Analytical Representation of Control Processes of Induction Motor and Synchronous Generator in Power Plants

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Abstract— A technique in the construction of a generalized mathematical model of an operator workstation was developed. The model provides a description of the user interface elements information and management functions displayed in a graphical form. A formalization method of the work process for the operator with on-screen controls in systems with human machine interfaces has been proposed. Structural-functional models of parameters measurement and system monitoring of the synchronous generator have been developed. The presented approach is based upon an object-oriented approach of description; and it contains information on the structure and types of information links between the ingredients and elements of the system.

Keywords— Control system, Human-machine interface, Induction motor, Modeling, Synchronous generator.

I. INTRODUCTION

Modern technical and technological objects and their control systems are characterized by a great number of items, numerous connections and relationships, and a significant amount of the processed information. In this work, we have developed and used several variants of formal logic-record dynamic processes arguments for voltage conversion. These variants include a description of the block diagrams, schematic diagrams, differential equations [1]-[3], and the simulation system MATLAB/Simulink [4]-[7]; the investigated systems and their elements are represented using different levels of abstraction obtained as a result of the decomposition of the original system into separate subsystems [8], [9]. These subsystems perform the conversion of the input signal to the output. If the input signal is regarded as an argument and the output as a function, the subsystem is given a specific functional structure. Thus, the description of the system can be represented in the form of structures interacting functionally. Each performs a conversion of input arguments. The aforementioned functional structure describes the corresponding mathematical models [10].

Control and automation of electrical power plant systems are extremely difficult because of the nonlinear components and large number of interrelated and interacting elements used to employ such systems. Due to the large amount of information transmitted between elements of the system and the number of operator-controlled parameters, the development of new approaches to model, analyze, and improve the operation of such systems is needed. An analytical representation of the user interface of the program will identify the redundancy provided by the operator information to investigate the correctness of the information on the conversion path from the source to the receiver. Displaying the status data for the elements in the power system will be more convenient for the operator.

Fundamentals of the analytical method used in the description of the interface workstation were previously studied [11]-[13]. In addition, common approaches to the synthesis of

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mathematical models of logic-dynamic processes of monitoring and control method are presented in [10], [14]. However, in the aforementioned work, authors considered the description of individual elements of the system for monitoring and automation tools. They also considered the need for the construction of a complete model of the operator workstation power system.

In [15], authors described an approach used for modeling systems, which monitor the parameters and microprocessor control systems of generating units in the autonomous power, using a variety of simulation packages installed on multiple computers. However, the proposed model of interface workstation operator contains redundant information. Many of the monitored parameters are duplicated. This may distract the operator and complicate the observation of information.

The absence of a mathematical description for the user interface in operator workstations complicates the optimization process of its structure and the study of the processes of information exchange.

Microprocessors are used in modern control systems for power converter control, where a software-implemented control algorithm handles: input signals, feedback signals, and the formation of control signals representing the voltage. Essential understanding of the process of the transformation of signals is required for the development of electronic equipment; this can be performed by developing appropriate system algorithms. However, the use of a simulation environment allows for the consideration of specific aspects of the system behavior. The first level of understanding the signals transformation processes is implemented for the developer in a concept block diagram form. The second level of understanding the functional structure of the computational core microcontroller ($Core^{MK}$) is implemented in the form of computer mathematical models converted to input arguments.

A characteristic feature of the initial stage of designing control systems for asynchronous motors is the independency of information about the properties of the future system, which primarily refers to the structure of the system and the information contained therein. The study of the characteristics of this information is the subject of systems analysis. In-depth description of the level of detail is determined by the purpose and description of the system used for modeling systems. In [16], the approach to the description of the user interface on the operator workstation is illustrated; however, for a complete analysis of the control system a description is required for the hardware. Therefore, the actual problem is to develop a method and a system description of the individual elements, which may have different physical nature.

The analysis of these studies shows that there is a need to build a complete model of workstation operation and highlight the external borders of monitoring and control systems as well as the boundaries between the individual elements of the system. Isolation of the system boundaries will be performed by structural optimization to determine the functions of the system and eliminate redundancy.

The main aim of this work is to develop a methodology for the analytical description of the models and rules of symbolic representation for the control systems of asynchronous motors at various levels of decomposition. The methodology will be used to study the structural properties of the system and subsystems. In addition, it will be used to draw conclusions about the optimal structure of the system and recommendations for further improvement.

II. CONTROL SYSTEM BREAKDOWN

Fig. 1 shows the model used for the control system of asynchronous motors. MATLAB/Simulink simulation system allows the user to explore energy processes and management processes in asynchronous motors [17]. Thus, it is possible to represent the system at different breakdown levels [18]. The model includes a power source, an electrical network voltage of 6.3kV, a step-down transformer, three phase rectifier (uncontrolled), a passive LC-filter, three-phase inverter, induction motor and the subsystem generating signals and controlling the inverter. It as well includes virtual instruments for measurement and visualization of signals at various points of the model.

