DOI https://doi.org/10.30525/978-9934-26-142-8-8

ANALYSIS AND SYNTHESIS OF SHIP POWER PLANT AUTOMATED CONTROL SYSTEMS AND ITS ELEMENTS BY MEANS OF THE ANALYTICAL METHODS

Ushkarenko O. O.

INTRODUCTION

According to the Rules of classification and construction of marine vessels[1] ship electric power plants (SEPP) automation systems must satisfy the following requirements:

– provide remote start and stop diesel-generators from the central control panel (CCP); remote synchronization, connectivity and load sharing between parallel working generators from the CCP;

– each diesel (generator's drive motor) must have a speed controller with characteristics corresponding to the requirements of the factory, and for each drive motor must be a system for protection and controlling the parameters; each alternator must include a separate, independent automatic voltage regulation system;

– generators, which designed for parallel operation, shall be protected against overload, reverse power, short-circuit (over current), field loss and under voltage;

– the maximum permissible load of the operating power alternators shall be capable of automatic start-up of additional diesel-generators with the subsequent synchronization connection to the bus bars of the main switchboard (MSB) and the sharing of loads;

– machinery remote control from the CCP;

– remote indication of monitored parameters of ship power (voltage, current, frequency, resistance insulation for ship network load (current) and loaned a total load capacity – for the generating units) in a convenient form for the operator.

The modern approach to the design of automated control systems (ACS) is to use a hierarchical management system architecture, which in relation to the ship's electrical installation can be divided into three vertical subordinate levels (listed in order from bottom to top):

[1] Zhang Erhu, Wang Kelu, Guangfeng Lin. Classification of Marine Vessels with Multi-Feature Structure Fusion. *Applied Sciences*. 2019. № 9. P. 2153.

– local control motors and generators, which include automatic control systems for engine speed and generator voltage, means to implement algorithms to start and stop the engine in accordance with their factory instructions and tools to ensure the protection of the generator;

– automation tools that are essential for interoperability power trains and optimize their usage by correcting given and consumed electricity that are made by sending commands via the digital signals corresponding to local control systems;

– computerized control system (CCS), which allows remote monitoring and control of electric power plant through information exchange with automation midrange.

Automatic control system and sub-system of electric power unit protection will not work adequate without providing them with timely and accurate information about technical condition of diesel-generator sets and other components. Inasmuch as generating units start up and putting into operation requires relatively long time, the reliable information about damages should be acquired as soon as possible. Therefore, the tasks of information flows analyses and assessment of impact of autonomous power system on the information network are urgent.

The most difficult step in the implementation of automated control system is the development of software that meets the appropriate quality standards[2]. The top-level software task is remote monitoring and control of electric power system. To implement the essential functions of electric power system remote control through the network, the software must have means for the creation of electric power station layout, for monitoring and control of autonomous electric power system in real time, analysis of power unit operating modes and software[3]. At the same time, as noted in article[4], it is important to use a formal approach to describe the interaction of software components and automation hardware.

In the control system under consideration, the time delay connected with providing the operator with information for actions can be considered as a superposition of several factors: duration of analogue and digital signals processing by lower level subsystems, data transfer to middle level

[2] Sylwester Filipiak, Andrzej Stobiecki, Franciszek Strzelczyk. Application of evolutionary programming to optimization of reliability power distribution grids. *Przegląd Elektrotechniczny*. 2017. № 2. P. 273.

[3] Gardner C., Johnson D., Provine J. Networked Intelligent Instrumentation & Control for Switchboards. *The IEEE Electric Ship Technologies Symposium* ESTS '07 (Arlington, May 21-23, 2007). Arlington, 2007. P. 510–518.

[4] Juncao Li, Fei Xie, Levin V. Formalizing hardware/software interface specifications. *26th IEEE Int. Conf. Automated Software Engineering* (Washington, November 6-10, 2011). Washington, 2011. P. 235–252.

subsystems, data processing by means of middle level, and subsequent exchange of information with a CCS.

The presence of delay has a negative influence on system availability in whole. It is not always possible to remove delays only with a help of technology. Therefore it becomes necessary theoretically to estimate and prognose delays, and also determine the influence of delays on the system stability. In the paper[5] it was researched the influence of Ethernet network dynamics' on quality of controlling the simulated autonomous electric power installation, however there was not got any time delays statistical characteristics of information and control packets transmission.

The objectives of this research are the selection and implementation of the method of description and subsequent optimization of structural and algorithmic blocks of microprocessor systems automation of ship power plants, studying the information channel timing characteristics of a ship electric power system by means of analytical methods for the assessment of necessity to separate information flows in a distributed control system into multiple independent channels, as well as formalization of the separation process and simplifying iterative actions on calculating timing characteristics, and solving the problem of theoretical prognosis of time delays of information packets transmission through the Internet network on basis of statistical analysis of experimental data.

1. Using the method of logic circuits of algorithms in the synthesis of microprocessor control systems

In accordance with the common approach[6] to the synthesis of ACS in its initial design is performed functionally-oriented architecture to build automated and more for each functional block diagram of the unit is developed. To prevent hardware redundancy automation systems must have a means of analysis of the structural schemes. The work proposed for this purpose consideration microprocessor systems automation SEPP in the form of control machines. Then, if for each system to allocate a set of operations, where each element will determine not only the algorithmic block action, but also the associated complex hardware to describe the functioning of the control automaton can use the language of logic algorithms allow to optimize the structure of the individual and the totality

[5] Рябенький В.М., Ушкаренко А.О. Управление распределенной моделью автономной электростанции. *Техническая электродинамика*: тем. выпуск. 2008. № 6. С. 45–48.

[6] R. Dorf., R. Bishop. Modern control systems. Moscow: Laboratory of Basic Knowledge, 2002. 832 p.

of control machines[7]. Last-level microprocessor systems will lead to their unification to eliminate hardware redundancy and rationalization of resource use microprocessors

Monitoring system parameters of ship network serves for remote control of the current and the instantaneous values of voltage and frequency shipboard network; averaging time for the measurements of the current voltage and frequency is 120 sec. The system can be represented by the following logic:

$$y_0 \downarrow^1 \left[y_{1.1}\ y_{1.2}\ y_{1.3}\ y_2 \uparrow^1 \right]^{T=120s}, \qquad (1)$$

where y_0 – the initial state; $y_{1.1}$-$y_{1.3}$ – measurement of the ship's mains: RMS voltage, frequency and instantaneous voltage, respectively; y_2 – communication with upper level (here and after will be used the same notation).

System requirements for monitoring parameters are diesel-generator units (DGU) measurement and transmission for remote display of current and instant values of voltage and frequency, current, active and reactive power supplied by the generator set to the total load. Time averaging measurements is 120 sec.:

$$y_0 \downarrow^1 \left[y_{1.5} - y_{1.10}\ y_2 \uparrow^1 \right]^{T=120s}, \qquad (2)$$

where $y_{1.5}$-$y_{1.10}$ – measurements of the electricity generated by diesel generator: instantaneous voltage, instantaneous current, RMS voltage, RMS current, values, power factor and frequency, respectively.

The device for protection of generator from reverse power should be included after connecting DGU for parallel operation with other power alternators and perform periodic continuous measurement of active power supplied by the generator to the total load. If a situation arises in which the DGU will consume active power from the network (the magnitude of 8-12% of the rated power of the generator), longer than a certain time (5-15 sec.) this device must disconnect the generator from the network by acting on the generator circuit breaker:

[7] Babakov R.M. Barkalov A.A. Structural representation of synthesis methods of finite state machine with datapath of transition. *IEEE 9th International Conference on Dependable Systems, Services and Technologies* (Kyiv, May 24-27, 2018). Kyiv, 2018. P. 229–233.

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.7}\ y_{1.8}\ y_{1.9} \\ z_{2.1} \\ x_{2.1} \uparrow^1 y_{3.1} \uparrow^1 \end{bmatrix}^{T=5-15\,s}, \qquad (3)$$

where x_1 – the condition "the breaker open"; $z_{2.1}$ – calculation of active power; $x_{2.1}$ – condition "power consumption exceeds the limit $P \leq -(0.08...0.12)P_{rat}$"; $y_{3.1}$ – generating the signal to the relay, disconnecting the generator breaker.

The device for protection of generator from loss of excitation is also included after connecting DGU parallel operation with the network and serves to isolate the generator from the network in the event of their consumption of reactive power (value of 8-12% of the generator reactive power Q_{rat}) for more than a certain period of time (5-15 sec.):

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.7}\ y_{1.8}\ y_{1.11} \\ z_{2.2} \\ x_{2.2} \uparrow^1 y_{3.1} \uparrow^1 \end{bmatrix}^{T=5-15\,s}, \qquad (4)$$

where $z_{2.2}$ – reactive power calculation; $x_{2.2}$ – the condition "power consumption exceeds the limit $Q \leq -(0.08...0.12)Q_{rat}$".

The device for protection of DGU against current overload is used to measure RMS current generator and the output relay closes when the current exceeds the threshold value (100-120% of the nominal value I_{nom}) lasting longer than a certain period of time (5-10 sec.).

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.8} \\ x_{2.3} \uparrow^1 y_{3.2} \uparrow^1 \end{bmatrix}^{T=5-10\,s}, \qquad (5)$$

where $x_{2.3}$ – condition "current generator exceeds the limit $I \leq -(1...1.2)I_{nom}$"; $y_{3.2}$ – generating the signal to relay signals the operator overload fault.

The task of the generator protection device overload capacity is alarm (relay output circuit) in excess of given DGU in the total active power load limit (100-120% of rated power P_{rat}) for more than a certain period of time (5-10 sec.):

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.7}\ y_{1.8}\ y_{1.9} \\ z_{2.1} \\ x_{2.4} \uparrow^1 y_{3.2} \uparrow^1 \end{bmatrix}^{T=5-10\,s}, \qquad (6)$$

where $x_{2.4}$ – condition "Power supplied by the generator to the network exceeds the limit $P \geq (1...1.2)P_{rat}$". The device for under voltage and the minimum frequency is designed to prevent reducing the effective value of the voltage is more than 70% and frequency by more than 5% from the nominal values for a certain time (5–30 sec.). By disconnecting from the network DGU:

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.7} \\ x_{2.5} \uparrow^1 y_{3.1} \uparrow^1 \end{bmatrix}^{T=5-30\,s}, \quad (7)$$

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.10} \\ x_{2.6} \uparrow^1 y_{3.1} \uparrow^1 \end{bmatrix}^{T=5-30\,s}, \quad (8)$$

where $x_{2.5}$ – condition "generator voltage below the limit $U \leq 0.3U_{ref}$"; $x_{2.6}$ – the condition "current frequency generator below the limit $f \leq 0.95 f_{nom}$".

