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ORGANIZING THE AUTOMATED SYSTEM OF DISPATCH CONTROL OVER PUMP UNITS AT WATER PUMPING STATIONS

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The design and operation of modern dispatch control systems for pumping units involves comprehensive solution to separate engineering, technical, and scientific problems.

The object of research is information processes enabling the operational modes of electrically driven pumping units at water pumping stations.

This paper solves the scientific and technical task related to developing topology, hardware, and software tools, control algorithms, dispatch interface, and researching the modes of operation of pumping units in dispatch control systems at water pumping stations.

Algorithms for controlling pumping units have been implemented, the advantage of which is the possibility of automated calculation of parameters for technological PID-controllers, taking into account the current electrical parameters of the frequency-controlled electric drive of pumping units and operating conditions.

The WEB-oriented dispatch interface of the SCADA-based pumping unit control system was designed and tested, which enables control process in real time.

Features of the developed dispatch control system are improved topology, expanded functionality, energy-saving control modes, and the possibility of further modernization based on the principles of standardization and unification of hardware and software tools and design procedures.

The developed dispatch control system for pumping units at water pumping stations has been implemented and is successfully operated at an industrial water supply enterprise.

The results provided for an increase in technical and economic indicators during the operation of technological equipment due to the efficiency of control and management procedures, energy-saving operational modes of the frequency-controlled electric drive of pumping units

Keywords: water supply, topology, pump unit, PLC, SCADA, TIA Portal, Sinamics, PID

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1. Introduction

The tasks of organization, design, implementation, and operation of systems for dispatching control over pumping units at water pumping stations under modern conditions are connected with solutions to relevant scientific and technical problems. Priority among them is the construction of WEB-oriented topologies of automated control systems for technological objects (TO ACS), the unification of hardware and software based on Programmable Logic Controller (PLC), Frequency Converter (FC), and SCADA (Dispatch Control And Data Acquisition – dispatching management and data collection). Next, it is necessary to solve the tasks of developing effective algorithms and application software for frequency control over the electric drive of pumping units, researching operating modes and information processes during the operation of technological equipment. In addition, the use of modern complex automated design systems significantly accelerates and eliminates errors through the methods and procedures of simulation modeling and testing of TO ACS components at the design stages.

As a result, this will make it possible to build TO ACS with extended functionality, will increase the efficiency of processes of control and management of technological objects, as well as energy efficiency and technical and economic indicators of dispatch control systems as a whole.

Given the above, the identified scientific and technical tasks in the construction of dispatch control systems for pumping units at water pumping stations are relevant, especially under the harsh conditions of energy supply and operation of critical infrastructure enterprises.

2. Literature review and problem statement

Analysis of the current state, methods, means, and experience in construction and operation of systems for dispatching control in pumping units at water pumping stations, first of all, reveals the complexity of scientific and technical tasks for the organization of such systems. Such tasks include the development of WEB-oriented topologies, standardized and unified hardware and software tools based on PLC, FC, and SCADA, effective algorithms and application software based on the state-of-the-art information technologies.

In addition, the indicated problems are widely reported both in the scientific literature and electronic publications and in the technical documentation by manufacturers of hardware and software for control systems, which complement and expand each other.

Directions for solving tasks related to the organization of TO ACS topologies of water supply are shown in [1, 2] and are based on modern hardware and software tools PLC S7-1200 and TIA Portal by "Siemens" and "Allen-Bradly". FC "LG" is used in [1], which does not provide for its full integration into the project, and accordingly limits the functionality. In [2], the original topology and analytical calculations of the parameters of the control system are presented. In [1, 2], the problems of cascade control over several pump units and automatic calculation of PID controller parameters are not solved, which requires the development of algorithms for cascade control of pump units with one FC with an adaptive PID controller.