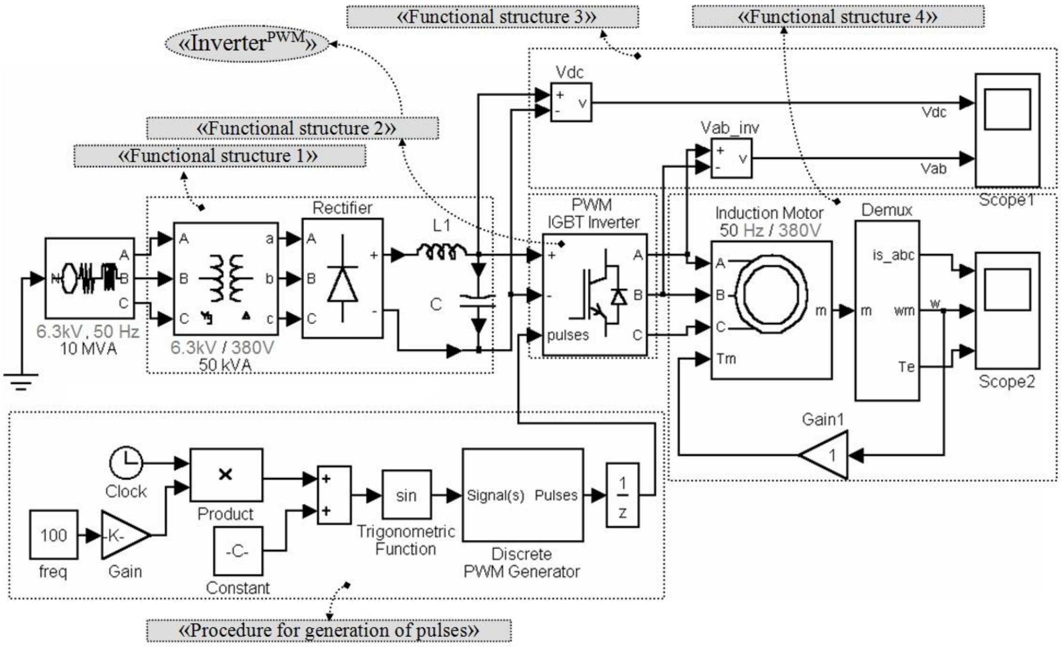

Fig. 1. Model for control system of asynchronous motors

For systems consisting of a large number of interrelated subsystems, the most effective approach is to outline the main subsystems and set the main link between them, before moving on to detailed modeling mechanisms of various subsystems. The model in Fig. 1 shows a graphical analytical expression. Its graph-analytical expression can be represented by four «Functional structure 1-4», where «Functional structure 1» realizes the process of converting the arguments of the input voltage and corresponding graph-analytical expression shown in Fig. 2.

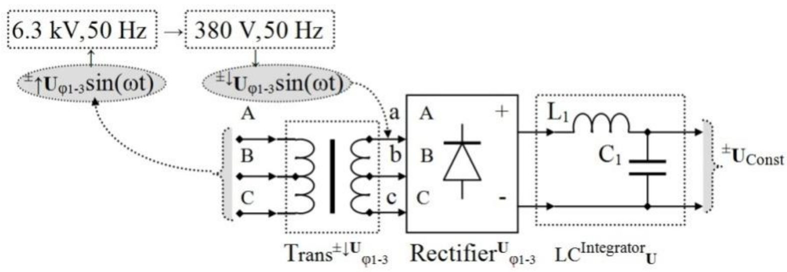

Fig. 2. Graph-analytical expression of the transformation arguments of input voltage

$Trans^{\pm}{\downarrow}U_{\varphi 1\text{-}3}$ is the input step-down transformer, which implements the procedure for converting an input voltage of the argument $^{\pm}{\uparrow}U_{\varphi 1\text{-}3}\sin(\omega t)$, increasing (↑) the level of the output voltage argument $^{\pm}{\downarrow}U_{\varphi 1\text{-}3}\sin(\omega t)$, and decreasing (↓) energy level; $Rectifier^{U}_{\varphi 1\text{-}3}$– voltage three phase rectifier (φ1-3); $LC^{Integrator}U$– integrator (passive low-pass filter), which is implemented by means of inductance (L_1) and a capacitor (C_1) to form the resulting argument voltage $^{\pm}U_{Const}$ with the constant (Const) level.

The paper seeks to develop the technology of analytical records into arguments and functional structures of various logic-dynamic processes of transformation arguments voltage. The input argument *x* in the functional structure is subjected to transformation or action (Action). It may be described in the form of the following expression:

$$x \rightarrow f(Action^{x}) \rightarrow y \quad (1)$$

Taking into account the analytical form of the functional structure of (1), the implementation of the transformer circuit «Transformer»-«Trans» can be written in the form of analytical expressions as shown in Fig. 3.