For optimal use of DGU there was used the control device start/stop generators. Its task was to measure the active power delivered by all DGU common load, and to inform the operator or automatic control of additional generator at startup running generators for more than 80–90% (requires additional training to the parallel operation of the generator) or less than 10–20% from the nominal values (required unloading and stop additional generator):

$$y_0 \downarrow^1 x_1\, y_{1.7}\, y_{1.8}\, y_{1.9}\, z_{2.1}\, x_3 \uparrow^2 \omega \uparrow^1 \downarrow^2 x_{4.1} \uparrow^3 y_{3.3} \downarrow^3 x_{4.2} \uparrow^1 y_{3.4} \omega \uparrow^1, \quad (9)$$

where x_3 – condition "check the status of generator circuit breakers all DGU"; $x_{4.1}$ and $x_{4.2}$ – conditions "must include ($x_{4.1}$) or disable ($x_{4.2}$) additional DGU"; $y_{3.3}$ and $y_{3.4}$ – signal generation circuit for the relay, signaling the operator to turn on ($y_{3.3}$) or turn off ($y_{3.4}$) additional generator.

Sync generator system with tires main switch board (MSB) is used to adapt the current voltage and frequency of the generator connected to the main switchboard bus parameters. Requirements are the ability to change device settings synchronization (differences between the existing values of voltage and frequency, the angle between the voltage vectors) and the presence of outputs for connection to control inputs of the excitation system of generator and engine control. Upon reaching the synchronization conditions:

$$|U_1 - U_2| = |\Delta U| \le \Delta U_{adm}, \tag{10}$$

$$f_2 - f_1 = \Delta f \le \Delta f_{adm}, \tag{11}$$

$$|\varphi_1 - \varphi_2| = |\Delta\varphi| \le \Delta\varphi_{adm}, \tag{12}$$

where U_1, U_2, f_1, f_2 – valid values of voltages, frequencies and angles of the vectors of mains voltages and plug the generator, respectively; and – sync settings, the system should generate a signal generator circuit breaker to:

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 x_4 \uparrow^2 \omega \uparrow^3 \downarrow^3 \begin{bmatrix} y_{1.1}\ y_{1.2}\ y_{1.4}\ y_{1.7}\ y_{1.10} \\ z_{2.3} \\ (x_5 \,\&\, x_6 \,\&\, x_7) \uparrow^5\ y_{3.5}\ \omega \uparrow^1 \\ \downarrow^5 \overline{x_5} \uparrow^4\ y_{3.6}\ \omega \downarrow^4 \overline{x_6} \uparrow^3\ y_{3.7}\ \omega \uparrow^3 \end{bmatrix} \tag{13}$$

where x_4 – condition “received command initiates the synchronization process”; $z_{2.3}$ – payment differences voltage and frequency, and plug the generator; x_5-x_6 – synchronization conditions (10) – (12); $y_{3.5}$ – signal conditioning circuit on the generator circuit breaker; $y_{3.6}$ and $y_{3.7}$ – formation correction signal generator excitation frequency and speed of the diesel engine, respectively.

The task of the distribution of active loads between generators operating in parallel is to measure the active power delivered by each of DGU in the total load, and the formation, if necessary, corrective action to change the frequency speed diesels. Active load distribution between the generators should be in proportion to their nominal capacity and shall not differ by more than 15% of the rated load of the larger generators or 25% of the rated load of the generator under consideration whichever is less:

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.7}\ y_{1.8}\ y_{1.9} \\ z_{2.1} \\ x_{8.1} \uparrow^1\ y_{3.7} \uparrow^1 \end{bmatrix}, \tag{14}$$

where $x_{8.1}$ – condition "given DGU network active power exceeds the set value".

The distribution system of reactive loads should monitor reactive power supplied by the DGU to the network and, if necessary, to carry out an adjustment by changing the generator excitation. Distribution of reactive load should be proportional to nominal generator power and will not vary by more than 10% of the rated load of the largest generator reactive or not more than 25% of rated capacity of the smallest generator, if this value is less than the above:

$$y_0 \downarrow^1 x_1 \uparrow^2 \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.7}\ y_{1.8}\ y_{1.11} \\ z_{2.2} \\ x_{8.2} \uparrow^1 y_{3.6} \uparrow^1 \end{bmatrix}, \qquad (15)$$

where $x_{8.2}$ – condition "give DGU network reactive power exceeds the set value".

Expansion Modules and PLC are to be able to remote control circuit breakers and/or soft starter asynchronous motors; implementation of various sequences connecting / disconnecting electricity consumers.

Based on the analysis of the principles of marine power plants and expressions (1) – (9), (13) with respect to modes of automation can be formulated in the following theses:

1. with parallel operation of DGU voltage and frequency, measured for each of them coincide with the corresponding parameters of the shared bus (ship's network); in terms of logic, this corresponds to the equivalence of measurement and $y_{1.1}$, $y_{1.7}$, $y_{1.2}$ and $y_{1.10}$, $y_{1.3}$, $y_{1.5}$ and falsity conditions at x_1;
2. in each section there is one DGU, which is essential for this section (first come into work and runs continuously);
3. generator protection devices included in the work after it is connected to a common bus, which corresponds to the falsity condition x_1;
4. synchronization system is needed to ensure connection to a common bus DGU and its running time is limited to the interval from starting the engine to the generator circuit breaker circuit – time the condition x_1 is true;
5. distribution system of active and reactive loads and device to control start/stop of DGU generator circuit breakers associated with all DGU this section, and for those generators, switches are closed, measuring power delivered them into the network. Thus, measurement of active and reactive power for each DGU performed only after it is connected to a common bus, which corresponds to the result of checking the condition x_1 part of DGU "false".

We can notice the following results:

1. The ship to monitor network parameters may be used, as measured by the monitoring system of the main parameters of DGU (logic device obtained coincides with the expression (2).

2. Most protection devices require measuring the same parameters with comparable frequency, so the implementation of all the protections of the generator can be combined in a single device – the protection system.

3. Many parameters required to run the system for monitoring parameters of DGU coincide with the parameters measured for the implementation of protection of generators, however, the time averaging for their monitoring system significantly (order of magnitude) more. If you realize the measurement units required for system protection, said to her cycles and averaging these values programmatically in the interval corresponding to the time characteristics of the monitoring system, the two systems can be combined into a single unit – automation controller:

$$y_0 \downarrow^1 x_1 \uparrow^2 y_{1.5}\ y_{1.7}\ y_{1.10}\ \omega \uparrow^1 \downarrow^2 \begin{bmatrix} y_{1.5} - y_{1.11} \\ y_2 \\ z_{2.1}\ z_{2.2} \\ (x_{2.1} \mid \ldots \mid x_{2.6}) \uparrow^1 (y_{3.1} \mid y_{3.2})\, \omega \uparrow^1 \end{bmatrix}^{T=5\,s} . \quad (16)$$

To ensure correct operation of the load distribution systems in their design must know the exact amount of DGU, which can be connected in parallel. This condition is contrary to the principle of system development, so the modern automated SEPP often used together individual units (Units job settings – tolerance of active and reactive power; blocks measuring and adjusting the active and reactive power) for each DGU bound through information channel. However, if we use a computerized control system as a subsystem of the upper level and transfer function at its reference level setting can minimize the amount of required hardware. Then the task of top level software will poll generator switches to determine the structure and management of the power plant (initiation measurements to commands on the formation of corrective actions) distribution system loads. The above decision will minimize the addition of hardware to implement remote monitoring and control processes of distribution of active and reactive loads dynamically change the distribution and transient time, remotely adjust the parameters of discrete signals used to control the frequency and voltage regulators.

Transferring control systems of distribution of active and reactive loads on the top-level subsystem determines the necessity of their presence for each DGU, except basic. Some parameters required for monitoring parameters and ensure protection of the generator set, coincides with the measured system load distribution parameters, so protection functions can be transferred to the DGU level computerized control system, using for their implementation, as well as for monitoring parameters of DGU measured load distribution systems values. At the same time to the measured at least one of the systems parameters need to add the current frequency.

$$y_0 \downarrow^1 x_1 \uparrow^2 \begin{bmatrix} y_{1.5} - y_{1.11} \\ z_{2.1} - z_{2.2} \\ y_2 \\ (x_{2.1} \mid \ldots \mid x_{2.6}) \uparrow^3 (y_{3.1} \mid y_{3.2})\, \omega \uparrow^3 \\ \downarrow^3 (x_{8.1} \mid x_{8.2}) \uparrow^1 (y_{3.6} \mid y_{3.7})\, \omega \uparrow^1 \end{bmatrix}, \tag{17}$$

$$\downarrow^2 x_4 \uparrow^1 \downarrow^6 \begin{bmatrix} y_{1.1}\ y_{1.2}\ y_{1.4}\ y_{1.7}\ y_{1.10} \\ z_{2.3} \\ (x_5 \,\&\, x_6 \,\&\, x_7) \uparrow^4 \ y_{3.5}\ \omega \uparrow^1 \\ \downarrow^4 \overline{x_5} \uparrow^5 y_{3.6} \downarrow^5 \overline{x_6} \uparrow^6 y_{3.7}\ \omega \uparrow^6 \end{bmatrix}. \tag{18}$$

According to the expressions (13), (15), it can be noted that the distribution of active and reactive load, and simultaneously used for measuring the work required substantially the same parameters: synchronization system and load distribution are used consistently and require measurement of several matching parameters. As noted above, the measurement for the implementation of the protection and monitoring functions of the generator parameters can be made in the VAr load sharing system. Therefore, it is advisable all five devices (synchronization distribution of active and reactive loads, protection and monitoring parameters DGU) to combine into one device – the system synchronization and load distribution.

Thus, for the automation of electric power system in the proposed method for each section, which consists of n and k DGU electricity consumers need: automation controller for monitoring network settings, monitoring and protection of the main parameters of the generator; n-1 systems synchronization and load distribution, additional features which will be the protection and monitoring of parameters DGU monitoring necessary start/stop additional generating units; *m* extension modules and/or PLC (the number depends on *k* and device characteristics) for state management of electricity consumers and display warning and/or emergencies.

