of variable-frequency control systems requires optimization of model structure. This will enable us to determine the structure of feedback signals, to identify model blocks that may be implemented in software in the microprocessor (an analog-to-digital converter, timers, generators, calculations of trigonometric functions, etc.), and to eliminate model redundancy.

However, such models are difficult to formalize. They represent in some sense a transition from informal description of the system to the mathematical description [8-10].

The models and methods considered in these studies allow us to analyze control systems for asynchronous motors and synthesize various control laws. However, this is not enough due to the variety of these control processes. Therefore, a large number of scientific trends emerged, that deal with specific aspects of control processes - improving the reliability of control systems, the quality of control systems, and speed of action. System analysis points to the fact that such processes should be studied in accordance with certain principles. Therefore, the task of creating and using such a mathematical apparatus that would allow us to combine control processes of different physical, organizational and target nature is currently of high importance.

A block diagram of a model is not a structural model. Therefore, developing a special tool for analysis and design of structures of system models is a topical problem. The main requirement for the study of an object as a system is the possibility to consider and describe not only its real-valued and power aspects, but also its informational aspects [2,11,12]. This is due to the fact that developing new system models and evolving existing models depend on solving issues related to analysis of available data, elimination of redundant part, identification of key data, evaluation and generation of alternatives for decision-making. This leads to the problem of optimizing the model structure.

Optimization of models is their simplification for a given level of adequacy. It is noted in [13-15] that the main criteria of model optimization are time and costs for model analysis. The optimization is based on the possibility of transforming models from one form to another. In this case, the model can be distributed; it can become a multicomputer model. As considered in [3,16,17-19], a model of a power part can be created in the Matlab Simulink environment, and a control part can be implemented in the Proteus modeling environment. Furthermore, a model of a microprocessor-based control system can be replaced by a real device connected to a computer, and this model can control the power part of a converter using special communication modules in Matlab. . It should be noted that each of the methods of formal mapping has its advantages, or rather its structural qualities, which must be preserved and strengthened by the structural qualities of other methods of formal mapping.

The transformation may be performed using either mathematical or heuristic methods. The application of mathematical methods avoids unreasonable simplifications of the model. In such a case, there remains the possibility of analyzing data conversion processes in the model. This enables us to evaluate the model adequacy.

3 Model structure of induction motor control system

When operating an induction motor, a number of parameters need to be controlled for generating control actions. In Matlab Simulink, the special Machine Measurement Demux block is used for this purpose. The settings window of this block enables us to select the parameters to be controlled [6].

Fig.1 shows a fragment of the model, in which the Machine Measurement Demux block makes measurements of phase currents, the rotor speed and torque on the motor shaft. The measured value of the induction motor rotor speed is used in a feedback loop to create a load torque on the motor shaft, as described in [1]. An oscilloscope block enables us to observe signal waveforms. Fig.1 also gives an analytical description of certain blocks. This will allow us to form a model of system structure.

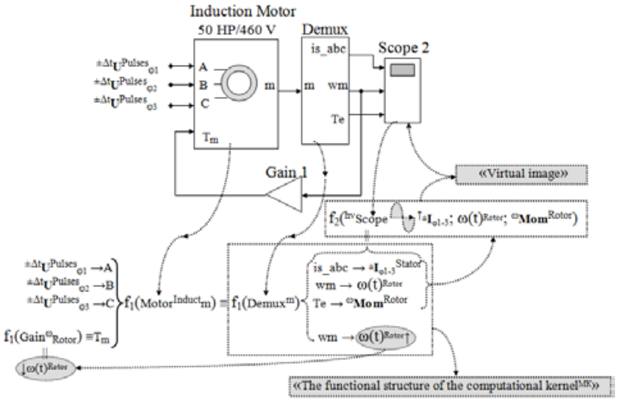


Fig.1. Analytical description of the elements of measuring the parameters of an asynchronous motor in the model

The symbol (→) in Fig.1 is a functional analog connection, and the symbol (≡) is a functional logical connection.