In works [3, 4], a comprehensive assessment of the performance of industrial PROFIBUS and PROFINET networks in control systems based on PLCs PLC S7-300, PLC S7-1200, and FC Sinamics G120 by Siemens was performed. The advantages [3, 4] are the use of unified hardware and software from one manufacturer, the use of I-Devices technology and the control function of the electric drive through the "Incremental Rotary Encoder", as well as the results of statistical data processing. Despite the advantages, papers [3, 4] does not solve the problem of automatic calculation of PID controller parameters with reference to a technological object, therefore it is advisable to study control systems with the functionality of automatic calculation of PID controller parameters.

Work [5] reports the results of the design, implementation, and evaluation of the automation system based on PLC S7-300 hardware and software and SCADA WinCC by Siemens with simulation based on the PLCSIM simulator. At the same time, there are no results of configuration and parameterization of FC and technological regulator, which does not provide a comprehensive solution to the stated research problems.

In [6], the results of designing a dispatch control system based on SCADA, PLC, and FC in the TIA Portal "Siemens" are given. However, the results of configuration and parameterization of FC, technological regulator, and control of additional parameters of the electric drive are not provided, which significantly limits the functionality and application of the proposed solutions.

As a result of analysis of the problems in the area of organization of TO ACS topologies, it was established that the construction of such systems involves a comprehensive approach to the design, testing, and operation of hardware and software based on PLC, FC, and SCADA.

At the same time, special attention should be paid to the integration in one software environment of all unified hardware and software tools of the dispatch control system. Tasks that require additional solutions and research include the tasks of virtualizing server system components, designing and testing the communication environment, and protecting system components from unauthorized access.

The functionality, modes of operation, and technological parameters of dispatch control systems for pumping units are reflected in [7], a prestigious publication of "Energy Reports". The work concerns the indirect estimation of the parameters of the cascade control scheme for pumping units based on FC using the method of automatic adaptation of the performance curve of the pumping unit. The work is voluminous, contains both analytical calculations of control parameters, statistical processing of research results, and experimentally obtained oscillograms of operating modes and transient processes. In [7], it is substantiated that the energy consumption of pumping units is up to 22 % of global energy consumption in the commercial and industrial sectors, and attention is focused on the energy efficiency of adopted solutions. The methodology proposed in [7] was tested using an experimental setup under laboratory conditions, and therefore does not take into account the peculiarities of operation of technological equipment under industrial conditions.

In [8], the results of modeling and research of an energy-efficient frequency control system with many pumping units are reported. The work deals with certain issues but is largely theoretical and is based on an analytical apparatus for studying the modes of operation of pumping units. Thus, it is appropriate to compare the results obtained as a result of analytical calculations, both in [8], and obtained on the basis of simulation modeling methods and experimental data.

Analysis of the functionality, operating modes, and technological parameters of TO ACS reveals that in order to enable optimal control modes, it is necessary to control additional technological parameters of the electric drive in pumping units by indirect evaluation methods (without sensors).

At the same time, unification, and improvement of the procedure for determining such parameters are required, which involve their calculation and reading from the corresponding registers directly from frequency converters (for example, Sinamics G120 "Siemens").

The tasks of hardware and software development of pump unit control systems reported in [9, 10] relate to the method of optimizing motion curves in electric drive control systems and a simulator for electric motors based on Siemens automation tools. In works [9, 10], the tasks closest to our paper are solved in terms of automating the procedure for setting up a technological PID controller but the results of industrial approval and testing are not given.

In [11], techniques for controlling a direct current electric motor based on PLC S7-1200 "Siemens" are implemented; there are results of automatic tuning of a technological PID controller. At the same time, as in most of the reviewed literaure, the task of expanding the functionality of pump unit control systems due to indirect control of electric drive parameters directly from FC remains unsolved.

In [12], a separate task of designing and testing an electric drive control system based on FC Sinamics S120 "Siemens" is solved, while the complex task of building dispatch control systems is not addressed.

Generalized conclusions based on the results of analysis of the development and testing of hardware and software tools for dispatch control systems indicate that unified hardware and software tools based on FC, PLC, and SCADA should be used in the design process.