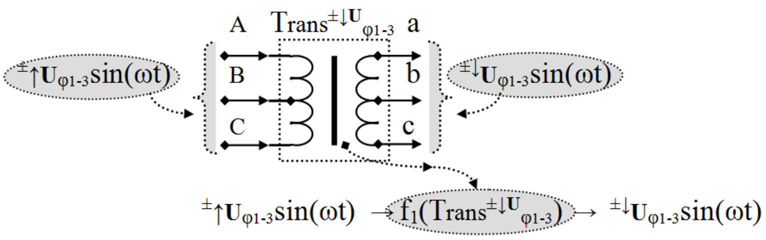

Fig. 3. Description of the transformer as an analytical expression

where $^{\pm}\uparrow U_{\varphi 1\text{-}3}\sin(\omega t)$– three-phase (φ1-3) AC argument (±) voltage $^{\pm}\uparrow U_c$ with the increased level ($^{\pm}\uparrow$); $f_1(Trans^{\pm\downarrow U}{}_{\varphi 1\text{-}3})$– functional structure of the transformer (Trans), which forms the argument of the AC voltage ($^{\pm}\downarrow U_{\varphi 1\text{-}3}$) with the decreased level $^{\pm}\downarrow U_{\varphi 1\text{-}3}\sin(\omega t)$.
Integrator circuit realization «Integrator» (passive low-pass filter), a three-phase rectifier unit $Rectifier^{U}{}_{\varphi 1\text{-}3}$ can be written in the form of analytical expressions as shown in Fig. 4.

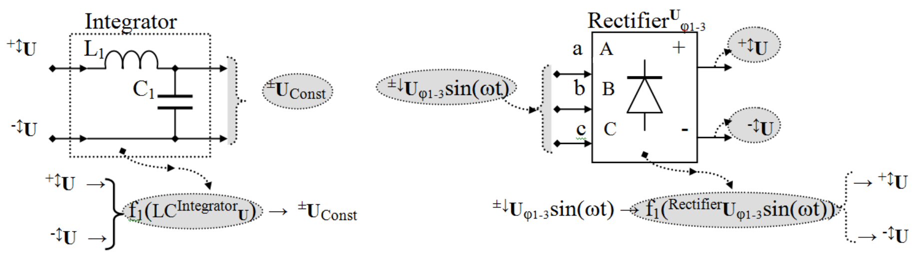

Fig. 4. Analytical representation of the filter and rectifier

Analytical description of the components: After combining the functional structures of the mathematical model of the process of transformation of arguments voltage $^{\pm}\uparrow U_{\varphi 1\text{-}3}\sin(\omega t) \rightarrow {}^{\pm}U_{Const}$ can be written in the form of the following analytical expression:

$$^{\pm}\uparrow U_{\varphi 1\text{-}3}\sin(\omega t) \rightarrow f_1(Trans^{\pm\downarrow U}{}_{\varphi 1\text{-}3}) \rightarrow f_1({}^{Rectifier}U_{\varphi 1\text{-}3}\sin(\omega t)) \left.\begin{matrix} {}^{+\updownarrow}U \rightarrow \\ {}^{-\updownarrow}U \rightarrow \end{matrix}\right\} f_1(LC^{Integrator}{}_{U}) \rightarrow {}^{\pm}U_{Const} \quad (2)$$

To control the induction motor, the control system converts the input voltage of the argument, which passes through a series of functional structures. In general terms, this transformation may be represented as follows:

$$Filter^{U} \rightarrow Inverter^{PWM} \rightarrow Motor^{Induction}$$

When changing the level of the fundamental voltage generating circuit of arguments, which lead to the emergence of torque (Mom^{ω}) in the functional structure of the induction motor «$Motor^{Induction}$», graph-analytical expression will have the form shown in Fig. 5.

