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Research on information channel characteristics of a ship electric power system

***Abstract**. This article deals with the developed methodology of research information flows in the distributed control system network of a ship electric power system, based on the notion of software structure in the form of pattern network, in which each generator is assigned to a particular software object, and communication relations represent different types of information interactions between objects. Using the queuing and pattern theories gave the opportunity to develop the algorithm of software formal reorganization in the context of reduction system's response time.*

Streszczenie.** Badano przepływ informacji w systemie zasilania okrętu w którym w sieci wykprzystano oprogramowanie sterujące. W algorytmie sterowania każdy generator jest przypisany do odpowiedniej partii oprogramowania. Opracowany algorytm komunikacji odpowiedniego przewidywania kolejkowania i redukcji czasu odpowiedziu. **Badania kanału informacji w systemie zasilania okrętu

Keywords: Power plant, Information flows, Pattern network, Request queue.
Słowa kluczowe: przesyłania informacji, sieć okrętowa, sieć zasilająca .

Introduction

Modern automation systems are spatially distributed systems. They are created with the use of multi-task controllers and have network organization [1, 2]. Different parts of the system have different physical nature (continuous object and discrete control part), while the whole system can be described by a complex combination of differential equations, algebraic equations, inequalities, and logical conditions. The tasks in a microcontroller are overlapped and blocked out while waiting for shared resources. The time of tasks execution may vary. Network transmission takes place with delays, magnitude and stability of which depends both on the communication protocol and on channels utilization. To avoid the negative impact of such delay and make the best use of computing resources, which are available for control system, design engineering of control algorithms and software should be conducted with the consideration of these factors. Non-optimal management of information flows without taking into account the inertia of facilities management and delays in time that occur when sending commands over the network will lead to degradation of quality control. 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 [3–5]. 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 [6]. At the same time, as noted in article [7], 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 subsystems, data processing by means of middle level, and subsequent exchange of information with a computerized control system (CCS). According to the principles of hierarchical control systems, the higher level of hierarchy increases the degree of information uncertainty about the state of the system and, consequently, increases the period of control actions formation [8, 9]. 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. Articles [10, 11] stated that the most significant delays (enormously higher than others) with the topology of "common bus" with master device, caused by congestion of the communication channel, but there were not considered the features of calculating characteristics of information flow in relation to autonomous electric power facilities.

Autonomous electric power system pertains to real-time control systems [1], 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, as shown in articles [12–15]. 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 [16]. 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.

Optimal allocation of buffers in network nodes, adaptive message flows routing [17–19] allow to reduce load on the network and keep its parameters unchanged under load fluctuations. 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. In this paper [20], principles of network load regulation and setting of thresholds – limit values of the number of messages in the whole network – are considered. 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.

All modern vessels are equipped with technical facilities automation systems. The general trend for ships automation based on the microprocessor computing facilities has been determined. Ship electric power systems (SEPS) have hierarchical structures [21–23]. Therefore, the ship's power station control system can be considered as hierarchical computing system. In the event of upper-level elements failure, SEPS operation is ensured by means of the lower levels elements of the system [24]. Controllable SEPS elements with sensors and actuators are at the lower (zero) level of hierarchy. This level is intended for controlling SEPS 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 SEPS 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 drive motors of generators by a signal from an automatic device or operator, monitoring and protection of generators, synchronization with subsequent load distribution, frequency control. Also, there are generator sets local control devices at this level.

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 SEPS technical condition, protection against short-circuit currents.

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, SEPS utilization modes are set depending on the mode of vessel operation on which composition of SEPS 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 [25, 30]. In this case, one of industrial protocols is used such as Modbus RTU [26, 27], Profibus [28], DeviceNet, CANopen [29], and many others. This protocols are widely used in power systems [31]. 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.

Objectives of this article is to study information channel timing characteristics of a ship electric power system 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. Calculating of queuing systems performances for distributed control system of ship electric power system has its own specificity, which is considered in this article.