At the same time, algorithms for controlling pump units require further improvement in terms of control and consideration of additional parameters of the frequency-controlled electric drive, protection of technological equipment, and automatic restart of pump units for emergency stop modes.

The tasks of expanding the functionality of dispatch control systems for pumping units are described in [13] and relate to torque measurement based on FC Sinamics G120 "Siemens" with vector control. At the same time, the problems of extended functionality for full dispatch control with protection and diagnostics functions based on SCADA remain unsolved.

In [14], the results of a comparison of the characteristics of the built-in PLC Simatic S7-1200 and the developed auto-tuning algorithm of the PID controller are reported. Original research integrated "MATLAB&Simulink" but did not solve the complex task of building dispatch control systems based on SCADA with testing under industrial conditions.

Analysis of the functionality of dispatch control systems for pumping units reveals the need to integrate additional control and management functions to optimize the operating modes of technological equipment. At the same time, the problem of indirect monitoring of the presence of water in pipelines and defects in pump units based on the value of the torque on the electric drive shaft and other diagnostic parameters is required to be solved and further investigated.

The tasks of researching operating modes and information processes based on technological PID controllers in dispatch control systems for pumping units reported in [15] are solved by integrating the PID controller function on the basis of Siemens PLC. The research results given in [15] are similar in content to this work but do not provide extended functionality of the system in terms of protection and diagnostics of technological equipment.

In [16], a comparison of the auto-tuning procedures of PID controllers based on the hardware and software tools of "Siemens" and "REX Controls" is given, which provides additional information about the ways of solving the specified problem by different manufacturers of hardware and software tools for control systems.

In [17], only a separate problem of auto-tuning of PLC PID controllers is solved by the feedback method. In this case, the response of the optimal PID controller provides a smoother transient control process.

As a result of our review and generalization of methods and means for researching work modes and information processes based on technological PID controllers, it is possible to formulate the main tasks that are relevant and require further research. In particular, these are the tasks of organization, implementation, hardware and software, and testing of technological PID controllers with the functionality of auto-tuning directly at the technological object and taking into account the operating modes of pumping units and operating conditions. In addition, it is necessary to solve the problems of compiling and saving sets of parameters for technological PID controllers for their automatic loading into control algorithms under different modes of technological equipment operation.

3. The aim and objectives of the study

The purpose of our research is the design and implementation of systems for dispatching control over pumping units at water pumping stations based on modern hardware and software tools and information technologies. This will make it possible to improve the efficiency of control and management of technological equipment, expand functionality, and enable optimal operation modes in systems of dispatching control over pumping units at water pumping stations.

To achieve the goal, the following tasks were set:

– to design the topology of a dispatching control system for pumping units based on the requirements for functionality and operating modes;

– to develop hardware and software tools for the system of dispatching control over pumping units at water pumping stations;

– to develop and implement algorithms for controlling pumping units at water pumping stations;

– to design the dispatching interface for the control system over pumping units at water pumping stations;

– to investigate the modes of operation and information processes in the system of dispatching control over pumping units at water pumping stations.

4. The study materials and methods

The object of our research is information processes for enabling operational modes of electrically driven pumping units at water pumping stations.

The main criterion for enabling operational modes of electric pump units is the calculation and algorithmic support of optimal technological PID controllers.

Analysis of the theory and practice of designing optimal technological PID controllers reveals that such tasks are mostly solved by analytical calculations based on the theory of automatic control with further refinement based on standardized technical characteristics. But this approach does not take into account the time-varying technical characteristics and operating conditions of specific technological equipment.

The research hypothesis assumes that in order to enable optimal operational modes of pumping units at water pumping stations, it is additionally necessary to take into account the adaptive component. This component involves correcting the parameters of technological PID controller in real time based on the current technological parameters of the electric drive in the pumping units and operating conditions.

It is assumed that on the basis of modern information technologies, topologies of control systems of technological objects, hardware and software tools, communication components, developed algorithmic and application software, it is possible to achieve the defined goal of research.