Gain is an amplification factor of the rotor speed (Rotor) for the functional structure of the virtual induction motor $f_1(\mathrm{Motor}^{\mathrm{Induct}}m) \rightarrow f_1(\mathrm{Motor}^{\mathrm{Induction}}m)$. It is used to simulate the motor shaft load. This can be represented as an analytic expression

$$\begin{tikzcd}\omega(t)^{\mathrm{Rotor}} \arrow[r] & f_1(\mathrm{Gain}^{\omega}) \arrow[r] & T_m \arrow[r, bend left, dotted] & T_{\omega}\end{tikzcd}.$$

Induction Motor (see Fig.1) is the functional structure of the virtual induction motor $f_1(\mathrm{Motor}^{\mathrm{Induction}}m)$ where the symbol (m) means the combination of actual arguments. The arguments can be written as an analytic expression

$$(m)\cdots\begin{cases} {}^{\pm}\mathbf{I}_{\varphi 1\text{-}3}{}^{\text{Stator}} \\ \omega(t)^{\text{Rotor}} \\ {}^{\omega}\mathbf{Mom}^{\text{Rotor}} \end{cases}$$

where $\pm I_{\varphi 1\text{-}3}{}^{\text{Stator}}$ is the energy argument of the three-phase current in the stator inductance (Stator); $\omega(t)^{\text{Rotor}}$ is the rotor speed (Rotor); ${}^{\omega}\text{Mom}^{\text{Rotor}}$ is the rotor torque.

The functional structure of the demultiplexer (Demux) → $f_1(\text{Demux}^m)$ is used to implement the procedure of forming the optical information of the arguments in the functional structure of the virtual oscilloscope. It is described as an analytic expression

$$f_2({}^{hv}\text{Scope} \cdots\!\!\rightarrow {}^{\uparrow\pm}\mathbf{I}_{\varphi 1\text{-}3};\ \omega(t)^{\text{Rotor}};\ {}^{\omega}\mathbf{Mom}^{\text{Rotor}})$$

including the arguments required for subsequent adjustment by using the functional structure of the microcontroller compute core (CoreMK).

Fig.2 shows energy conversion. The input energy flow comes from an outside source. The output energy flow is directed to the induction motor.

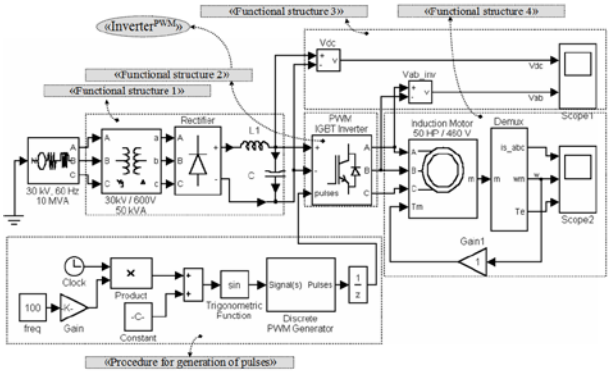


Fig.2. Initial model of the control system of an asynchronous motor

The model on Fig. 2 can be represented in the form of four “Functional structure 1-4”. “Functional structure 1” implements a virtual model of mathematical formula of input voltage conversion. “Functional structure 2” performs the conversion of direct voltage into alternating one, which is then fed to the induction motor windings. “Functional structure 3” performs measurement and reflection of rectified voltage fed to the inverter input, and of line voltage on the inverter output, which is fed to the induction motor windings. “Functional structure 4” makes measurement of phase currents, engine rotor spinning speed and moment on the motor shaft.

The process of energy conversion naturally requires information. The microcontroller performs the functions of receiving and processing information, and generating control signals.

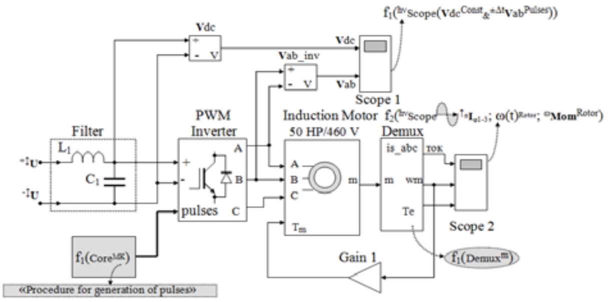


Fig.3. Model of control system with microcontroller

In the circuit of Fig.3, the voltmeter Vdc is used to measure the direct-current voltage at the output of the filter. It can be described by an analytic expression

$$\left.\begin{array}{r} {}^{+}U_{Const} = \\ {}^{-}U_{Const} = \\ [U_j] = \end{array}\right\} f_1(\text{ADC}) = [\mathbf{V}_i{}^{dc}] \quad \mathbf{Vdc}^{Const}$$