2. The method for analysis of information flows in the network of a ship electric power plant automated control system

According to the principles of building the hierarchical control systems, the higher level of the hierarchy increases the degree of information uncertainty about the system state and, consequently, increases the control actions formation[8] period. Furthermore, since the CCS information communication with middle level means of automation constitutes a network logical structure "one to many", implemented in the form of topology "common bus", the largest contribution to the duration of time delay will make factors associated with data transmission over the network: data rate restrictions, distance between devices and CCS, and the communication channel utilization.

Ship electric power plant automated control system pertains to real-time control systems, so yet at the design stage, one of the essential steps is the calculation of its time efficiency. For this purpose, we can use the queuing theory, which is applied in various fields for studying queuing queries[9]. The most characteristic feature of functioning of queuing systems is the presence of queues where queries are waiting for the release of the communication channel. The analysis of microprocessor network of the distributed control system as a queuing system allows to determine the number of packets that are in the network at different stages of service, time of waiting in queues, time of packet transmission, and other characteristics of flows processing[10]. However, this method is applicable only for multimicroprocessor systems with shared memory, and is not applicable to the analysis of information flows of the ship electric power control network, since it has no shared memory in its structure. The known methods of analysis of information flows in network, which are applicable to traditional computer networks, require refinement for their applicability to microprocessor networks taking into account their features. In particular,

---

[8] Zbigniew Huzar, Anita Walkowia. Specification of real-time systems using UML sequence diagrams. *Przegląd Elektrotechniczny*. 2010. № 9. P. 226.
[9] Bakari H.R., Chamalwa H.A., Baba A.M. Queuing Process and Its Application to Customer Service Delivery. *International Journal of Mathematics and Statistics Invention*. 2014. № . 1. P. 14–21.
[10] Peter Hanuliak. Analytical Method of Performance Prediction in Parallel Algorithms. *The Open Cybernetics & Systemics Journal*. 2012. № . 6. P. 38–47.

each element of the distributed microprocessor network of the ship power station control also performs functions of measurement of the parameters of power units, network voltage parameters, and monitoring of electricity quality. Therefore, the nodes of such a network can be considered as sensors, and the network itself is sensory in this case. In this case, communication channel between individual nodes can be either wired or wireless.

With a sharp increase in the level of flows in network, overloads may occur which lead to blocking of the flow of messages to the network. One of the reasons leading to decrease in productivity is occupation of queues processing systems representing the queuing systems. The query received at the system entry waits for the queue to be executed. This waiting time depends on such factors as the intensity of flows, time of packets processing in the queuing system. One approach to address such problems is to optimize the use of all available network resources. In particular, it is preferable to ensure that nodes are not overloaded, while similar nodes on the alternative routes are underloaded. It is possible to use feedback algorithms that take into account the presence and size of queues, rate at which packets arrive, and interval between the successive packets where only information about input and saturation flows is used[11]. Such management mode where the claims flows are maintained strictly according to a predetermined law is most often used in large-load service systems, when rates of claims arrival via different flows are almost the same. Nevertheless, when breaks appear in flows, the cyclic control method is not expedient: for a certain flow the serving device is idle, while the other flows may be in queries processing queues. In such cases, it is more rational to use other control algorithms that use additional information about the structure of input flows of claims. At each next moment of time, on every port of communication modules node, there is some unit of the flow under generation from the set of units that corresponds to this port. The frequency of occurrence of each of the flow units depends on intensity. In such a way, there are intervals of inaccessibility where flows are not serviced. Any other information packet received at the system entry in this period is lost. This leads to decreasing efficiency of information and control flows processing and decrease in performance of the distributed control system network. Such situations should be determined in advance at the stage of designing

[11] Grzyb S., Orłowski P. Congestion feedback control for computer networks with bandwith estimation. *20th International Conference on Methods and Models in Automation and Robotics* (Miedzyzdroje, August 24-27, 2015). Miedzyzdroje, 2015. P. 1151–1156.

of information processing network. For these purposes, the approach proposed in this paper can be used.

At the stage of designing of the control system microprocessor network, its parameters ensuring the required quality are determined on the basis of the input flows characteristics. The increase of intensity of arrival of messages to the network leads to overload – saturation of network elements with information flows. At the same time, network characteristics (packets loss, increase in data transmission delays) are significantly degraded, and therefore it is necessary to include flow control procedures in the algorithms of network operation.

Optimal allocation of buffers in network nodes, adaptive message flows routing allow to reduce load on the network and keep its parameters unchanged under load fluctuations[12]. However, with a spur increase of the flows level in the network, these methods can not eliminate overloads, and it is necessary to impose load restrictions. Proper network design and classification of flows with a breakdown into a small number of priority classes may be sufficient to ensure adequate operation of the control system. Consequently, proper allocation of resources during the periods of peak load or emergencies, along with protection against the flows with lower priority, will provide necessary level of service.

When applying load control procedures, it is usually recommended to combine two methods:

– general control (isothermal method), when threshold $N_{\max}$ value is set against the number of messages in the whole network;

– end-to-end control when $N_{\max}(i, j)$ threshold value is set on a fixed route (i, j) connecting source i to destination j. When using these methods in network design, the problem arises of estimation of parameters N_{max} and $N_{max}\ (i, j)$, $i, j = 1, 2, ..., M$, where M is a number of nodes in network. For a specific network, it is necessary to select effective values of these parameters which ensure an acceptable quality of service under load increase.

Flow control-oriented tasks involve the aspects of improvement of quality of information flows servicing. The key objective of flows control include: minimization of packet loss and delays, optimization of throughput, and negotiation of the best level of services.

---

[12] Lacroix Y., Malbranque J.-F. A Unified Approach for Naval Telecommunication Architectures. *World Academy of Science Engineering and Technology International Journal of Electronics and Communication Engineering.* 2017. № . 9. P. 1–7.

One of approaches aimed to solve such problems is to optimize the use of all available network resources. In particular, it is preferable to ensure that nodes are not overloaded, while similar nodes on the alternative routes are underloaded.

Within the network, there are different flows that impose close requirements to the quality of service. The distributed control systems operating in real-time require the rigid and accurate service quality guarantees. Proper network design and classification of flows with a breakdown into a small number of priority classes may be sufficient to ensure adequate operation of the control system. Consequently, proper allocation of resources during the periods of peak load or emergencies, along with protection against the flows with lower priority, will provide necessary level of service. Three groups of parameters are used to characterize the required class of service:

– throughput parameters, include the average, maximum, and minimum transmission rates;

– parameters of delays – the average and maximum delays;

– transmission reliability parameters — the percentage of lost as well as distorted packets.

For the purpose of solving these issues, it is necessary to investigate the characteristics of information flows in order to determine their temporal characteristics, and, if necessary, carry out restructuring of software part of the system or topology of information processing network at the design stage of SEPS automated control system. This confirms the relevance of researches conducted in this direction.

All modern vessels are equipped with technical facilities automation systems. The general trend for ships automation based on the micro-processor computing facilities has been determined. The ship control system is considered as a set of microprocessor systems dispersed over the ship's production facilities and combined according to a trunk, ring or otherwise, to ensure centralization of control (collection, processing, presentation of information to personnel at the management posts) on the technical state of equipment and quality of technological processes which should be managed automatically and remotely. Thus, the system is distributed according to topology and management organization. Ship power plants have hierarchical structures. Therefore, the ship's power station control system can be considered as hierarchical computing system. In the event of upper-level elements failure, SEPP operation is ensured by means of the lower levels elements of the system.

Controllable SEPP elements with sensors and actuators are at the lower (zero) level of hierarchy. This level is intended for controlling SEPP actuators. Different types of locks are implemented here too. If a fault occurs, information is escalated.

The first hierarchical level is a complex of local automation facilities that provide stabilization of voltage and frequency of generators, their protection against overload and short-circuiting, as well as against reverse power. They allow formation of the control actions for the purpose of preservation of SEPP serviceability when its elements fail.

The second hierarchical level is a level of local control systems including generator control systems where the following functions are performed: control of the generators' drive motors o by a signal from an automatic device or operator, monitoring and protection of generators, synchronization with subsequent load sharing, frequency control. Also, there are generator sets local control devices at this level.

The third level of hierarchy is a level of functional complexes control systems. At this level, the following functions are performed: monitoring of operating generators load, monitoring of power reserve to ensure the start-up of powerful energy consumers, selection of the priority of starting up standby generator sets, monitoring of SEPP technical condition, protection against short-circuit currents.

The fourth level of hierarchy is a level of integrated system for technical facilities management where the ship is generally managed by operator. At this level, SEPP utilization modes are set depending on the mode of vessel operation on which composition of SEPP elements depends.

Diesel generators control systems, systems of generator synchronization and power distribution between them, various protection systems are combined into a single microprocessor network. In this case, one of industrial protocols is used such as Modbus RTU, Profibus, DeviceNet, CANopen, and many others. The choice of communication protocol has a significant effect on the characteristics of information flows, so the actual task is to develop a methodology for calculating the characteristics of information flows, which would be different in its simplicity and flexibility, and would allow analysis not only for hardware systems but also for hardware and software systems.

The choice of topology of network nodes connection is determined by SEPP structure, reliability requirements, the allowable time of waiting for data packet from one level to another. In general, the configuration of network relationships can remain unchanged during operation (static), or can be changed quickly by software (dynamic). The use of dynamic configuration of relationships within the control system is more desirable. So, in case of emergent situation (for example, if one of generator sets fails), it is necessary to quickly disconnect the failed node from the main switchboard buses. At the same time, control system should give a signal to start the backup generator. This signal is transmitted from the third hierarchical level to the second one. In this case, data packet length makes the very few bytes. At the same time, from the lower hierarchical level to the top a considerable amount of information is transmitted from sensors about the state of the technical means for solving diagnosis problems and SEPP operating modes control. Therefore, time of waiting for transmission of backup generator start command is significantly increasing. The use of a dynamic topology allows creation of less loaded redundant paths and usage of these paths to transmit control commands.

To study the processes, which take place in the information channel of monitoring and control system of a ship electric power system, have been used simulation models of objects and means of automation, as well as the top-level software with power plant mnemonic scheme, which interface shown in Fig. 1. SCADA is used to control of ship power system, to identify faults and allows to protect motors and other equipment[13].

When examining information processing network of the ship automated control system, the following structural and functional elements can be distinguished: worker node, communication node (multiplexor, hub, or router), channel and flow. The flow is a sequence of packets moving from source to destination, each of which may be uniquely identified by the packet header.