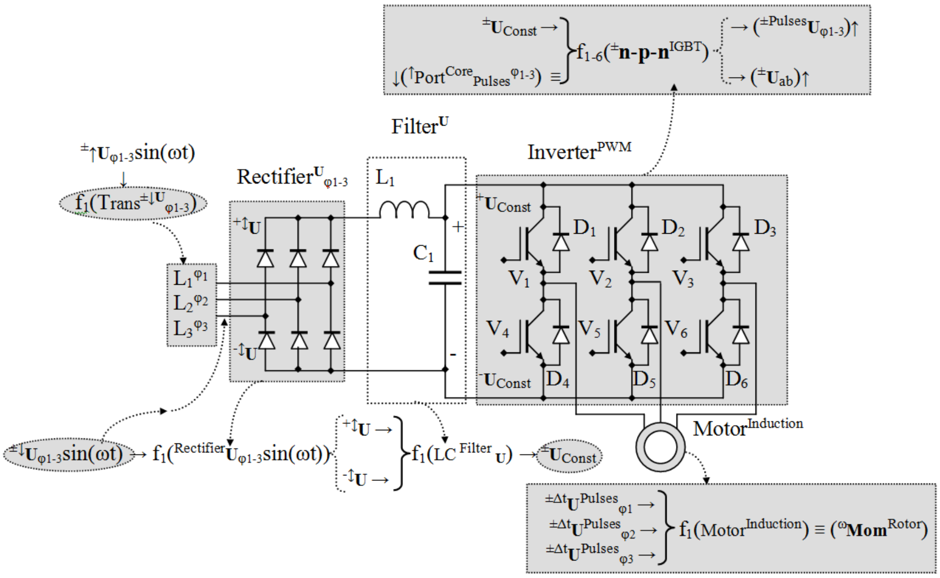

Fig. 5. Description of the semiconductor power inverter at the component level

The schematic implementation of the PWM inverter «$Inverter^{PWM}$» can be written in the form of the following analytical expression:

$$\left.\begin{array}{r} \downarrow {}^{\pm}\mathbf{U}_{Const} \rightarrow \\ \downarrow({}^{\uparrow}Port^{Core}{}_{Pulses}{}^{\varphi 1\text{-}3}) \equiv \end{array}\right\} f_{1\text{-}6}({}^{\pm}\mathbf{n\text{-}p\text{-}n}^{IGBT}) \left\{\begin{array}{l} \rightarrow ({}^{\pm Pulses}\mathbf{U}_{\varphi 1\text{-}3})\uparrow \\ \rightarrow ({}^{\pm}\mathbf{U}_{ab})\uparrow \end{array}\right. \qquad (3)$$

where $f_{1\text{-}6}({}^{\pm}n\text{-}p\text{-}n^{IGBT})$– the functional structure of the PWM-inverter «$Inverter^{PWM}$» on IGBT transistors n-p-n; ${}^{\pm}U_{Const}$– input argument of the constant (Const) voltage; (→)– functional analog connection; (≡)– functional logical connection; (${}^{\uparrow}Port_{Core}Pulses^{\varphi 1\text{-}3}$)– port of the computational core (Core) microcontroller, the output of which is formed by a sequence of pulses ($Pulses^{\varphi 1\text{-}3}$) control for the three phases (φ1-3).

An abstract model of the asynchronous motor «$Motor^{Induction}$» is written in the form of the following analytical expression:

$$\left.\begin{array}{r} \pm\Delta t_{\mathbf{U}}Pulses_{\varphi 1} \rightarrow \\ \pm\Delta t_{\mathbf{U}}Pulses_{\varphi 2} \rightarrow \\ \pm\Delta t_{\mathbf{U}}Pulses_{\varphi 3} \rightarrow \end{array}\right\} f_1(Motor^{Induction}) \equiv ({}^{\omega}\mathbf{Mom}^{Rotor}) \qquad (4)$$

where $f_1(Motor^{Induction})$– functional structure of the asynchronous machine with the input control voltage pulses (${}^{\pm\Delta t}U^{Pulses}\varphi 1\text{-}3$) three phases; (${}^{\omega}Mom^{Rotor}$)– the converted energy argument moment (Mom) of the rotation (ω) of the rotor (Rotor) of the asynchronous machine $f_1(Motor^{Induction})$.

From the comparative analysis of the expressions (3) and (4), it is clear that only the analytical level representation conversion processes signals can be recorded through any functional structures with the ability to understand their semantic content.

«Procedure for generation of pulses» can be realized with the help of the functional structure of the computational core microcontroller $f_1(Core^{MK})$. On the input ports ($Port^{Core}$) computational core of the microcontroller $f_1(Core^{MK})$ comes the controlled arguments such as the motor phase currents, rotor speed and other. The functional structure of the computational core microcontroller $f_1(Core^{MK})$ includes the procedure of the analog-to-digital conversion. Considering the functional structure of the induction motor $f_1(Motor^{Induct}L_3)$, the procedure of information change of the argument ${}^{\pm}U^{\omega}_{\varphi 1\text{-}3}$ can be represented in the form of the following analytical expression:

$$
\left.\begin{array}{l}
\downarrow{}^{\pm\Delta t}\mathbf{U}^{Pulses}_{\varphi 1}\rightarrow A\\
\downarrow{}^{\pm\Delta t}\mathbf{U}^{Pulses}_{\varphi 2}\rightarrow B\\
\downarrow{}^{\pm\Delta t}\mathbf{U}^{Pulses}_{\varphi 3}\rightarrow C
\end{array}\right\} f_1(Motor^{Induct}L_3)\left\{\begin{array}{l}
\equiv {}^{\omega}\mathbf{Mom}^{Rot\ or}\\
\rightarrow {}^{\pm}\mathbf{U}\omega^{\varphi 1\text{-}3}L_3\rightarrow f_1(Port\downarrow)
\end{array}\right.
$$