The voltmeter is represented by the functional structure of the analog-to-digital converter f1(ADC) with the reference voltage input structure $[U_j]$ and input voltages $+U_{Const}$ and $-U_{Const}$.

The voltmeter Vab_inv is used to measure the line voltage at the inverter output. It can be described by an analytic expression

$$\left.\begin{array}{r} {}^{\pm\Delta tPulses}U_{\varphi 1} = \\ {}^{\pm\Delta tPulses}U_{\varphi 2} = \\ [U_j] = \end{array}\right\} f_2(\text{ADC}) = [\mathbf{V}_i{}^{ab}] \quad {}^{\pm\Delta t}\mathbf{Vab}^{Pulses}$$

The voltmeter is represented by the functional structure of the analog-to-digital converter f_2(ADC) with the reference voltage input structure $[U_j]$ and input pulse voltages ${}^{\pm\Delta tPulses}U_{\varphi 1}$ and ${}^{\pm\Delta tPulses}U_{\varphi 2}$.
The feature of system description is the analytical notation form of the oscilloscope «Scope 1» as an expression

$$f_1({}^{hv}\text{Scope}(\text{Vdc}^{Const}{}_{\&}{}^{\pm\Delta t}\text{Vab}^{Pulses})).$$

In Fig.4 the structural models of rectifier, filter and PWM inverter sub-blocs, used in model in Fig.2, are shown.

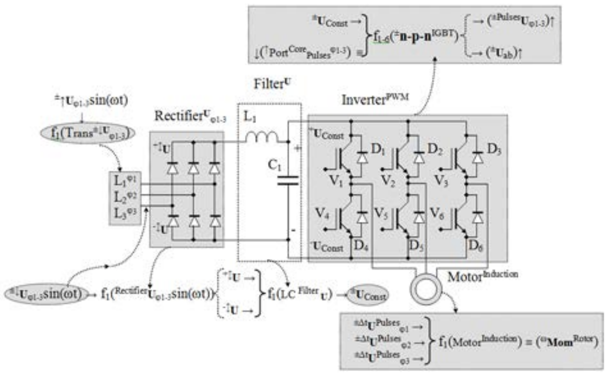
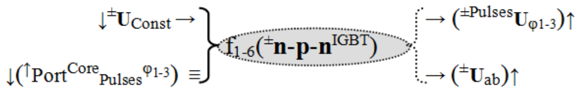


Fig.4. Structural models of the rectifier, filter and inverter

Circuital implementation of the “InverterPWM” can be represented in the form of analytical expression



$$\left.\begin{matrix}\downarrow {}^{+}U_{Const}\rightarrow\\ \downarrow({}^{\uparrow}Port^{Core}_{Pulses}{}^{\varphi1\text{-}3})\equiv\end{matrix}\right\} f_{1\text{-}6}({}^{\pm}\mathbf{n\text{-}p\text{-}n}^{IGBT})\left\{\begin{matrix}\rightarrow({}^{\pm Pulses}U_{\varphi1\text{-}3})\uparrow\\ \rightarrow({}^{\pm}U_{ab})\uparrow\end{matrix}\right.$$

On Fig. 4 $f_{1\text{-}6}({}^{\pm}\mathbf{n\text{-}p\text{-}n}^{IGBT})$ is a functional structure of “Inverter^{PWM}” on **n-p-n** IGBT transistors; ${}^{+}U_{Const}$ is an input constant (Const) energy argument of voltage; (→) — functional analog communication; (≡) — functional logical connection; $({}^{\uparrow}Port^{Core}_{Pulses}{}^{\varphi1\text{-}3})$ — a port of microcontroller compute core (Core), on which output the sequence of pulses ($Pulses^{\varphi1\text{-}3}$) of three phases being activated.