Class of hierarchical systems has a most flexible architecture of all the topological classes of computing systems used in the construction of real-time control systems, including ship electric power systems. The idea of thick-tree-like network topology consists in the increase of throughput capacity of switching lines at root levels of the network. To this end, at the upper levels of the network, the parent and daughter nodes are connected not by one but several channels, and the higher the level, the more channels are. The size of network is determined by the number of network nodes and depends on the level of power system automation. Network diameter – a

[13] Guillermo A Francia III, Nourredine Beckhouche, Terry Marbut. Curtis Neuman, Portable SCADA Security Toolkits. *International Journal of Information & Network Security*. 2014. № . 4. P. 265–274.

minimum path through which the message passes between the two most distant from each other nodes – is determined by the expression $D_1=2(h-1)$, where h is a height of tree[14]. At the lower levels of hierarchy, RS485, CAN interfaces are used for communication between network nodes. As volume of information flow increases at upper hierarchical levels of the distributed control system, the communication channels congestion becomes significant thereby increasing the transmission time of information control packets. Therefore, at upper levels of hierarchy Ethernet network is used.

The research of information channel characteristics performed on a ship power plant physical model that consists three sections: the section of power supply to consumers implementing the process (H1-H9, AD1-AD6), and the section of power supply to the left bank ground tacking (H10, H11, AD7) and to the right bank ground tacking (AD8). In normal power plant operation mode, sections are autonomous (K19-K22 circuit breakers are opened), but in case of emergency (failure al least one of the generating units) it is possible to include generator sets of different sections by closing the respective intersectional automatic circuit breakers.

Processes that require software data exchange with lower level devices of the control system, by periodicity can be conditionally divided into three groups: monitoring parameters of network and diesel-generator sets (DGS), monitoring the states of circuit breakers with deterministic time interval (not exceeding the minimum time value necessary for implementing DGS protection functions); monitoring of DGS parameters, control of synchronization devices, and changing the circuit breakers state at operator's request; tripping the DGS protection functions and signal generation to change diesel-generator loading. Functioning of the above processes further can be regarded as processing of queries from software components, which maintenance is performed using the mechanism of dataset exchange between CCS and the power unit microprocessor control system. Using the given processes of data exchange grouping, the flow of queries can be viewed as the aggregation of deterministic flow associated with actions of the first group and two random actions related to the second and the third groups. At that, having properly adjusted control system and serviceable power units, the queries flow from components associated with ensuring actions of third group, will be absent.

[14] Sasa Klampfer, Joze Mohorko, Zarko Cucej, Amor Chowdhury. Wykorzystanie teorii grafów do poszukiwania najkrótszej ścieżki routingu w protokole RIP. *Przegląd Elektrotechniczny*. 2012. № . 8. P. 224.

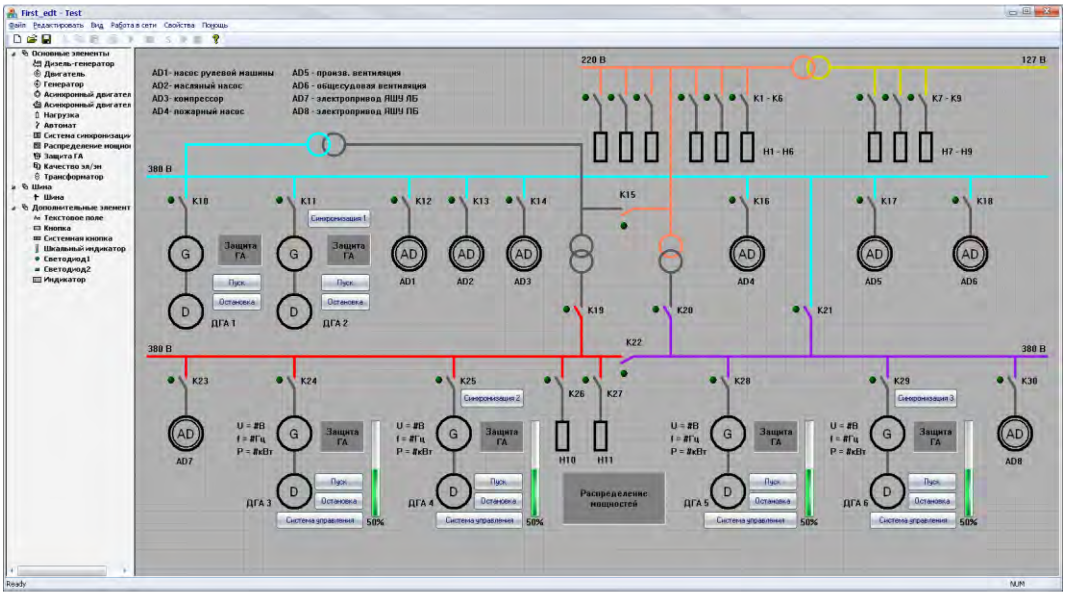

Fig. 1. Software for managing of a ship electric power station

The process of each component's query maintenance includes transmitting packages with information and control data to a particular microprocessor system and obtaining response packages for subsequent transmitting to the requesting component. Since the size of data packages used for interface and protocol (RS-485, Modbus RTU) is strictly regulated, and the speed of information exchange is the same for all devices, then each query maintenance time is deterministic and, in general, is different for different queries.

Thus, the control and monitoring of electric power system parameters by interacting software components with microprocessor automation tools can be considered as a closed single-channel queuing system with an input flow of queries obtained by combining the random and deterministic flows, and deterministic maintenance time ($\vec{G} \cup \vec{D} \mid \vec{D} \mid 1$).

The main characteristics of queuing system (QS) are average, minimum, and maximum queue length and channel utilization. Since the projected ACS refers to a class of real-time control systems, the QS characteristics should be complemented with minimum, maximum, and average queue processing time: based on their values, one can draw a conclusion about the possibility of transferring hardware functions to a program level (protection of DGS and circuit breakers control).

To study characteristics of information flows, the electric power station operation was simulated in normal mode.

The subsequent calculation performed using the pattern network theory[15]. Each electric power station component corresponds to a particular software object, which implementation encapsulates the generatrixes: *g*1 – Text field for displaying electrical parameters; *g*2 – Bar-graph indicator; *g*3 – Pointer indicator; *g*4 – Generator; *g*5 – Diesel (with generator unit forming the DGS set); *g*6 – Dialog box "Diesel parameters"; *g*7 – Dialog box "Oscillograms"; *g*8 – Synchronization system; *g*9 – GS protection; *g*10 – Automatic circuit breaker; *g*11 – LED; *g*12 – Loading; *g*13 – Induction motor; *g*14 – Control button; *g*15 – Load sharing system.

Generators *g*1–*g*3 are used to designate the display units of measured electrical parameters; every diesel-generator set (DGS) may be bound with arbitrary but finite number of such units (designated as l_1, l_2 and l_3 respectively).

Electric power station is remotely controlled and managed by means of displaying and processing the received data from particular hardware resources of automation and sending to them commands (signals for changing the state of protective relays, automatic circuit breakers and generator circuit breakers, diesel rotation speed and generator excitation). To take into account the priority of operations and control of data exchange process, it is necessary to create a common queries queues and expected responses. The whole set of queries can be divided into two sets: information type queries (to receive the value of DGS parameters and automatic and generator circuit breakers conditions) and control type queries (commands to change the electric power station structure and / or parameters of electric energy, given up by DGS to the network). For this reason, three generators correspond to queries and responses queues formation: *g*16 – variable length queue shaper; *g*17 – constant length queue shaper; *g*18 – final queue shaper.

Functions of the higher-level software also include information flows statistical data accumulation and storage in the database of capacity values given up by DGS to the network and consumed by loading (*g*20 generator).

Information channel research supposes the following actions:

– for each section: determining the composition of software objects; calculation of attribute values for generators $g1^{i,j}$ – $g15^{i,j}$ and determining the intensity of queries flow from their respective components; arities and calculation of attribute values of generators $g16^{i}$ – $g18^{i}$;

[15] Tsekouras G.J., Hatzilau I.K., Prousalidis J.M. A new pattern recognition methodology for classification of load profiles for ships electric consumers. *Journal of Marine Engineering and Technology*. 2009. № 14. P. 45–58.

– for the entire electric power station: calculation of attribute values of generators $g16 - g18$; calculation of minimum, average and maximum queue length and the time of its processing; calculation of communication channel utilization.

Here it is proposed to use lengths of the query packets and expected response (in bytes) for each corresponding communication indicator as the attributes of generators, connections of which can form connections by means of the relations listed.

Then the following characteristic vectors can be put into correspondence with generators $g4 - g18$:

$$a\left(g4^{i,j_1}\right)=\left(4,\gamma_{4,30}^{i,j_1},\gamma_{4,31}^{i,j_1},\left[\beta_{4,0}^{i,j_1}\right]^{l_1},\left[\beta_{4,1}^{i,j_1}\right]^{l_2},\left[\beta_{4,2}^{i,j_1}\right]^{l_3},\beta_{4,3}^{i,j_1}\right),$$

$$a\left(gp^{i,j_1}\right)=\left(p,\gamma_{p,00}^{i,j_1},\gamma_{p,01}^{i,j_1},\beta_{p,0}^{i,j_1}\right)\ \text{for}\ p=\{6,7,8,10,11,14\},$$

$$a\left(gp^{i,j_1}\right)=\left(p,\gamma_{p,00}^{i,j_1},\gamma_{p,01}^{i,j_1},\gamma_{p,10}^{i,j_1},\gamma_{p,11}^{i,j_1},\beta_{p,0}^{i,j_1},\beta_{p,1}^{i,j_1}\right)\ \text{for}\ p=\{9,15\},$$

$$a\left(g16^{i}\right)=\Bigg(16,\gamma_{16,00}^{i},\gamma_{16,01}^{i},\left\{\left[\gamma_{16,p0}^{i,j_1}\right]^{n_i},\left[\gamma_{16,p1}^{i,j_1}\right]^{n_i}\,\middle|\,p=\{1,2,4,5\}\right\},$$

$$\left[\gamma_{16,30}^{i,j_1}\right]^{n_i-1},\left[\gamma_{16,31}^{i,j_1}\right]^{n_i-1},\left[\gamma_{16,50}^{i,j_1+j_2}\right]^{k_i},\left[\gamma_{16,51}^{i,j_1+j_2}\right]^{k_i},\left[\gamma_{16,60}^{i,j_1}\right]^{2n_i},\left[\gamma_{16,61}^{i,j_1}\right]^{2n_i},\gamma_{16,70}^{i},\gamma_{16,71}^{i},$$