In the work, simplification is adopted in terms of analytical calculations of typical technological PID controllers, and more attention is paid to simulation modeling and testing of technological PID controllers in real time.

During the research, the methods and means for building dispatch control systems, the theory of automatic control, system and application software, communication environment, dispatch interface and simulation modeling of control system components were applied.

The state-of-the-art software platform TIA Portal V14 SP1 (Totally Integrated Automation Portal) "Siemens" was used for research and development work (at present, the project can be modified to the current version TIA Portal V19) aimed at designing and testing automated control systems for technological objects [18].

The TIA Portal software platform includes the following functionality:

– design and management of automation projects at technological facilities;

– hardware configuration of PLC-based control systems;

– hardware parameterization of PLC-based control systems;

– construction and parameterization of communication environments for control systems;

– development of application software for PLC-based control systems;

– integration of frequency converters and technological PID controllers in automation projects;

– integration of SCADA functions into control systems of technological objects;

– simulation of PLC and SCADA operation for tasks of simulation modeling and testing of components of dispatch control systems for technological objects.

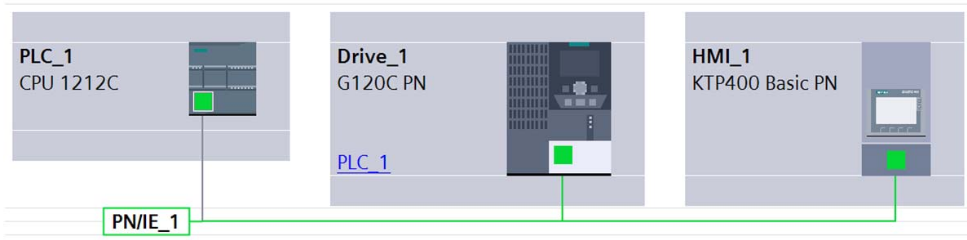

Fig. 1. Topology of local hardware and software for a separate booster and pumping station: PLC_1 CPU 1212C – PLC Simatic S7-1200; Drive_1 G120C PN – frequency converter; HMI_1 KTP400 Basic PN – operator panel; PN/IE_1 – communication based on PROFINET/Industrial Ethernet

5. Results of organizing the system of dispatching control over pumping units at water pumping stations

5. 1. Development of the topology of the dispatch control system for pumping units based on requirements for functionality and operating modes

The main task of the water supply systems in populated areas is the uninterrupted round-the-clock supply of water resources according to the specified regulations.

In addition, there are requirements for water supply systems under modern conditions, which are fixed in the relevant regulatory and legal documents. One of the requirements for the design and operation of water supply systems is the equipment of such systems with means of automation with the functions of dispatch control and control of technological objects.

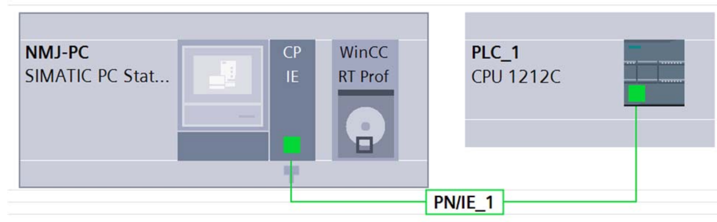

Fig. 2. Topology of the hardware and software tools for the central control room in the pumping unit control system: NMJ-PC SIMATIC PC Station – server workstation; SP IE – Communication Processor Industrial Ethernet; WinCC RT Prof - SCADA; PLC_1 CPU 1212C – PLC Simatic S7-1200; PN/IE_1 – communication based on PROFINET/Industrial Ethernet

One of the main and complex technological objects in water supply systems that requires equipment with means of automation and dispatching are electric pump units at water pumping stations.

Our paper reports the results of designing, commissioning, and studying the operating modes of an automated dispatching control system for pumping units using an example of the booster and pumping station (BPS) at the utility company "Ivano-Frankivskvodoekotehprom" [19].

The system is designed for automatic control over BPS pumping units, collection and transmission of technological parameters to dispatch centers, and also provides functions of remote dispatch control and management.