Coming back to analysis of the induction motor system virtual model which is represented on Fig. 3, the successive sequence of virtual structures may be represented as is shown on Fig. 4.

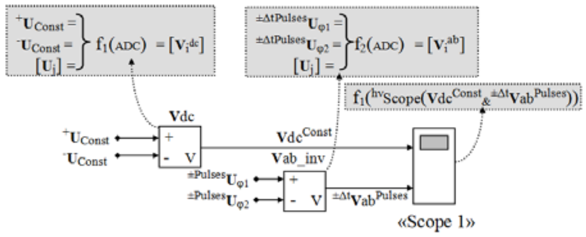


Fig.5. Graphic and analytical description of measuring units in the model

On Fig. 5. Vdc — a voltmeter (direct voltage on filter output), which is a functional structure of the analog-to-digital converter $f_1(ADC)$ with reference voltages input structure $[U_j]$ and input voltages ${}^{+}U_{Const}$ and ${}^{-}U_{Const}$; Vab_inv — a voltmeter (line voltage on the inverter output), which is a functional structure of the analog-to-digital converter f_1(АЦП) with reference voltages input structure $[U_j]$ and input pulse voltages ${}^{\pm\Delta tPulses}U_{\varphi1}$ and ${}^{\pm\Delta tPulses}U_{\varphi2}$.

The semantic content is that the result information in this functional structure is presented in optical form (hν) and includes the procedure of presenting the information content of the DC voltage argument (Vdc^{Const}) and pulse voltage arguments (${}^{\pm\Delta t}Vab^{Pulses}$). In the functional structure of the oscilloscope «Scope 1», these arguments are presented in optical form, as illustrated in Fig.6.

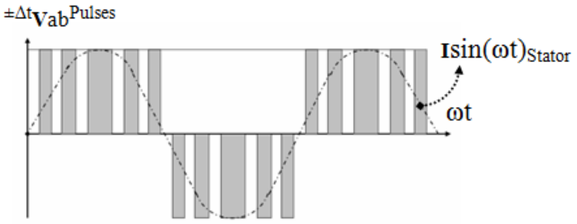


Fig.6. Transition to the analytical description of signals

In Fig.6, $I\sin(\omega t)_{Stator}$ is the stator sine-wave current. In this case, it is reasonable to write the functional structure of the oscilloscope $f1({}^{h\nu}Scope(Vdc^{Const}\&{}^{\pm\Delta t}Vab^{Pulses}))$ without functional and graphical relationships but with input functional analog-to-digital converters $f_1(ADC)$ and $f_2(ADC)$ in the form of a graph-analytic expression as shown in Fig.7.

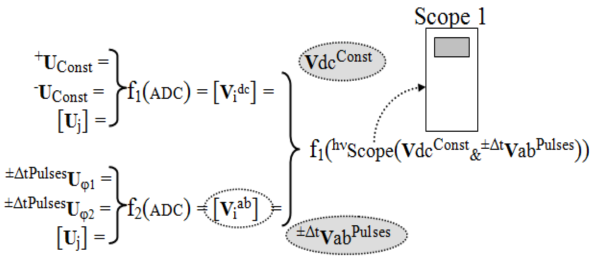


Fig.7. Graphic and analytical representation of analog-to-digital converters

Fig.8 shows a detailed model of the subsystem generating control signals. It is represented as a set of separate blocks.

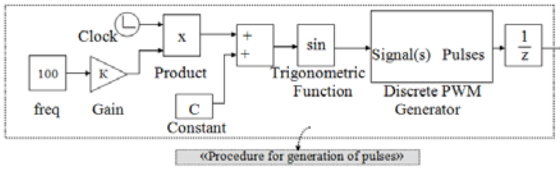


Fig.8. detailed model of the control pulse generator

In Fig.8, we use the following notation: freq is a frequency setter; Gain is an amplification factor; Product is multiplication; Clock is a time signal.

The procedure for generation of pulses can be implemented using the functional structure of the microcontroller compute core f_1(CoreMK).

As a result of considering the analytical description of the system and analyzing data conversion processes, we may conclude that certain functional structures can be eliminated when physically implementing the system.