$$\beta_{16,0}^{i},\left\{\left[\beta_{16,p}^{i,j_1}\right]^{n_i}\,\middle|\,p=\{1,2,4,5\}\right\},\left[\beta_{16,3}^{i,j_1}\right]^{n_i-1},\left[\beta_{16,5}^{i,j_1}\right]^{k_i},\left[\beta_{16,6}^{i,j_1}\right]^{2n_i},\beta_{16,7}^{i}\Bigg),$$

$$a\left(g17^{i}\right)=\Bigg(17,\gamma_{17,00}^{i},\gamma_{17,01}^{i},\left\{\left[\gamma_{17,p0}^{i,j_1}\right]^{n_i},\left[\gamma_{17,p1}^{i,j_1}\right]^{n_i}\,\middle|\,p=\{1,2,3\}\right\},\left[\gamma_{17,30}^{i,j_1+j_2}\right]^{k_i},$$

$$\left[\gamma_{17,31}^{i,j_1+j_2}\right]^{k_i},\gamma_{17,40}^{i},\gamma_{17,41}^{i},\beta_{17,0}^{i},\left\{\left[\beta_{17,p0}^{i,j_1}\right]^{n_i}\,\middle|\,p=\{1,2,3\}\right\},\left[\beta_{17,3}^{i,j_1+j_2}\right]^{k_i},\beta_{17,4}^{i}\Bigg),$$

$$a\left(g18^{i}\right)=\left(18,\left\{\gamma_{18,p0}^{i},\gamma_{18,p1}^{i}\,\middle|\,p=\{2,3,4\}\right\},\beta_{18,0}^{i},\beta_{18,1}^{i},\left\{\beta_{18,p}^{i}\,\middle|\,p=\{2,3,4\}\right\}\right),$$

where the lower indexes of generators attributes are formed by adding 0 to the index of corresponding connection to denote the query length of the request and 1 to indicate the length of the expected response; designation $\left[\beta_{4,0}^{i,j_1}\right]^{l_1}$ is an abbreviated notation for the number of instances of communication indicators in vector. In this case, attributes corresponding to relationships connected via $\rho_2 - \rho_4$ relations are equal to each other.

Binary relationships can be considered as an overlap of input and output connections. Then, in the course of formation of the queries queues, generators $g16$ $g18$ function as synthesis generators (with output $\beta_{16,7}$, $\beta_{17,4}$ and $\beta_{18,4}$ connections, respectively), and during backward data transfer of analysis generators (with input $\beta_{16,7}$, $\beta_{17,4}$ and $\beta_{18,4}$ connections).

If we assume that $g16$ performs functions of formation of a queue with variable length, $g17$ function of generation of a queue of conditionally constant length, $g18$ function of formation of a final queue; $\rho 2$ many-to-one communication relation, $\rho 3$ one-among-many communication relation, $\rho 4$ "inclusion" communication relation and equality of attributes connected by $\rho 2$-$\rho 4$ communication relations, then minimum, maximum and average values of QSQ queries queue length (in bytes; the initial calculation of values in bytes makes it possible to ignore differences between the elements claims) can be compared with the values of attribute $\gamma_{18,40}$, during calculation of which execution of operation which correspond to determined relationship and queue length should be considered (Table 1).

Table 1

Operations for calculating the queue lengths

Link relation	Queue length / operation with attributes of input links		
	max	min	avg
$\rho 2$	sum	for attributes of $g16$:	
		multiply by 0	sum of vector's elements*
		for another attributes:	
		sum	sum
$\rho 3$	max	multiply by 0	sum of vector's elements
$\rho 4$	sum	sum	sum
*vector resulting from the production of vectors of attributes and corresponding queries rates			

Considering inseparable logical connection existing between generator blocks, diesel engines, dialog windows for displaying diesel and generator parameters, protection systems, synchronization systems, diesel control buttons, generator circuit breakers (circuit breaker represented by a component) and LEDs of the states of generator, as well as of load and asynchronous engines, circuit breakers with LED-indicators of their states, and conditionally inseparable connection between the groups listed, the software structure of computer for each section ($i = const$) can be written as a subset:

$$G^i = G_1^i + G_2^i + G_0^i ,$$

where

$$G_1^i = \{[g1]^{l_1^i}, [g2]^{l_2^i}, [g3]^{l_3^i}, [g4]^{n_i}, [g5]^{n_i}, [g6]^{n_i}, [g7]^{n_i}, [g8]^{n_i-1},$$

$$[g9]^{n_i}, [g10]^{n_i}, [g11]^{n_i}, [g14]^{2\cdot n_i}, [g15]^{1}\},$$

$$G_2^i = \{[g12]^{k_1^i}, [g13]^{k_2^i}, [g10]^{k_i}, [g11]^{k_i}\},$$

$$G_0^i = \{[g16]^{1}, [g17]^{1}, [g18]^{1}, [g19]^{1}, [g20]^{1}\},$$

and $[g1]^{l_1^i}$ designation is an abbreviated notation for the number of instances in subset ($l_1^i = (g1, G_1^i)$).

Then, structure of the entire power plant control software is a set formed by the sum of the amounts of subsets G_1^i and G_2^i and intersection of subsets G_0^i of each section:

$$G = \sum_{i=1}^{m}\left(G_1^i + G_2^i\right) + \bigcap_{i=1}^{m} G_0^i .$$

According to discrete theory of patterns, each generator is characterized by certain arity. Thus, with $j1$-th DGA in the i-th section, l_1^{i,j_1} text fields, l_2^{i,j_1} scale and l_3^{i,j_1} dial indicators can be associated, and here communication relationship $g1$ is "one-to-many", i.e. generator $g4$ can be connected with arbitrary but finite number of generators $g1 - g3$, and generators $g1 - g3$ with only one $g4$. Hence, arities $g1 - g3$ are equal to unity:

$$\omega\left(g1^{i,j_1}\right) = \omega\left(g2^{i,j_1}\right) = \omega\left(g3^{i,j_1}\right) = 1 ,$$

which corresponds to the principle of realism: each indicator nit displays data obtained from only one DGA unit, while these data (electrical parameters of generator) can be displayed in various combinations by various means of indication. The generator block itself, in addition to links to

$$N = \sum_{p=1}^{3} l_p^{i,j_1}$$

indicator units, should support informational connection with automation means, which is carried out by means of the queue forming unit, and is represented as communication relationship $\rho 2$ of multiple inclusion ("many-to-one" relationship) between generators *g4* and $g17$: for each j1-th DGA in the *i*-th section, values of electrical parameters of generator are interrogated. This implies arity *g4*:

$$\omega\left(g4^{i,j_1}\right) = \sum_{p=1}^{3} l_p^{i,j_1} + 1$$

Similarly to arity of generators $g9 - g11$, $g14 - g15$:

$$\omega\left(g10^{i,j_1}\right) = \omega\left(g11^{i,j_1}\right) = \omega\left(g14^{i,j_1}\right) = 1,$$

$$\omega\left(g9^{i,j_1}\right) = \omega\left(g15^{i,j_1}\right) = 2.$$

Communication "one-of-many-to-one" relationship $\rho 3$ means possibility of the existence of connection at each moment of time of only one of the plurality of instances of corresponding generator with the other generator. For example, communication $\beta_{6,0}\rho_3\beta_{16,1}$ stands for *ni*-th amount of "Diesel Parameters" blocks (generator $g6$) at each time only one can participate in data exchange with automation facilities by means of communication with the block of formation of queues with variable lengths (generator $g16$). Thus, the arities of generators $g16$ and $g17$ are calculated as:

$$\omega\left(g16^{i}\right) = 4 + 4 \cdot n_i + k_i,$$

$$\omega\left(g17^{i}\right) = 1 + 3 \cdot n_i + k_i,$$

i.e. arity of communication for relationships $\rho 2$ is equal to power of corresponding generator in the *i*-th subset, and for relationships $\rho 3$ is set to unity.

Generator $g18$ is unifying with respect to generators which reflect the formation of queues of constant and variable lengths ($g16$ and $g17$), and is responsible for the formation of final queues of queries and responses for the purpose of arrangement of data exchange over the physical communication channel. Since through it all information about electric power parameters and state of the circuit breakers passes, the functions of block represented by $g18$ generator include transmission of statistical data on information flows and electrical power parameters to the database to corresponding blocks (represented by $g19$ and $g20$ generators).

Therefore, communication relationships between $\rho5$ and $\rho6$ are "purely" informational "one-to-one" relations without direct exchange of data with automation facilities, while relationship $\rho4$, inclusion relationship (also "one-to-one") means full inclusion of data obtained from generators into other.

Thus, the use of pattern networks apparatus allows formal description of software structure of SEPS automated control system; such form of presentation makes it possible:

– to make changes in the composition of software by introducing or removing generators and organizing their interaction with existing generators by means of certain communication relationships;

– to take into account behavior of all software objects that affect the system time of response to actions of the operator and affect the workload of data exchange channel with automation tools;

– to formally perform reorganization of software structure, if it is necessary to change the time of system response.

According to patterns theory[16], software objects for each section can be expressed in the form of the following subsets:

– for the first section:

$$G_1^1 = \{g4^{1,1}, g4^{1,2}, g5^{1,1}, g5^{1,2}, g6^{1,1}, g6^{1,2}, g7^{1,1}, g7^{1,2}, g8^{1,1}, g9^{1,1}, g9^{1,2}, g10^{1,1}, g10^{1,2}, g10^{1,18}, g11^{1,1}, g11^{1,2}, g11^{1,18}, g14^{1,1} - g14^{1,4}, g15^{1,1}\},$$

$$G_2^1 = \{g10^{1,3} - g10^{1,11}, g10^{1,12} - g10^{1,17}, g11^{1,3} - g11^{1,11}, g11^{1,12} - g11^{1,17}, g12^{1,1} - g12^{1,9}, g13^{1,1} - g13^{1,6}\},$$

$$G_0^1 = \{g16^1, g17^1, g18^1, g19^1, g20^1\};$$

– for the second section:

[16] Banks S.P. Pattern Theory: from Recognition to Inference by Ulf Grenander and Michael Miller. *IMA Journal of Mathematical Control and Information*. 2009. № 1. P. 129–130.