Thus, the topology of the proposed dispatch control system for pumping units includes two components:

1) local hardware and software in the pump unit control system for a separate BPS (Fig. 1);

2) hardware and software tools for the central control room in the pump unit control system (Fig. 2).

The communication network is built on the basis of a VPN (Virtual Private Network) of the GSM standard, which provides access to technological equipment across almost the entire territory of Ukraine, as well as and protection against unauthorized access [20].

At the local level, the pump unit control system includes the following additional components:

– primary converters of input and output pressure at BPS;

– means of communication and routing of information flows;

– electrical protection and electrical starting equipment;

– backup power supply components of automation equipment.

At the dispatcher level, the pump unit control system includes the following additional components:

– means of communication and routing of information flows;

– components of backup power supply of server equipment.

The main requirements for BPS dispatching control system are:

– the type of control over the electric drive of pumping units – cascade, with one frequency converter;

– dispatch control in real time;

– power of the electric drive of pumping units – 3x2.5 kW;

– archiving of controlled technological parameters (input and output pressure in BPS pipelines; temperature, output frequency of the frequency converter, other electrical parameters) in graphical and tabular form;

– data archiving with discreteness (1 min);

– the ability of the dispatcher to set the required pressure in the outlet pipeline and select the "MAIN" pump unit;

– the system must enable continuous operation (a backup power subsystem may be installed at the facility);

– openness of the system (possibility of modernization and retrofitting by integrating additional components and functions).

The main functions of the dispatch control system:

– automatic and dispatch control over BPS pumping units;

– measurement, processing, transmission, and archiving of technological parameters;

– operator interface directly on the control object;

– signaling of system component failures;

– accounting of pumped water and energy consumption of pumping units.

Dispatching functions:

– visualization of the control process based on SCADA mnemonics;

– remote control and setting of operating modes of BPS pumping units;

– archiving of controlled technological parameters in the control system;

– output and registration of specified emergency messages in the control system;

– support of local and global communications in the dispatch control system;

– administration (granting access rights to the components and functions of the dispatch control system).

Protection functions:

– protection against overvoltage in the BPS input power supply network;

– protection against phase interruption in the input power supply network of BPS;

– short circuit protection;

– protection against over-revving of the pump unit;

– protection against dry running of the pump unit;

– protection against excess water pressure in the output pipeline;

– protection due to the lack of torque on the shaft of the electric drive of the pump unit.

Diagnostic functions:

– diagnosis of electrical parameters of the electric drive of the pumping unit;

– accounting of consumed electricity by pumping units.

Modes of operation of the dispatch control system:

– automatic mode of control of pumping units (basic);

– 1st semi-automatic mode of control over pumping units (without a frequency converter with output pressure control via an analog water pressure sensor in BPS output pipeline);

– 2nd semi-automatic emergency mode (without a frequency converter with control over the output pressure through discrete pressure relays of the limit upper and lower water pressures in BPS output pipeline).

Under automatic mode, the operation of BPS pumping units is carried out by a frequency converter, which regulates the revolutions of the (main) electric drive of the pumping unit depending on the water pressure in the outlet pipeline.

BPS is switched to the 1st semi-automatic mode to enable uninterrupted water supply to the network in the event of the following malfunctions:

– interruption in operation or failure of the frequency converter;

– interruption in operation or failure of the control and communication controller;

– interruption in operation or failure of other elements of the automatic mode scheme.

Pressure regulation for each BPS pump unit under the 2nd semi-automatic mode is carried out using a pressure relay.

The main control functions and indication of operating modes are provided locally at the BPS level through electrical switching components and on the control panel. The Simatic KTP 400 local operator panel is used for advanced functions and archive viewing.

Based on analysis of the requirements, functionality, and modes of operation of the BPS dispatching control system and technological regulations, we have compiled the following list of technological parameters for controlling and managing BPS pump units (PUs) (Table 1).