$$
\left.\begin{array}{r}
{}^{\pm}\mathbf{U}\omega^{\varphi 1\text{-}3}L_3\rightarrow f_1(Port\downarrow)\\
\mathbf{Vdc}^{Const}\rightarrow f_2(Port\downarrow)\\
{}^{\Delta t}\mathbf{Vab}^{Pulses}\rightarrow f_3(Port\downarrow)\\
{}^{\pm}\mathbf{I}_{\varphi 1\text{-}3}{}^{Stator}\rightarrow f_4(Port\downarrow)\\
\omega(t)^{Rotor}\rightarrow f_5(Port\downarrow)\\
{}^{\omega}\mathbf{Mom}^{Rotor}\rightarrow f_6(Port\downarrow)
\end{array}\right\} f_1(Core^{MK})\left\{\begin{array}{l}
f_1(Port\uparrow)\rightarrow {}^{\pm\Delta t}\mathbf{U}^{Pulses}_{\varphi 1}\uparrow\\
f_2(Port\uparrow)\rightarrow {}^{\pm\Delta t}\mathbf{U}^{Pulses}_{\varphi 2}\uparrow\\
f_3(Port\uparrow)\rightarrow {}^{\pm\Delta t}\mathbf{U}^{Pulses}_{\varphi 3}\uparrow\\
f_4(Port\uparrow)\rightarrow {}^{\pm}\mathbf{I}_{\varphi 1\text{-}3}{}^{Stator}(is\_abc)\\
f_5(Port\uparrow)\rightarrow \omega(t)^{Rotor}(wm)\\
f_6(Port\uparrow)\rightarrow {}^{\omega}\mathbf{Mom}^{Rotor}(Te)
\end{array}\right. \qquad (5)
$$

The analysis of the analytical expressions (2)-(5) follows that an external high voltage argument ${}^{\pm\uparrow}U_{\varphi 1\text{-}3}\sin(\omega t)$ of the three-phase (φ1-3) through the functional structure of the transformer $f_1(Trans^{\pm\downarrow}U_{\varphi 1\text{-}3})$ is transformed to the energetic argument of the low voltage (${}^{\pm\downarrow}U_{\varphi 1\text{-}3}$). The functional structure of the rectifier $f_1(Rectifier^{U}{}_{\varphi 1\text{-}3}\sin(\omega t))$ generates voltage arguments of two polarities «${}^{+\updownarrow}U$» and «${}^{-\updownarrow}U$». In order not to let arguments to have the variable voltage component, they are supplied to the functional structure of the filter $f_1(LC^{Integrator}U)$, whose output voltage generates arguments (${}^{+}U_{Const}$) and (${}^{-}U_{Const}$) of the constant level. These arguments come to the functional structure $f_{1\text{-}6}({}^{\pm}n\text{-}p\text{-}n^{IGBT})$ of the PWM invertor «$Inverter^{PWM}$», on which output through the control input arguments ${}^{\downarrow}Core^{\pm\Delta tU}Pulses^{\varphi 1\text{-}3}$ formed conclusions in the form of voltage pulses ${}^{\pm\Delta tU}Pulses^{\varphi 1\text{-}3}Motor$, which are applied to the functional structure of the asynchronous machine $f_1(Motor^{Induct}L_3)$. Also, information arguments for the core arguments of the microcontroller $f_1(Core^{MK})$ are formed. From the analysis of (5), it follows that arguments pulse voltage ${}^{\pm\Delta tU}Pulses^{\varphi 1\text{-}3}$ on the input of the functional structure of the asynchronous machine $f_1(Motor^{Induct}L_3)$ on the one hand creates an energy argument ${}^{\omega}Mom^{Rotor}$ the torque of the motor rotor; on the other hand, it forms an information argument voltage ${}^{\pm}U\omega_{\varphi 1\text{-}3}L_3$. Converting information in the functional structure of the argument computing core microcontroller $f_1(Core^{MK})$ is given the information arguments that may be reflected in the structure of the virtual oscilloscope function in the model, and if necessary, adjusted.