$$G_1^2 = \{ g1^{2,1} - g1^{2,6}, g2^{2,1}, g2^{2,2}, g4^{2,1}, g4^{2,2}, g5^{2,1}, g5^{2,2}, g6^{2,1}, g6^{2,2}, g7^{2,1}, g7^{2,2}, g8^{2,1}, g9^{2,1}, g9^{2,2}, g10^{2,1}, g10^{2,2}, g10^{2,6}, g11^{2,1}, g11^{2,2}, g11^{2,6}, g14^{2,1} - g14^{2,4}, g15^{2,1} \},$$

$$G_2^2 = \{ g10^{2,3} - g10^{2,5}, g11^{2,3} - g11^{2,5}, g12^{2,1}, g12^{2,2}, g13^{2,1} \},$$

$$G_0^2 = \{ g16^2, g17^2, g18^2, g19^2, g20^2 \};$$

– for the third section:

$$G_1^3 = \{ g1^{3,1} - g1^{3,6}, g2^{3,1}, g2^{3,2}, g4^{3,1}, g4^{3,2}, g5^{3,1}, g5^{3,2}, g6^{3,1}, g6^{3,2}, g7^{3,1}, g7^{3,2}, g8^{3,1}, g9^{3,1}, g9^{3,2}, g10^{3,1}, g10^{3,2}, g10^{3,4} - g14^{3,6}, g11^{3,1}, g11^{3,2}, g11^{3,4} - g11^{3,6}, g14^{3,1} - g14^{3,4}, g15^{3,1} \},$$

$$G_2^3 = \{ g10^{3,3}, g11^{3,3}, g13^{3,1} \},$$

$$G_0^3 = \{ g16^3, g17^3, g18^3, g19^3, g20^3 \}.$$

3. The technique for calculation of the automated control system communication channel characteristics

Calculation of generators' values is made for software components involved in data exchange with automation means ($g4^{i,j} - g15^{i,j}$), and the intensity of their queries flow. The next step for the determination of information channel characteristics is calculation of arities and attributes values of generators $g16^i - g18^i$ for each section. Since values of $g18^i$ attributes defined according to

$$\gamma_{18,40}^i = \gamma_{16,70}^i + \gamma_{17,40}^i,$$

based on the values of $g16^i$ and $g17^i$ let us consider their calculation at first (based on the example of attributes calculation for the first section; calculation for other sections is similar).

The number of generating units in the first section n_1=2; the number of induction motors, loads and automatic circuit breakers for connecting section with loading $k_1 = 16$, therefore, from the expression

$$\omega(g16^1) = 4 + 4 \cdot n_1 + k_1,$$

$$\omega\left(g17^1\right)=1+3\cdot n_1+k_1,$$

arities of generators $g16^1$ and $g17^1$:

$$\omega\left(g16^1\right)=4+4\cdot n_1+k_1=4+4\cdot 2+16=28,$$

$$\omega\left(g17^1\right)=1+3\cdot n_1+k_1=1+3\cdot 2+16=23.$$

Generator's arity value determines the number of terms used for determining values of its attributes, corresponding to communications involved in data exchange with automation tools.

$$\gamma^i_{16,70}\Big|_{G^i_1}=func_1\left\{\gamma^i_{15,00}\right\}+\sum_{p=6}^{7}func_2\left\{\gamma^{i,j_1}_{p,00}\,\Big|\,j_1\in\left[1,n_i\right]\right\}+$$

$$+func_2\left\{\gamma^{i,j_1}_{8,00}\,\Big|\,j_1\in\left[1,n_i-1\right]\right\}+\sum_{p=9}^{10}func_1\left\{\gamma^{i,j_1}_{p,00}\,\Big|\,j_1\in\left[1,n_i\right]\right\}+func_1\left\{\gamma^{i,j_1}_{14,00}\,\Big|\,j_1\in\left[1,2\cdot n_i\right]\right\},\quad(19)$$

$$\gamma^i_{17,40}\Big|_{G^i_1}=\gamma^i_{15,10}+\sum_{j_1=1}^{n_i}\left(\gamma^{i,j_1}_{4,30}+\gamma^{i,j_1}_{9,10}+\gamma^{i,j_1}_{11,00}\right);\quad(20)$$

– when calculating the value of attribute $\gamma_{18,40}$, corresponding to minimal length of queries queue ($\gamma^{\min}_{18,40}$):

$$func_1\left\{\gamma_i\,\big|\,i\in\left[1,n_{\max}\right]\right\}=func_2\left\{\gamma_i\,\big|\,i\in\left[1,n_{\max}\right]\right\}=0;\quad(21)$$

– when calculating the value of attribute $\gamma_{18,40}$, corresponding to maximal length of queries queue ($\gamma^{\max}_{18,40}$):

$$func_1\left\{\gamma_i\,\big|\,i\in\left[1,n_{\max}\right]\right\}=\sum_{i=1}^{n_{\max}}\gamma_i,$$

$$func_2\left\{\gamma_i\,\big|\,i\in\left[1,n_{\max}\right]\right\}=\max_{i\in\left[1,n_{\max}\right]}\gamma_i;\quad(22)$$

– when calculating the value of attribute $\gamma_{18,40}$, corresponding to middle length of queries queue ($\gamma^{avg}_{18,40}$):

$$func_1\left\{\gamma_i\,\big|\,i\in\left[1,n_{\max}\right]\right\}=func_2\left\{\gamma_i\,\big|\,i\in\left[1,n_{\max}\right]\right\}=\sum_{i=1}^{n_{\max}}\left(\gamma_i\cdot\lambda_i\cdot t_{ск\phi}\right).\quad(23)$$

To calculate the attributes of generators g16[1] и g17[1], expressions (19) – (23) take the form:

– generalized expression for $\gamma^{1}_{16,70}$:

$$\gamma^{1}_{16,70} = \gamma^{1}_{16,70}\Big|_{G^{1}_{1}} + \gamma^{1}_{16,70}\Big|_{G^{1}_{2}} = func_1\left\{\gamma^{1}_{15,00}\right\} +$$

$$+\sum_{p=6}^{7} func_2\left\{\gamma^{1,j_1}_{p,00}\,\middle|\, j_1 \in [1,2]\right\} + func_2\left\{\gamma^{1,1}_{8,00}\right\} +$$

$$+\sum_{p=9}^{10} func_1\left\{\gamma^{1,j_1}_{p,00}\,\middle|\, j_1 \in [1,2]\right\} + func_1\left\{\gamma^{1,j_1}_{14,00}\,\middle|\, j_1 \in [1,4]\right\} + func_1\left\{\gamma^{1,2+j_2}_{10,00}\,\middle|\, j_2 \in [1,16]\right\};$$

– expressions for calculating minimal, average and maximal values $\gamma^{1}_{16,70}$ and $\gamma^{1}_{17,40}$:

$$\gamma^{1,\,\min}_{16,70} = 0, \tag{24}$$

$$\gamma^{1,\,avg}_{16,70} = \Bigg(\gamma^{1}_{15,00}\cdot\lambda^{1}_{15,0} + \sum_{p=6,\,7}\sum_{j=1,\,2}\left(\gamma^{1,j}_{p,00}\cdot\lambda^{1,j}_{p,0}\right) + \gamma^{1,1}_{8,00}\cdot\lambda^{1,1}_{8,00} + \sum_{p=9,\,10}\sum_{j=1,\,2}\left(\gamma^{1,j}_{p,00}\cdot\lambda^{1,j}_{p,0}\right) +$$

$$\sum_{j=1}^{4}\left(\gamma^{1,j}_{14,00}\cdot\lambda^{1,j}_{14,0}\right) + \sum_{j=1}^{16}\left(\gamma^{1,2+j}_{10,00}\cdot\lambda^{1,2+j}_{10,0}\right)\Bigg)\cdot t_{ск\,ф}, \tag{25}$$

$$\gamma^{1,\max}_{16,70} = \gamma^{1}_{15,00} + \sum_{p=6}^{7}\max\left\{\gamma^{1,1}_{p,00}, \gamma^{1,2}_{p,00}\right\} + \gamma^{1,1}_{8,00} + \sum_{p=9,10}\sum_{j=1,2}\gamma^{1,j}_{p,00} + \sum_{j=1}^{4}\gamma^{1,j}_{14,00} + \sum_{j=1}^{16}\gamma^{1,2+j}_{10,00}, \tag{26}$$

$$\gamma^{1,\,\min}_{17,40} = \gamma^{1,\,avg}_{17,40} = \gamma^{1,\,\max}_{17,40} = \gamma^{1}_{17,40}\Big|_{G^{1}_{1}} + \gamma^{1}_{17,40}\Big|_{G^{1}_{2}} = \gamma^{1}_{15,10} + \sum_{j=1}^{2}\left(\gamma^{1,j}_{4,30} + \gamma^{1,j}_{9,10} + \gamma^{1,j}_{11,00}\right) + \sum_{j=1}^{16}\gamma^{1,2+j}_{11,00}. \tag{27}$$

To calculate the generator g18[1] attribute values, use the expression:

$$\gamma^{1}_{18,40} = \gamma^{1}_{16,70} + \gamma^{1}_{17,40}.$$

The process of serving each query coming from software component includes the transmission of packages with information and control data to a particular microprocessor system and obtaining response packages with subsequent transmission to the requesting component. Because dataset size for interface and protocol (RS-485, Modbus RTU) strictly regulated, so query serving time is deterministic for each query and determined by three factors: the speed and the size of data exchange frame, the query length and the length of response package. The last two factors are attributes of generators bound with the relevant objects and their values are known at the stage of designing the control system.

Characteristics of “Generator” component (Fig. 1) are measured with the use of Modbus-function “read the value from input register” (0x04), which corresponds to the query length of 8 bytes and response of 7 bytes. These values define the values of generator g41, 1, corresponding to this component: for outgoing communication the attribute value is the sum of all queries lengths, for incoming communication – the sum of all responses lengths. Superscripts of generators and attributes are formed of section’s sequence numbers and component of a given type in the section, separated by comma. Read out values for “Generator” component (frequency, power factor, operating voltage and current values) are displayed in the window that appears when you hover over a component, and as indicated in the settings of “DGS protection” component, are used to calculate the values required for the implementation of protection functions.

The latter determines equality of generator attributes values g91,1, corresponding to querying the parameters of electric power given up by DGS into the network, to zero: as values read out by the Generator component are used, the component “DGS Protection” does not perform additional querying of automation tools. Since the protection of generator set involves the change of conditions of certain discrete outputs in case of emergency or adverse situations, the values of communication attributes corresponding to the transmission of commands to perform these actions and receive the response package, will be the length of these commands and responses. Settings of “DGS protection” component contain implementation of all protection functions. In this connection, to execute the commands has been selected the Modbus function “one flag value record” (0x05) that determines the length of each command as 8 byte and the response – as 11 byte.

Substituting in expressions (24) – (27) numerical values and taking into account that indicated in the software settings data exchange period ($t_{ск.ф}$) is 5 seconds, we can obtain numerical values of attributes for the first section; calculation of attribute values for the second and the third sections is similar.