Table 1

Technological parameters for controlling and managing BPS pumping units

No.	Technological parameter (TP) ID	Unit
1	2	3
1	“Water pressure at the inlet of BPS”	kgf/cm^2
2	“Water pressure at the outlet of BPS”	kgf/cm^2
3	“Set water pressure at the outlet of BPS”	kgf/cm^2
4	“Absence of minimum water pressure at BPS inlet” or “Minimum water pressure at BPS inlet is normal”	yes-no
5	“Maximum permissible water pressure at the outlet of BPS”	kgf/cm^2
6	“Set the water pressure at the outlet of BPS”	kgf/cm^2
11	“Temperature of the electric motor PU No. 1”	°C
12	“Temperature of the electric motor PU No. 2”	°C
13	“Temperature of the electric motor PU No. 3”	°C
15	“Constant voltage of the rectifier of frequency converter No. 1”	V
19	“Output AC voltage of frequency converter No. 1”	V
23	“Electric motor current PU No. 1”	A
24	“Electric motor current PU No. 2”	A
25	“Electric motor current PU No. 3”	A
27	“Power of the electric motor PU No. 1”	kW
28	“Power of the electric motor PU No. 2”	kW
29	“Power of the electric motor PU No. 3”	kW
31	“Torque on the shaft of the electric motor PU No. 1”	Nm
32	“Torque on the shaft of the electric motor PU No. 2”	Nm
33	“Torque on the shaft of the electric motor PU No. 3”	Nm
43	“Speed of the electric motor PU No. 1”	Hz
44	“Speed of the electric motor PU No. 2”	Hz
45	“Motor speed PU No. 3”	Hz
47	“Speed of rotation of the electric motor PU No. 1”	rpm
48	“Speed of rotation of the electric motor PU No. 2”	rpm

Continuation of Table 1

1	2	3
49	“Speed of rotation of the electric motor PU No. 3”	rpm
51	“Activated PU No. 1”	yes-no
52	“Activated PU No. 2”	yes-no
53	“Activated PU No. 3”	yes-no
55	“Period of operation of activated PU”	hour
56	“START/STOP of the electric motor PU No. 1”	yes-no
57	“START/STOP of the electric motor PU No. 2”	yes-no
58	“START/STOP of the electric motor PU No. 3”	yes-no
60	“ACKNOWLEDGEMENT of the failure of electric motor PU No. 1”	yes-no
61	“ACKNOWLEDGEMENT of the failure of electric motor PU No. 2”	yes-no
62	“ACKNOWLEDGEMENT of the failure of electric motor PU No. 3”	yes-no
64	“Overcurrent of the electric motor PU No. 1”	yes-no
65	“Overcurrent of the electric motor PU No. 2”	yes-no
66	“Overcurrent of the electric motor PU No. 3”	yes-no
68	“Phase break of the electric motor PU No. 1”	yes-no
69	“Phase break of the electric motor PU No. 2”	yes-no
70	“Phase break of the electric motor PU No. 3”	yes-no
72	“The temperature of the electric motor PU No. 1 is exceeded”	yes-no
73	“The temperature of the electric motor PU No. 2 is exceeded”	yes-no
74	“The temperature of the electric motor PU No. 3 is exceeded”	yes-no
76	“Emergency STOP”	yes-no
77	“The incoming three-phase network is normal”	yes-no
78	“Permission to operate an electric motor PU No. 1”	yes-no
79	“Permission to operate an electric motor PU No. 2”	yes-no
80	“Permission to operate an electric motor PU No. 3”	yes-no
82	“Hysteresis of pressure at the outlet of BPS”	kgf/cm^2
83	“PLC supply voltage is normal”	yes-no
84	“Frequency Converter Accident No. 1”	yes-no
85	“Frequency Converter Accident No. 2”	yes-no
86	“Frequency Converter Accident No. 3”	yes-no
88	“Automatic protection of the electric motor No. 1”	yes-no
89	“Automatic protection of electric motor No. 2”	yes-no
90	“Automatic protection of electric motor No. 3”	yes-no
92	“Activation of magnetic starter No. 1”	yes-no
93	“Activation of magnetic starter No. 2”	yes-no
94	“Activation of magnetic starter No. 3”	yes-no

Thus, the list of basic technological parameters for controlling and managing BPS pump units compared to common classical control schemes is supplemented with parameters of the functionality for protecting and diagnosing the electric drive.