In order to monitor the synchronous generator process parameters and to autonomously control the whole system, a MATLAB model has been developed as shown in Fig. 6. The model contains a synchronous generator (synchronous machine), a resistive load, which can be connected and disconnected from the generator, through a three-phase circuit breaker, a demultiplexer to separate the controlled parameters of the generator, and blocks to communicate with the workstation operator. Block «RS232 Setup» is used to configure the communication interface (data rate and data packet format). Block «RS232 Write Format» is responsible for the creation of data packets and their transmission over serial interface. Block «RS232 Read Format» receives data packets from the workstation operator, verifies the

checksum, and finally outputs the control signal to the synchronous generator and another signal to the circuit breaker for load controlling.
The parameters entering into the model either through microprocessor or any other hardware drive the synchronous generator and control its voltage. The output parameters of the model are "rms value" of the generator current phase. The value of the generator rotor speed ω_m and the amount of electric power P are passed by the model workstation operator.

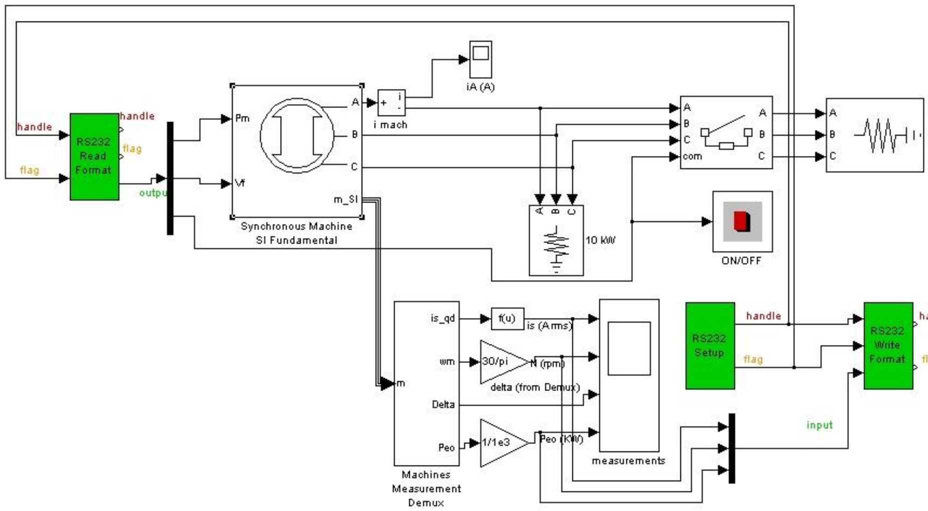

Fig. 6. Model of power system for research control processes

To construct a model of the monitoring system, it is necessary to perform an analytical description of various elements and processes that are fundamentally different in nature [12], [13]. Fig. 7 graphically depicts the three-phase voltage system. The three voltages values are shifted in time phase by 120 degrees among each other. It is also possible to present these parameters analytically using voltage equations.

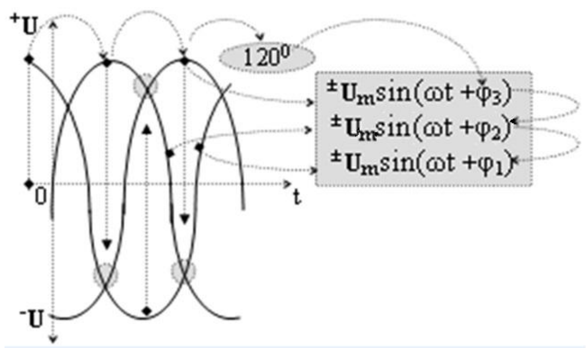

Fig. 7. Graphically analytical model of the three-phase voltages

III. MODELING OF HUMAN-MACHINE INTERFACE

Fig. 8 shows a simplified model of the workstation operator which was created using MATLAB. It allows the user to monitor and control the parameters of the electric power system. The model is shown in Fig. 6. The developed model includes a standard Graphical User Interface which supports the operator with information about the parameters of the generator. The power system workstation model contains blocks for communication with power systems by RS232. The operator may change the input of the synchronous generator which changes and displays information about: value of generator current, speed, the diesel engine mechanical input to the generator and the load of the generator with respect to the rated power. All parameters have been selected and displayed with the help of specialized graphics. The design of the graphical user interface is a complex task and has many technical challenges. It requires consideration of many factors, including the amount of information you want to display, the presentation of information (text, switch device, waveform, and bar graph), and the qualification of the operator. To solve such problems, an analytical description of the user interface must be available. This allows users to use a variety of mathematical methods in order to solve optimization problems and conduct objectives analysis.