Research method

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 Figure 1. The software to control of ship power system was developed by the authors by means of Visual Studio and MFC Library.

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 size of network is determined by the number of network nodes and depends on the level of power system automation. Network diameter – a 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 [31]. At the lower levels of hierarchy, RS485, CAN interfaces are used for communication between network nodes.

The research of information channel characteristics performed on a ship power plant physical model, consisting of 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 operation mode of the power plant, sections are autonomous (K19 – K22 circuit breakers are open), but in case of emergency (failure of one of the generating units) it is possible to include generator sets of different sections to total loading 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.

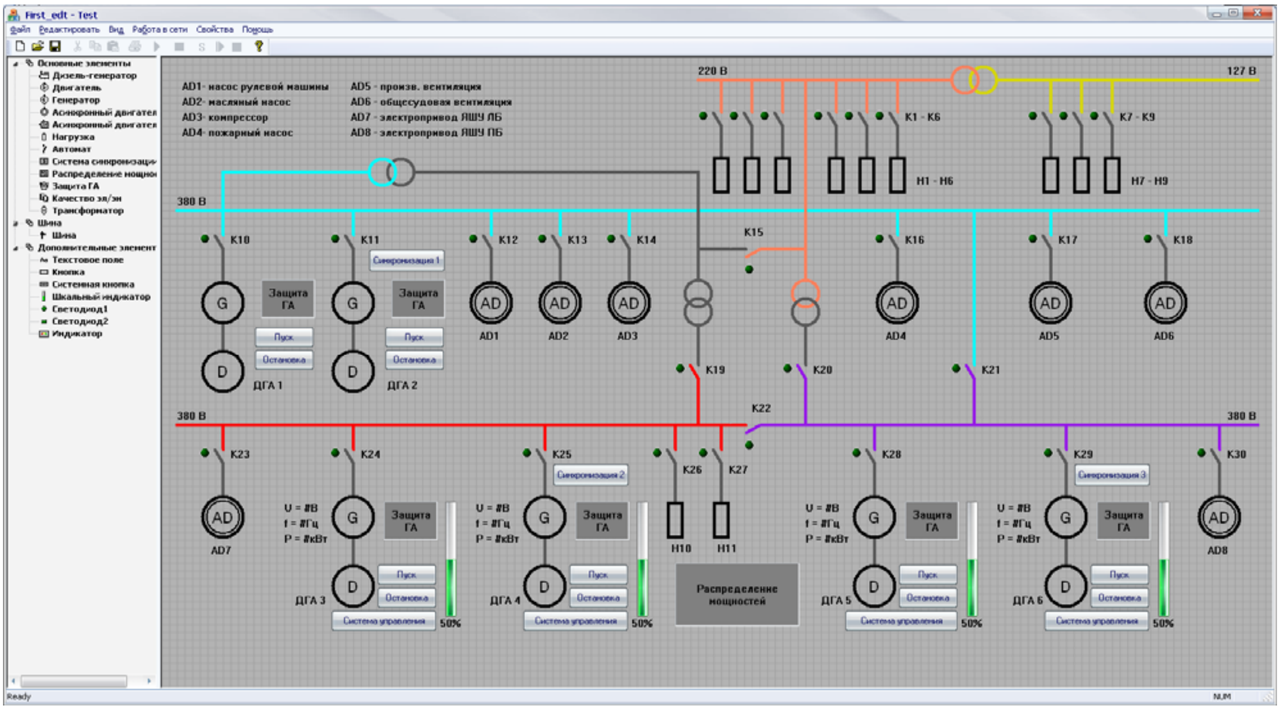

Fig. 1. Software for managing of a ship electric power station

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 (RS485, 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 $(\vec{G} \cup \vec{D} | \vec{D} | 1)$.