Attributes for the set corresponding to the entire electric power station control system calculated as:

$$\gamma_{18,40} = \sum_{i=1}^{m} \left(\gamma_{16,70}^{i} + \gamma_{17,40}^{i} \right), \tag{28}$$

$$\sum_{i=1}^{m}\gamma_{16,70}^{i}=\sum_{i=1}^{m}\gamma_{16,70}^{i}\Big|_{G_2^i}+func_1\left\{\gamma_{15,00}^{i}\,\middle|\,i\in[1,m]\right\}+\sum_{p=9}^{10}func_1\left\{\,func_1\left\{\gamma_{p,00}^{i,j_1}\,\middle|\,j_1\in[1,n_i]\right\}\,\middle|\,i\in[1,m]\right\}+$$

$$+func_1\left\{\,func_1\left\{\gamma_{14,00}^{i,p}\,\middle|\,p\in[1,2\cdot n_i]\right\}\,\middle|\,i\in[1,m]\right\}+\sum_{p=6}^{7}func_2\left\{\,func_2\left\{\gamma_{p,00}^{i,j_1}\,\middle|\,j_1\in[1,n_i]\right\}\,\middle|\,i\in[1,m]\right\}+$$

$$+func_2\left\{\,func_2\left\{\gamma_{8,00}^{i,j_1}\,\middle|\,j_1\in[1,n_i-1]\right\}\,\middle|\,i\in[1,m]\right\}, \qquad (29)$$

$$\sum_{i=1}^{m}\gamma_{17,40}^{i}=\sum_{i=1}^{m}\gamma_{17,40}^{i}\Big|_{G_1^i}+\sum_{i=1}^{m}\gamma_{17,40}^{i}\Big|_{G_2^i}. \qquad (30)$$

Using expressions (28) – (30) we can calculate attributes values for the entire electric power station. Calculation results are shown in Table 2.

Table 2

Attributes of generators $g16^i – g18^i$

№	Attr. val.	$\gamma_{16,70}$	$\gamma_{17,40}$	$\gamma_{18,40}$	$\gamma_{16,71}$	$\gamma_{17,41}$	$\gamma_{18,41}$
1	Min	0	216	216	0	189	189
	Avg	10.19		226.19	8.89		197.89
	Max	288		504	506		695
2	Min	0	128	128	0	112	112
	Avg	7.59		135.59	6.78		118.78
	Max	224		352	446		558
3	Min	0	128	128	0	112	112
	Avg	5.01		133.01	4.39		116.39
	Max	144		272	139		251
Total	Min	0	472	472	0	413	413
	Avg	22.79		494.79	20.06		433.06
	Max	556		1028	768		1181

Then, according to expressions

$$L_{\min(\max,\,avg)}=\gamma_{18,40}^{\min(\max,\,avg)}+\gamma_{18,41}^{\min(\max,\,avg)},$$

and

$$t_{ск\ \min(\max,avg)}=\frac{L_{\min(\max,avg)}\cdot(8+n_{ad})}{\vartheta},$$

where ϑ – data rate (bit/s); n_{ad} – the number of service bits attributed to the bytes of data, and taking into account the fact that data exchange with automation tools occurs at a rate of 9600 bits/s and the package size is configured to no parity and one stop bit, the minimum queue length and the query processing time

$$L_{\min} = \gamma_{18,40}^{\min} + \gamma_{18,41}^{\min} = 472 + 413 = 885 \text{ (bytes)},$$

$$t_{ск\ \min} = \frac{L_{\min} \cdot (8 + n_{ad})}{\vartheta} = \frac{885 \cdot 10}{9600} \approx 0.92 \text{ (s)},$$

average queue length and query processing time:

$$L_{avg} = \gamma_{18,40}^{avg} + \gamma_{18,41}^{avg} = 494.79 + 433.06 \approx 927 \text{ (bytes)},$$

$$t_{ск\ avg} = \frac{L_{avg} \cdot (8 + n_{ad})}{\vartheta} = \frac{927.85 \cdot 10}{9600} \approx 0.97 \text{ (s)},$$

maximum queue length and query processing time:

$$L_{\max} = \gamma_{18,40}^{\max} + \gamma_{18,41}^{\max} = 1028 + 1181 = 2209 \text{ (bytes)},$$

$$t_{ск\ \max} = \frac{L_{\max} \cdot (8 + n_{ad})}{\vartheta} = \frac{2209 \cdot 10}{9600} \approx 2.30 \text{ (s)},$$

Coefficient of communication channel utilization:

$$k_{load} = \frac{t_{ск\ avg}}{t_{ск\ ф}} \cdot 100\% = \frac{0.97}{5} \cdot 100\% = 19.4\%$$

The obtained response time values of the system (average – 0.97 sec., maximum – 2.30 sec.) let draw a conclusion about the possibility to transfer diesel generator protection functions to a program level and to assess time delays resulting from the effects of environment on the system.

4. An experimental method for analysis of data transmission time delays in the automated control systems

Assigned task was solved in few stages.

1. There were made trial tests for the purpose of determination of minimum sample size, which was used for evaluation of the average time delays with prescribed accuracy. The essence of a test includes the following. From one computer sends request to another computer. Special program "ping" allows us to determine the time delay, which was measured in milliseconds.

2. The results of the tests in the form of 50 values are in Table 3.

3. There was made a test with minimum sample size, which was determined in item 1.

Table 3

The results of time delays' measuring

№	τ	№	τ	№	τ	№	τ	№	τ
1	23.349	11	23.262	21	23.081	31	27.323	41	23.156
2	23.143	12	23.293	22	23.413	32	23.92	42	23.334
3	23.333	13	23.645	23	23.442	33	22.684	43	23.205
4	23.325	14	23.338	24	25.072	34	23.439	44	23.654
5	24.312	15	25.436	25	23.28	35	23.303	45	23.368
6	23.571	16	23.951	26	23.365	36	23.59	46	23.72
7	23.17	17	22.451	27	23.397	37	23.514	47	23.242
8	22.31	18	23.776	28	22.82	38	23.403	48	23.537
9	23.572	19	24.104	29	23.041	39	22.409	49	27.452
10	25.575	20	23.869	30	23.411	40	27.942	50	23.234

4. There was made a statistical analysis of information packets transmission delays, presented in the form of variational series and identified the main characteristics of these series and a histogram of the relative frequencies.

5. In consideration of the form of histogram and by using least-squares method, there was selected the theoretical dependence, which defines probability density of time delay.

6. Theoretical determination of the time delays was performed by using a Monte Carlo. For evaluation of the delay's average value there was made a construction of confidence interval according to the experimental results. Theoretical value of average delay was obtained with a certain confidence interval.

For determination of minimum sample size there were made trial tests (5 series, 50 tests in each series). Testing accuracy δ is 0.1 ms. Confidence level $\gamma = 0{,}95$. Calculation of minimum sample size is made by using this expression:

$$n_{\min} = \frac{t_\gamma^2 S^2}{\delta^2},$$

where t_γ – reference parameter[17], t_γ (γ=0.95, n=50) = 2.006, S^2 – sample variance. As a result n_{min}=500.

There were made 6 series with size 500 samples in each. These tests are generalized in the form of average variation series.

Table 4

Results of the tests in the form of average variation series

i	$\tau_i - \tau_{i+1}$	n_i	$\frac{n_i}{n \cdot h}$
1	21 ÷ 23	264	0.264
2	23 ÷ 25	185	0.185
3	25 ÷ 27	25	0.025
4	27 ÷ 29	11	0.011
5	29 ÷ 31	4	0.004
6	31 ÷ 33	3	0.003

In Table 6 there are used next conventional signs: n_i – sampling frequency, n – sample size, h – the interval.

There were evaluated the main numerical characteristics: mode M_0=22; median M=27; average $\bar{\tau} = 27$; variance S^2=16.824; statistical deviation S=4.102; variation coefficient V=62.3%.

By results of the experiment there was constructed the histogram of relative frequencies (Fig. 2), on which a polyline is empirical probability density.

[17] Гмурман В.Е. Теория вероятностей и математическая статистика. Москва: Юрайт, 2016. 479 с.

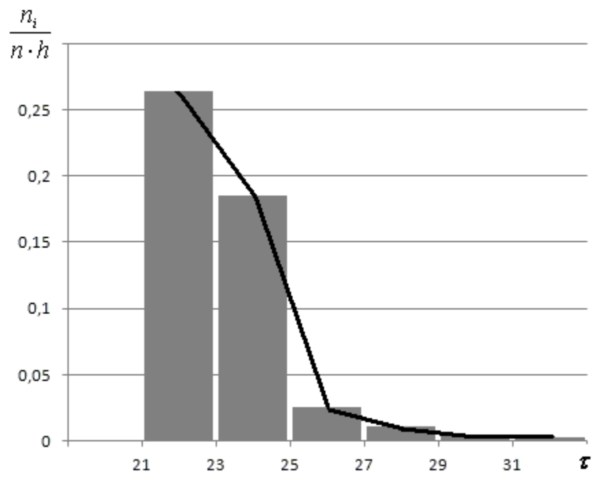

Fig. 2. Histogram of relative frequencies

By basing on the shape of observed distribution curve (Fig. 2), can be evaluated theoretical probability density by using this expression:

$$f(\tau) = ae^{b\tau}. \tag{31}$$

Coefficients *a* and *b* in the expression (31) can be evaluated with a help of least-squares method. Meanwhile must be found the logarithm of the expression (31). As a result it comes out a system of linear algebraic equations:

$$\begin{cases} nA + B\sum_{i=1}^{n} \tau_i = \sum_{i=1}^{n} \lg f(\tau_i) \\ A\sum_{i=1}^{n} \tau_i + B\sum_{i=1}^{n} \tau_i^{\ 2} = \sum_{i=1}^{n} \tau_i \lg f(\tau_i) \end{cases}, \tag{32}$$

where

$$A = lg\,a, \quad B = b\,lg\,e.$$

The system of equations takes the following form after substitution of numerical value:

$$\begin{cases} 6A + 162B = -9.793 \\ 162A + 4444B = -279.488 \end{cases} \tag{33}$$

The solutions of the system of equations (33) is: A=4.183, B=-0.215. Then $a=10^{4.183}=15240$, b=-0.495. Thereby the required probability density of a delay can be written as:

$$f(\tau)=15240\cdot e^{-0.495\tau}. \tag{34}$$

Delays, which were obtained by using the expression (34) changing the variable τ_i by 22 to 32 step 2, have next values: 0.284; 0.106; 0.039; 0.015; 0.005; 0.002. Comparing them with the experimental delays, we can note that they coincide. Theoretical determination of delays is done by using the Monte Carlo method[18]. Possible values of continuous random quantity are determined after solution the following equation by using the Monte Carlo method:

$$\int_k^{\tau_i} f(\tau)d\tau = r_i, \tag{35}$$

where k – the least of the recorded delays, r_i – random numbers.