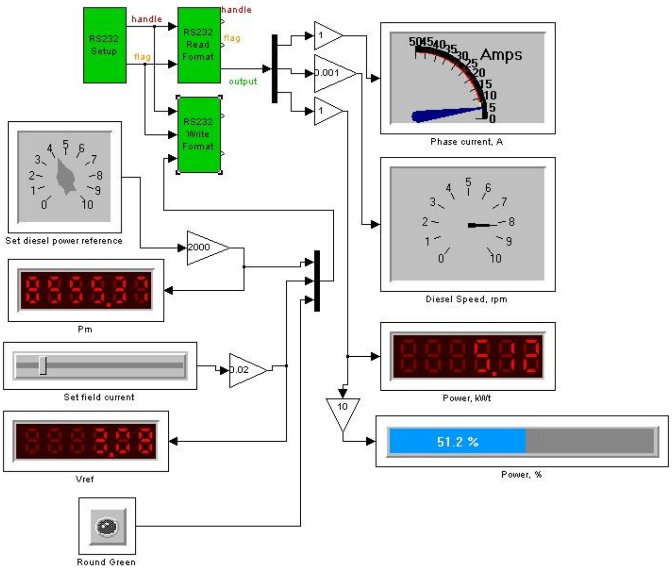

Fig. 8. Model of the operator's workstation

Fig. 9 describes the user interface elements, dial indicator and the digit seven-segment display. The source of information for these indicators pass through the communication interface, which provides a connection with the microprocessor to that perform the necessary calculations and measurements- $Conn^{Port}Core$. Data directions are indicated by arrows; incoming information flow is indicated by the down arrow (↓) for instance. The indicators show information regarding the operation parameters. The frequency of the voltage is represented by a common symbol *f* (Hz), while the diesel engine rotor speed is represented by the angular speed symbol ω. The frequency is displayed as a numerical value (Number). The display method is further indicated by a graphic image. For example, the characters «••••••» mean using six-digit digital display. Each element of the user interface is a functional structure that translates information. Therefore, the analytical description of the expression f(*x*) is used.

Fig. 10 is a model of user interface elements that represent a stylized dial device to display the generator phase current (I_{Ph}). Before displaying the controlled parameter, its value is subjected to scale, as informed symbols $\uparrow\%^{Mash}$. The arrow indicates that the scaled value is passed to the output of the functional structure. The word «Output» represents the description of the functional structures which are responsible for displaying information. The word «Input» represents all the elements needed for operating the power system.

Fig. 11 is an analytical description of the user interface elements which allow you to display real-time instantaneous values of the monitored parameters. It includes frequency *f*, voltage U, amperage I, active power P and reactive power Q. Statement $^{hv}Scope$ is an expression for the visual representation of the elements.