The functional structures of virtual oscilloscopes

$$f_1({}^{h\nu}\mathrm{Scope}(\mathbf{V}\mathrm{dc}^{\mathrm{Const}}{}_{\&}{}^{\pm\Delta t}\mathbf{V}\mathrm{ab}^{\mathrm{Pulses}})),\ f_2({}^{h\nu}\mathrm{Scope}\ {}^{\uparrow\pm}\mathbf{I}_{\varphi 1\text{-}3};\ \omega(t)^{\mathrm{Rotor}};\ {}^{\omega}\mathbf{Mom}^{\mathrm{Rotor}}),$$

can be eliminated because they are used for visual and optical monitoring of changes in the values of corresponding input arguments.

The functional structure of the demultiplexer $f_1(\mathrm{Demux}_m)$ can be eliminated because its functions are performed by the functional structure of the microcontroller compute core $f_1(\mathrm{Core}^{\mathrm{MK}})$.

Let's represent the circuit in Fig.3 by an analytic expression as shown in Fig.9.

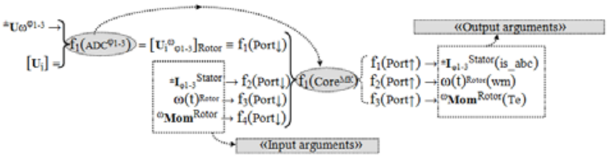


Fig.9. Graphic and analytical form of the representation of the control system model

From Fig.9, it can be observed that the functional structure of the microcontroller compute core $f_1(\mathrm{Core}^{\mathrm{MK}})$ includes the procedure of the analog-to-digital conversion $f_1(\mathrm{ADC}^{\varphi 1\text{-}3})$. Thus, we can rewrite equation in Figure 7 without the functional structure $f_1(\mathrm{ADC}^{\varphi 1\text{-}3})$ as follows:

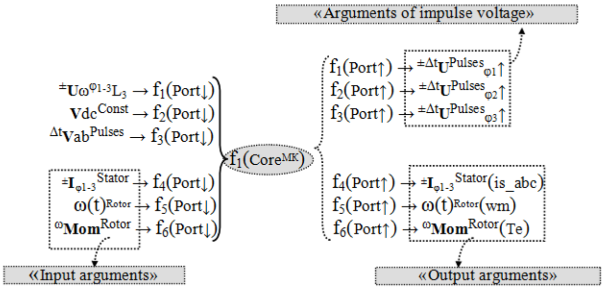


Fig.10. Representation of the input and output signals of the microcontroller

Therefore, the circuit providing induction motor control and parameter monitoring is shown in Figure 11. In this figure the optimization was added – the model of the subsystem generating control signals (Fig.8) was replaced with Procedure for generation of pulses. In such a case, control system part, which has been realized by separate blocks, is substituted for the single microcontroller block $f_1(\mathrm{Core}^{\mathrm{MK}})$. The algorithm of control signals generation on the inverter is programmatically implemented in microcontroller. Also, microcontroller receives feedback signals, which are containing information on phase currents and line voltages of the motor, and speed of motor rotor spinning. By means of an analog-to-digital converter integrated into the microcontroller, these signals may be converted into digital form and used when implementing control algorithm. Such solution enabled structural optimization and minimization of a number of control system model elements.

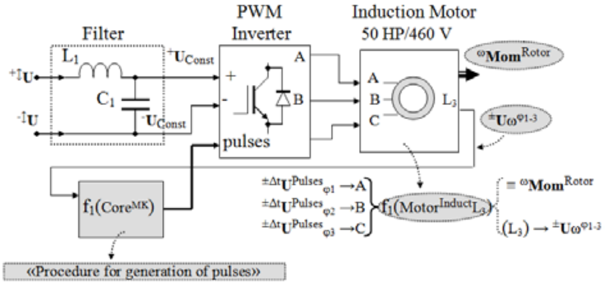


Fig.11. Optimized structure of control system model

A special feature of the model is the analytical notation of the induction motor functional structure $f_1(\mathrm{Motor}^{\mathrm{Induct}}L_3)$. It includes the resultant argument of the rotor torque ${}^{\omega}\mathrm{Mom}^{\mathrm{Rotor}}$ and the voltage information argument of the three-phase rotor speed in the stator inductances $\pm U\omega^{\varphi 1\text{-}3}$. The rotor is activated in the stator additional inductances.