Based on the dependence (31) and after its integration, the expression (35) is rearranged in the form:

$$\tau_i=\frac{1}{b}\ln\left(\frac{b}{a}r_i+e^{bk}\right). \tag{36}$$

Given a=15240, b=-0.495, k=21, expression (36) takes following the form:

$$\tau_i=-2.02\ln(-3.25\cdot 10^{-5}r_i+e^{-10.395}). \tag{37}$$

1. According to the direct experiment (5 series, 500 tests in each series) there was calculated the average delay in each series and the average delay of all 5 series. Group average delays are in Table 7.

Table 7

Average delay in the each test series

№	1	2	3	4	5
$\bar{\tau}$	23.845	24.332	23.63	23.666	23.99

[18] Гмурман В. Е. Руководство к решению задач по теории вероятностей и математической статистике. Москва: Издательство Юрайт, 2016. 404 с.

The results are following: average delay $\bar{\tau}_B = 23.89$, variance S^2=16.824, statistical deviation S_B=0.29.

2. There was constructed confidence interval (99%) for evaluation of the average delay.

3. There were calculated the theoretical delays in 5 series, 5 meanings in each series by using the expression (37). Results of the calculation are in Table 8.

Table 8

Theoretical meanings of delays

№	1		2		3		4		5	
	r_i	τ_i	r_i	τ_i	r_i	τ_i	r_i	τ_i	r_i	τ_i
1	0.1	21.22	0.34	21.91	0.61	23.11	0.85	25.71	0.26	21.65
2	0.09	21.20	0.07	21.16	0.19	21.46	0.15	21.35	0.89	26.87
3	0.73	24.01	0.27	21.68	0.69	23.67	0.74	24.11	0.8	24.83
4	0.25	21.62	0.68	23.59	0.04	21.09	0.79	24.69	0.93	29.87
5	0.33	21.87	0.5	22.53	0.46	22.35	0.54	22.72	0.54	22.72
Avg.		22.57		22.74		22.83		24.16		23.77
Var.		2.43		0.93		1.35		2.82		8.02
Stat. dev.		1.56		0.97		1.16		1.68		2.83

4. There were calculated group average delays and average delays among groups: $\bar{\tau}_{theor} = 23.216$.

Theoretically found the average delay $\bar{\tau}_{theor}$ was compared with a confidence interval of the experimental average delay.

Confidence interval for average delay's estimation is following[19]:

$$\bar{\tau}_B - \frac{t_\gamma \bar{S}_B}{\sqrt{n}} < \bar{\tau}_\Gamma < \bar{\tau}_B + \frac{t_\gamma \bar{S}_B}{\sqrt{n}},$$

where

$$\bar{S}_B = \frac{n}{n-1} S_B$$, γ=0.99, n=5, t_γ=4.6

Thereby, confidence interval is determined by the following expression:

$$23.149 < \bar{\tau}_{con} < 24.631$$

A very important characteristics of the network is that it can transmit a set of data at the same time. Theoretical received average value is not

[19] Moore D.S., Notz W.I, Flinger M.A. The basic practice of statistics. New York: W.H. Freeman and Co., 2013. 745 p.

outside of the confidence interval. It is indicated that the resulting scheme of delay's theoretical definition is consistent with experimental data. In order to compensate for the network transmission delay, a network delay compensator in the channel from the controller to the actuator shall be used.

CONCLUSIONS

Application of function-oriented approach in the design of microprocessor-based automation tools spatially distributed control system can cause hardware and software redundancy. One way to analyze obtained after the primary structural design schemes systems is their representation in the form of control automata described using the language of logic algorithms. Introduction to multi-operator functional logic algorithms (algorithmic and related to the implementation of structural algorithm) blocks allows to formalize the process of analysis and structural optimization of algorithmic systems. The application of the above method to the analysis of microprocessor automation SEPP revealed the presence of hardware redundancy and ways to resolve: the association of monitoring devices network settings, monitoring and protection of the basic parameters of the generator controller automation; association of devices for monitoring parameters of synchronization with the network protection, control diesel generator with parallel operation of the network in the system synchronization and load distribution.

SUMMARY

The algorithms of the microprocessor systems, such as electrical parameters monitoring systems, synchronizers and load sharers, protection devices etc., which are used in the control systems of the ship power plant with DGU, are discussed. The algorithms are described by means of the logic schemes algorithms language. Structural redundancy of the systems and the way to overcome it became possible by analyzing the content of the received sets: the association of systems for monitoring network parameters, for monitoring of the basic parameters and for protection of the generator in the automation controller; the association of devices for monitoring parameters and for protection of the generator, synchronizers and load sharers in the synchronization and load sharing system. Using the theory of discrete pattern networks to describe the interaction of software objects allows through the introduction of communication relationships to allocate inter-object communications involved in the formation of queuing system input flow, and further for objects, integrated by dedicated communications, introduces attributes as the lengths of network data packages. Identification of interface indivisible mnemonic scheme blocks and their description in the form of corresponding generators sets, make it possible with the help of these generators' attributes to determine the value

of time delay for each of the queuing system potential channels, which are the basis for the subsequent calculation of timing characteristics for the projected control system. In identifying the duration of time delays that fail to meet the regulatory requirements, the optimal number of channels and the composition of components-sources queries of the queuing systems determined based on the information from the previous stage characteristics constituting the queuing system.

REFERENCES

1. Zhang Erhu, Wang Kelu, Guangfeng Lin. Classification of Marine Vessels with Multi-Feature Structure Fusion. *Applied Sciences*. 2019. № 9. P. 2153. DOI:10.3390/app9102153

2. Sylwester Filipiak, Andrzej Stobiecki, Franciszek Strzelczyk. Application of evolutionary programming to optimization of reliability power distribution grids. *Przegląd Elektrotechniczny*. 2017. № 2. P. 273. DOI:10.15199/48.2017.02.60

3. Gardner C., Johnson D., Provine J. Networked Intelligent Instrumentation & Control for Switchboards. *The IEEE Electric Ship Technologies Symposium* ESTS '07 (Arlington, May 21-23, 2007). Arlington, 2007. P. 510–518. DOI:10.1109/ESTS.2007.372134

4. Juncao Li, Fei Xie, Levin V. Formalizing hardware/software interface specifications. *26th IEEE Int. Conf. Automated Software Engineering* (Washington, November 6-10, 2011). Washington, 2011. P. 235–252. DOI:10.1109/ASE.2011.6100048

5. Рябенький В.М., Ушкаренко А.О. Управление распределенной моделью автономной электростанции. *Техническая электродинамика*: тем. выпуск. 2008. № 6. С. 45–48.

6. Dorf R., Bishop R. Modern control systems. Moscow: Laboratory of Basic Knowledge, 2002. 832 p. DOI:10.1.1.824.657

7. Babakov R.M. Barkalov A.A. Structural representation of synthesis methods of finite state machine with datapath of transition. *IEEE 9th International Conference on Dependable Systems, Services and Technologies* (Kyiv, May 24-27, 2018). Kyiv, 2018. P. 229–233. DOI:10.1109/DESSERT.2018.8409134

8. Zbigniew Huzar, Anita Walkowia. Specification of real-time systems using UML sequence diagrams. *Przegląd Elektrotechniczny*. 2010. № 9. P. 226. DOI: 10.5772/38015

9. Bakari H.R., Chamalwa H.A., Baba A.M. Queuing Process and Its Application to Customer Service Delivery. *International Journal of Mathematics and Statistics Invention*. 2014. №. 1. P. 14–21. DOI:D021014021

10. Peter Hanuliak. Analytical Method of Performance Prediction in Parallel Algorithms. *The Open Cybernetics & Systemics Journal*. 2012. № 6. P. 38–47. DOI: 10.2174/1874110X01206010038

11. Grzyb S., Orłowski P. Congestion feedback control for computer networks with bandwith estimation. *20th International Conference on Methods and Models in Automation and Robotics* (Miedzyzdroje, August 24-27, 2015). Miedzyzdroje, 2015. P. 1151–1156. DOI: 10.1109/MMAR.2015.7284041

12. Lacroix Y., Malbranque J.-F. A Unified Approach for Naval Telecommunication Architectures. *World Academy of Science Engineering and Technology International Journal of Electronics and Communication Engineering*. 2017. №. 9. P. 1–7. DOI:10.5281/zenodo.1132202

13. Guillermo A Francia III, Nourredine Beckhouche, Terry Marbut. Curtis Neuman, Portable SCADA Security Toolkits. *International Journal of Information & Network Security*. 2014. №. 4. P. 265–274. DOI:10.11591/ijins.v1i4.819

14. Sasa Klampfer, Joze Mohorko, Zarko Cucej, Amor Chowdhury. Wykorzystanie teorii grafów do poszukiwania najkrótszej ścieżki routingu w protokole RIP. *Przegląd Elektrotechniczny*. 2012. № 8. P. 224.

15. Tsekouras G.J., Hatzilau I.K., Prousalidis J.M. A new pattern recognition methodology for classification of load profiles for ships electric consumers. *Journal of Marine Engineering and Technology*. 2009. № 14. P. 45–58. DOI:10.1080/20464177.2009.11020222

16. Banks S.P. Pattern Theory: from Recognition to Inference by Ulf Grenander and Michael Miller. *IMA Journal of Mathematical Control and Information*. 2009. № 1. P. 129–130. DOI:10.1093/imamci/dnm025

17. Гмурман В.Е. Теория вероятностей и математическая статистика. Москва: Юрайт, 2016. 479 с. ISBN 978-5-9916-6484-4.

18. Гмурман В. Е. Руководство к решению задач по теории вероятностей и математической статистике. Москва: Издательство Юрайт, 2016. 404 с. ISBN 978-5-9916-6109-6.

19. Moore D.S., Notz W.I, Flinger M.A. The basic practice of statistics. New York: W.H. Freeman and Co., 2013. 745 p.

Information about the author:
Ushkarenko Oleksandr Olehovych,
Doctor of Engineering Sciences,
Associate Professor at the Department of Programmable Electronics,
Electrotechnics and Telecommunications
Admiral Makarov National University of Shipbuilding
9, Heroiv Ukrainy avenue, Mykolaiv, 54000, Ukraine