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 [32, 33]. Each electric power station component corresponds to a particular software object, which implementation encapsulates the generatrixes as shown in Figure 2: $g1$ – Text field for displaying electrical parameters; $g2$ – Bar-graph indicator; $g3$ – Pointer indicator; $g4$ – Generator; $g5$ – Diesel (with generator unit forming the DGS set); $g6$ – Dialog box "Diesel parameters"; $g7$ – Dialog box "Oscillograms"; $g8$ – Synchronization system; $g9$ – GS protection; $g10$ – Automatic circuit breaker; $g11$ – LED; $g12$ – Loading; $g13$ – Induction motor; $g14$ – Control button; $g15$ – Load distribution system.

Generators $g1$ – $g3$ 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: $g16$ – variable length queue shaper; $g17$ – constant length queue shaper; $g18$ – 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 ($g20$ 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 $g16^{i}$– $g18^{i}$;

– 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.

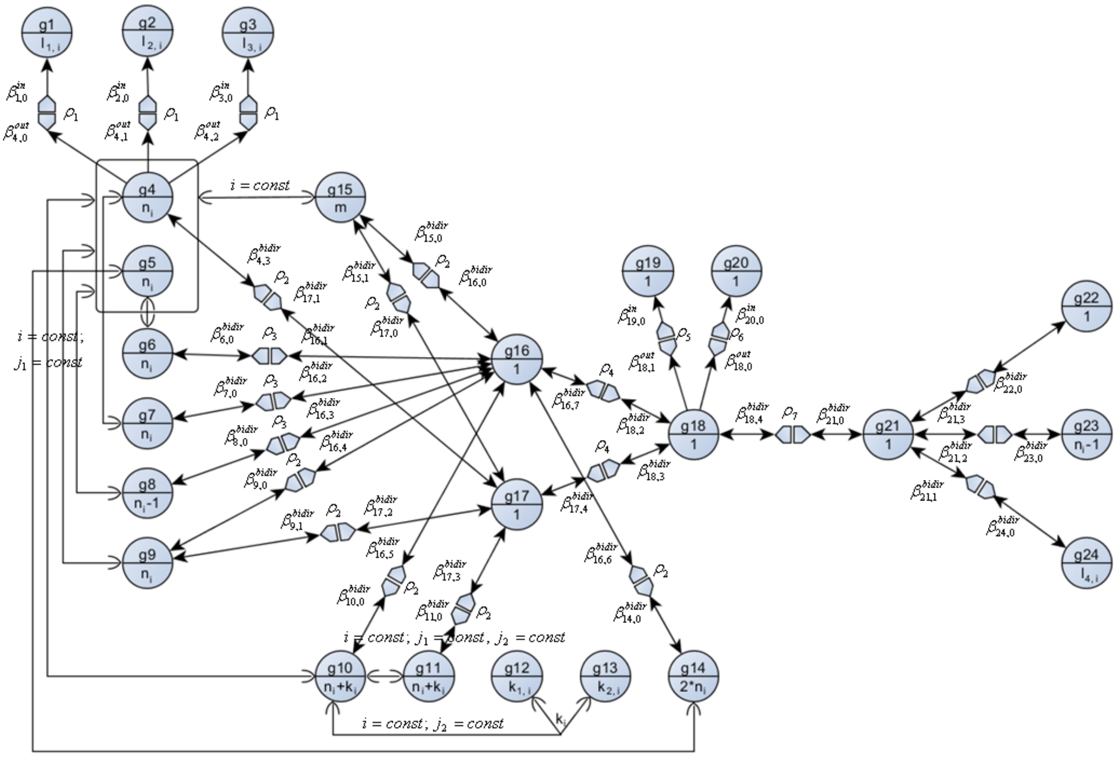

Fig. 2. Representing of the software structure as a pattern network

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 *g*4 – *g*18:

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

$$a\left(gp^{i,j_1}\right)=\left(p,\gamma^{i,j_1}_{p,00},\gamma^{i,j_1}_{p,01},\beta^{i,j_1}_{p,0}\right)$$

for $p=\{6,7,8,10,11,14\}$,

$$a\left(gp^{i,j_1}\right)=\left(p,\gamma^{i,j_1}_{p,00},\gamma^{i,j_1}_{p,01},\gamma^{i,j_1}_{p,10},\gamma^{i,j_1}_{p,11},\beta^{i,j_1}_{p,0},\beta^{i,j_1}_{p,1}\right)$$

for $p=\{9,15\}$,

$$a\left(gp^{i,j_1}\right)=\left(p,\gamma^{i,j_1}_{p,00},\gamma^{i,j_1}_{p,01},\gamma^{i,j_1}_{p,10},\gamma^{i,j_1}_{p,11},\beta^{i,j_1}_{p,0},\beta^{i,j_1}_{p,1}\right)$$

for $p=\{9,15\}$,

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

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

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

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

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

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

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 $\left[\beta^{i,j_1}_{4,0}\right]^{l_1}$ is an abbreviated notation for the number of instances of communication indicators in vector. In this case, attributes corresponding to relationships connected via ρ_2 – ρ_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 *g*16 *g*18 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 *g*16 performs functions of formation of a queue with variable length, *g*17 function of generation of a queue of conditionally constant length, *g*18 function of formation of a final queue; ρ2 many-to-one communication relation, ρ3 one-among-many communication relation, ρ4 "inclusion" communication relation and equality of attributes connected by ρ2 – ρ4 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.

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

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

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

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

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

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 *j*1-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 *g*1 is "one-to-many", i.e. generator *g*4 can be connected with arbitrary but finite number of generators *g*1 – *g*3, and generators *g*1 – *g*3 with only one *g*4. Hence, arities *g*1 – *g*3 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 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 *g*4 and *g*17: for each *j*1-th DGS in the *i*-th section, values of electrical parameters of generator are interrogated. This implies arity *g*4:

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

Similarly to arity of generators *g*9 – *g*11, *g*14 – *g*15:

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

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

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.

Generator *g*18 is unifying with respect to generators which reflect the formation of queues of constant and variable lengths (*g*16 and *g*17), 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 *g*18 generator include transmission of statistical data on information flows and electrical power parameters to the database to corresponding blocks (represented by *g*19 and *g*20 generators).

Therefore, communication relationships between $\rho 5$ and $\rho 6$ are "purely" informational "one-to-one" relations without direct exchange of data with automation facilities, while relationship $\rho 4$, inclusion relationship (also "one-to-one") means full inclusion of data obtained from generators into other.

According to patterns theory [33], software objects for each section can be expressed in the form of the following subsets:

– for the first section:

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

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

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

–for the second section:

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

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

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

– for the third section:

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

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

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

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

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

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

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.

(1) $$\gamma^i_{16,70}\Big|_{G^i_1} = func_1\left\{\gamma^i_{15,00}\right\} + \sum_{p=6}^{7} func_2\left\{\gamma^{i,j_1}_{p,00}\,\Big|\, j_1 \in [1, n_i]\right\} + func_2\left\{\gamma^{i,j_1}_{8,00}\,\Big|\, j_1 \in [1, n_i - 1]\right\} + \sum_{p=9}^{10} func_1\left\{\gamma^{i,j_1}_{p,00}\,\Big|\, j_1 \in [1, n_i]\right\} + func_1\left\{\gamma^{i,j_1}_{14,00}\,\Big|\, j_1 \in [1, 2 \cdot n_i]\right\}$$

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

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

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

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

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

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

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

(5) $$func_1\left\{\gamma_i \,|\, i \in [1, n_{\max}]\right\} = func_2\left\{\gamma_i \,|\, i \in [1, n_{\max}]\right\} = \sum_{i=1}^{n_{\max}}\left(\gamma_i \cdot \lambda_i \cdot t_{ск\,ф}\right)$$

To calculate the attributes of generators $g16^1$ и $g17^1$, expressions (1) – (5) take the form:

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

$$\gamma^1_{16,70} = \gamma^1_{16,70}\Big|_{G^1_1} + \gamma^1_{16,70}\Big|_{G^1_2} = func_1\left\{\gamma^1_{15,00}\right\} + \sum_{p=6}^{7} func_2\left\{\gamma^{1,j_1}_{p,00}\,\Big|\, j_1 \in [1, 2]\right\} + func_2\left\{\gamma^{1,1}_{8,00}\right\} + \sum_{p=9}^{10} func_1\left\{\gamma^{1,j_1}_{p,00}\,\Big|\, j_1 \in [1, 2]\right\} + func_1\left\{\gamma^{1,j_1}_{14,00}\,\Big|\, j_1 \in [1, 4]\right\} + func_1\left\{\gamma^{1,2+j_2}_{10,00}\,\Big|\, j_2 \in [1, 16]\right\}$$

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

(6) $$\gamma^{1,\min}_{16,70} = 0$$

(7) $$\gamma^{1,avg}_{16,70} = \left(\gamma^1_{15,00} \cdot \lambda^1_{15,0} + \sum_{p=6,7}\sum_{j=1,2}\left(\gamma^{1,j}_{p,00} \cdot \lambda^{1,j}_{p,0}\right) + \gamma^{1,1}_{8,00} \cdot \lambda^{1,1}_{8,00} + \sum_{p=9,10}\sum_{j=1,2}\left(\gamma^{1,j}_{p,00} \cdot \lambda^{1,j}_{p,0}\right) + \sum_{j=1}^{4}\left(\gamma^{1,j}_{14,00} \cdot \lambda^{1,j}_{14,0}\right) + \sum_{j=1}^{16}\left(\gamma^{1,2+j}_{10,00} \cdot \lambda^{1,2+j}_{10,0}\right)\right) \cdot t_{ск\,ф}$$

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

(9) $$\gamma^{1,\min}_{17,40} = \gamma^{1,avg}_{17,40} = \gamma^{1,\max}_{17,40} = \gamma^1_{17,40}\Big|_{G^1_1} + \gamma^1_{17,40}\Big|_{G^1_2} = \gamma^1_{15,10} + \sum_{j=1}^{2}\left(\gamma^{1,j}_{4,30} + \gamma^{1,j}_{9,10} + \gamma^{1,j}_{11,00}\right) + \sum_{j=1}^{16}\gamma^{1,2+j}_{11,00}$$

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 (RS485, Modbus RTU) strictly regulated, and the information transfer rate is the same for all devices, 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 (Figure 2) 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 *g*91,1, 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 (6) – (9) 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:

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

where

(11) $$\sum_{i=1}^{m} \gamma_{16,70}^{i} = \sum_{i=1}^{m} \gamma_{16,70}^{i} \Big|_{G_2^i} + func_1 \left\{ \gamma_{15,00}^{i} \,\middle|\, i \in [1,m] \right\} +$$
$$+ \sum_{p=9}^{10} func_1 \left\{ func_1 \left\{ \gamma_{p,00}^{i,j_1} \,\middle|\, j_1 \in [1,n_i] \right\} \,\middle|\, i \in [1,m] \right\} +$$
$$+ func_1 \left\{ func_1 \left\{ \gamma_{14,00}^{i,p} \,\middle|\, p \in [1, 2 \cdot n_i] \right\} \,\middle|\, i \in [1,m] \right\} +$$
$$+ \sum_{p=6}^{7} func_2 \left\{ func_2 \left\{ \gamma_{p,00}^{i,j_1} \,\middle|\, j_1 \in [1,n_i] \right\} \,\middle|\, i \in [1,m] \right\} +$$
$$+ func_2 \left\{ func_2 \left\{ \gamma_{8,00}^{i,j_1} \,\middle|\, j_1 \in [1,n_i - 1] \right\} \,\middle|\, i \in [1,m] \right\}$$

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

Using expressions (10) – (12) we can calculate attributes values for the entire electric power station. Calculation results are shown in Table 1.

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

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

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

Table 1. 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

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:

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

Results and analysis

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.

Conclusion

Application the theory of discrete pattern networks to describe the interaction of special 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 length 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 known from the previous stage characteristics constituting the queuing system.

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