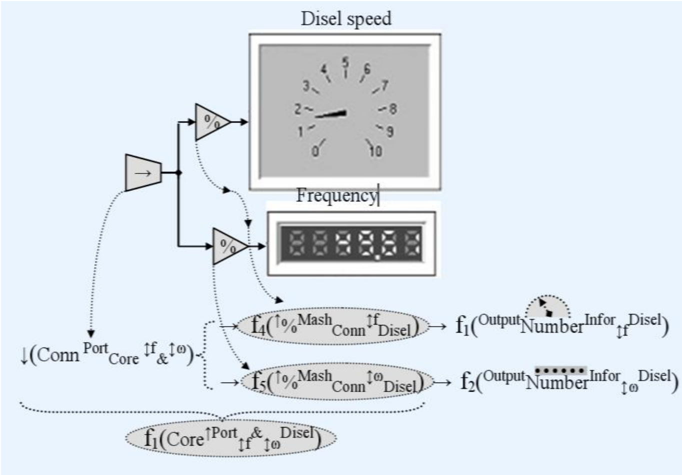

Fig. 9. Analytical description of the item display

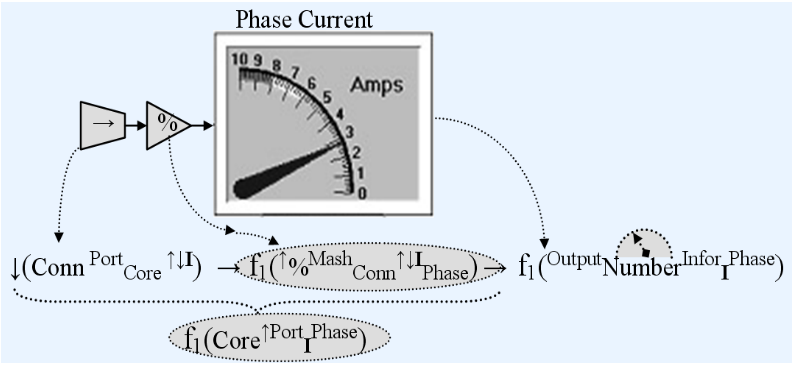

Fig. 10. The model of the user interface element

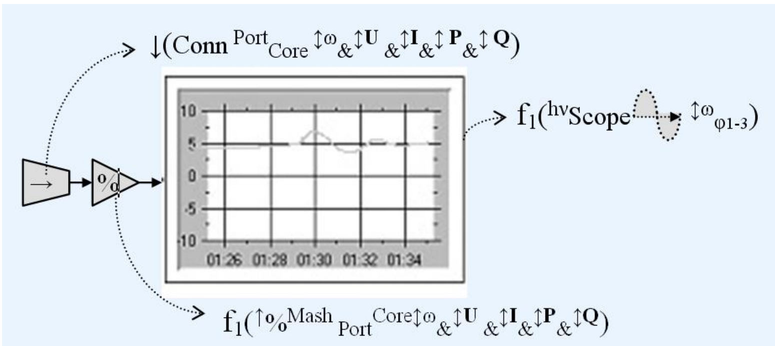

Fig. 11. Analytical description of the waveform display element

Fig. 12 is a generalized model of the operator workstation. Generator phase analog voltage is received at the input ports of microcontroller which is connected with the functional structure of an analog-to-digital converter $f_3(^{\downarrow}Port^{Mux}ADC)$. Reference values of revolutions per minute (RPM)and diesel/ generator voltage are given in digital form supplied with the input ports of functional structures. The system of the generator excitation control is shown as $(^{\downarrow}Port^{V}{}_{tref}{}^{\varphi 1\text{-}3})$, whereas a system of control of diesel f_1 is shown as $(^{\downarrow}Port^{w}{}_{ref}{}^{\varphi 1\text{-}3})$.

The functional structure $f_1(Core^{MK})$ is the microprocessor core that performs all the tasks associated with the measurements, conversion and transmission of information. At the same time, the operator hidden details of these procedures are directly controlled by different parameters, and displayed in the graphical user interface.

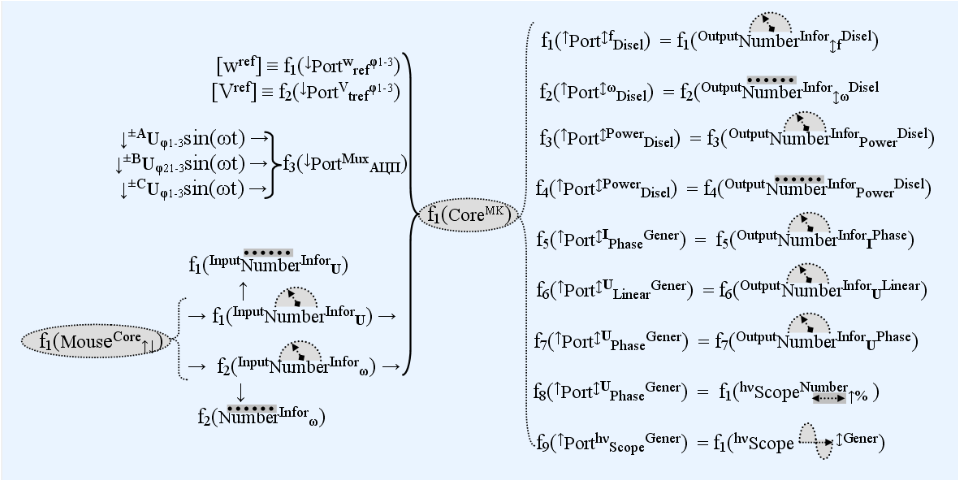

Fig. 12. Analytical model of the operator workstation to monitor and electrical control installation

The proposed approach makes the detection of the presence of duplicated information an easy task. In this example, it is clear that information on the generator voltage and phase voltage (functional structures f_6 and f_7) represents essentially the same value. It is known that these parameters differ by $\sqrt{3}$. Using the mouse, the operator can set both the reference voltage generator and the diesel engine speed. It is described as a functional structure $f_1(^{Mouse}Core^{\uparrow\downarrow})$. Reference values are displayed numerically using six-digit seven-segment indicators.

The developed model of an autonomous electric power plant with a synchronous generator and operator workstation can be used either together or separately. The developed model workstation can be connected to the real time system monitoring and management of the synchronous generator. It can also be used easily with other software. The developed model is useful in the early stages of the development for both monitoring and control systems in order to overcome the challenges in testing stages including hardware and software. This will accelerate the development of hardware and software in early stages, speed up the development of the real-time monitoring and control systems and reduce the cost of the developed system.

IV. CONCLUSIONS

The proposed method for the analytical description of the models of control systems for an asynchronous motor allowed the analysis at as many as needed levels to create understanding of the basic properties of the system. Analysis of the transformation processes for input arguments by functional structures allows making conclusions about the adequacy of the developed models. The analytical description considered in the model for the control of asynchronous motor allows the conclusion of the system type, the appointment of its segments during the early stages of system development to assess the quality of its structure and elements from the perspective of the total system approach. The developed model reflects information links between different elements of the system, solves the problem of optimizing the structure of the monitoring and management of power plants, and eliminates redundancy. The proposed approach can be used to validate the transformation of information management and monitoring systems. It also describes systems and reflects both the internal structure and behavior of the algorithm using a single mathematical formalism.

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