It should be noted that for the induction motor functional structure $f_1(\mathrm{Motor}^{\mathrm{Induct}}L_3)$ there is no need to generate voltages of three phases in the stator inductances by using the information argument $\pm U\omega^{\varphi 1\text{-}3}$. It is sufficient to obtain information on the voltage argument of one phase in the stator inductances.

4 Conclusion

In this paper, a method of analytical description has been developed for a variable-frequency induction motor control system in the form of a logical and dynamic data conversion process. A structural and functional model of a microprocessor-based variable-frequency control system of an induction motor has been devised. The rules for describing functional structures at various levels of decomposition of the variable-frequency induction motor control system have been determined.

The reviewed graphical-analytical method for analyzing logical-dynamic processes of argument conversion supplements earlier researches made by the authors in the field of modeling, analysis and structural optimization of automation systems [3, 11, 16, 17]. The proposed approach is applicable to the analysis of the functional structure of the computational core of a microcontroller of digital control systems, and is implemented in the form of computational mathematical models with input and converted arguments.

A method has been proposed for formalizing operation processes of the control system elements, such as a transformer, a rectifier, a passive filter, an inverter, an induction motor, a microprocessor-based control system, and instruments for measuring and displaying information. The physical and mathematical developments that are dealt with in this article have lead to determine a mathematical model of induction moor control system with reduced number of blocks (structural optimization). The described approach can be used similarly for the optimization and modeling of different types of motors and its control systems. The developed approach allows us to test the model of the variable-frequency induction motor control system for qualitative adequacy, that is, to test hypotheses of relationships between model parameters and variables, to check the model for internal consistency and correctness of data conversion, including substitution of continuous processes by discrete processes.

The model parameters can be measured with different experimental procedures. This verification is also a required preliminary phase of testing for adequacy of quantitative models for microprocessor-based variable-frequency control systems of induction motors. Furthermore, the proposed approach enables us to perform the structural optimization of the microprocessor-based control system.

As can be seen from the above, a scientific novelty of the results obtained in this paper resides in the fact that the developed method of analytical description of logical-dynamic processes of signals conversion in the induction motor control system and synthesis of system elements analytical models enables implementation thereof with the improved technological properties, as well as description of the processes of various physical natures. The approach proposed ensures moving from various structural and principal diagrams to their mathematical models for the following analysis and optimization. Following the use of the developed method, analytical expressions describing the structure and signals conversion processes in certain subsystems of the induction motor control system became available. The analysis of these expressions allows drawing the conclusion that it is possible to structurally optimize the reference model by means of replacing a variety of separate blocks by a single microcontroller, in which the control algorithm is programmatically implemented. In such a way, on the basis of analysis of analytical expressions describing the control system model elements, the composition of feedback signals necessary for implementation of the function of induction motor control was determined. The sufficiency of optimized model obtained in the paper is proved by means of conversion processes analysis of the arguments entering on microcontroller input and containing system status information.

The advantage of the proposed approach is the availability of different decomposition levels for describing elements and subsystems of the variable-frequency induction motor control system. This makes it possible to emphasize the most important aspects of description at various stages of system design and analysis. The considered approach uses an object-oriented description style and provides information on the structure and types of data connection of system elements. The notation of model elements and data conversion elements is presented in an explicit form, transparent to the developer, and provides information on the behavior of elements, requirements for their interaction and functional capabilities. With the introduction of the analytical form of recording the elements of the model of the control system of an asynchronous motor, it becomes possible to write the logical-dynamic process of converting arguments in the form of a generalized expression. The graphical and analytical form of the record allows us to supplement it with a logical content. On the one hand, this makes it possible to display the logical-dynamic process of converting arguments at the ultimate minimized level of formalization. On the other hand, this form of recording makes it possible to carry out a comparative analysis of different variants of control model structures for the subsequent selection of the most optimal of them and the formation of mathematical models at the analytical level.

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