5. 2. Development of hardware and software tools for the system of dispatching control of pumping units at water pumping stations

Application software has been developed for PLC and server workstation. The dispatcher’s dialog with the system is implemented in the form of mnemonics in the SCADA system. Archiving and documentation of the main technological parameters is provided (pressure in the inlet and outlet pipelines of BPS; temperature, revolutions, current, voltage, and power consumption of the electric drive of the pumping units).

Fig. 3 shows the hardware configuration of the pump unit control system at the BPS level based on PLC S7-1200 [21] in the Simatic STEP 7 software package [18], which is a component of the TIA Portal software platform.

The hardware configuration includes the following components:

1) PLC SIMATIC S7-1200 based on the processor module (CPU 1212C AC/DC/Rly) (Fig. 3);

2) analog input signal module (SM 1231 AI);

3) digital input/output signal module (SM 1223 DC);

4) SINAMICS frequency converter (Sinamics G120C) [22].

PLC Simatic S7-1200 enables the execution of the pump unit control algorithm, including the functions of the technological PID controller (Proportional-Integral-Derivative-Controller), supports Industrial Ethernet communication at the local and dispatching levels based on SCADA.

The SM 1231 AI analog input signal module provides digitization and primary processing of unified 4-20 mA current signals from pressure sensors in the input and output pipelines of BPS with 13-bit resolution (Fig. 4).

The SM 1223 DC digital input/output signal module provides processing of input and output digital signals for implementation of the control algorithm (local indication and signaling, control of electric starting equipment).

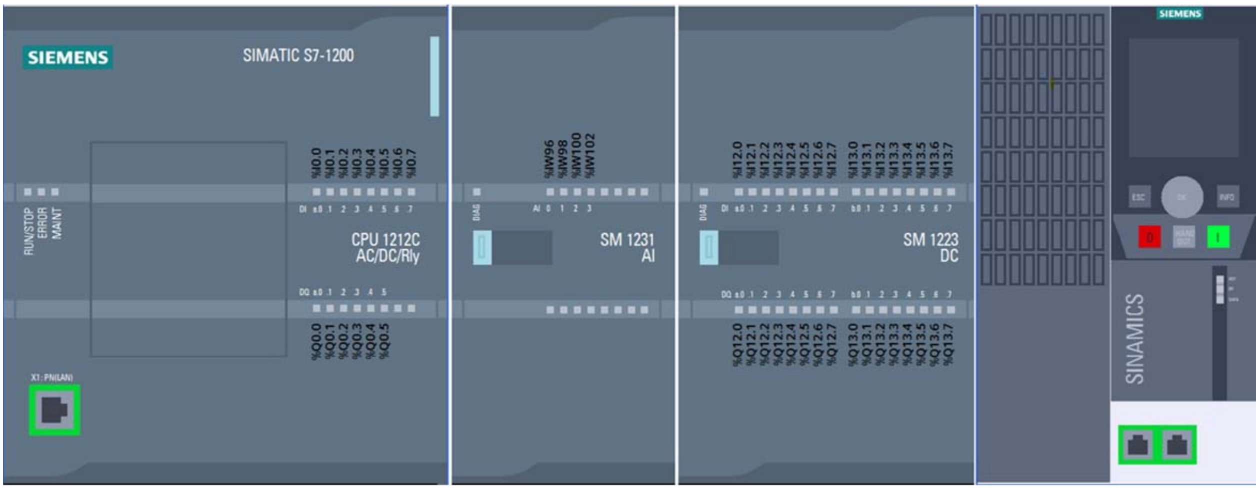

Fig. 3. Hardware configuration of the pumping unit control system based on PLC S7-1200

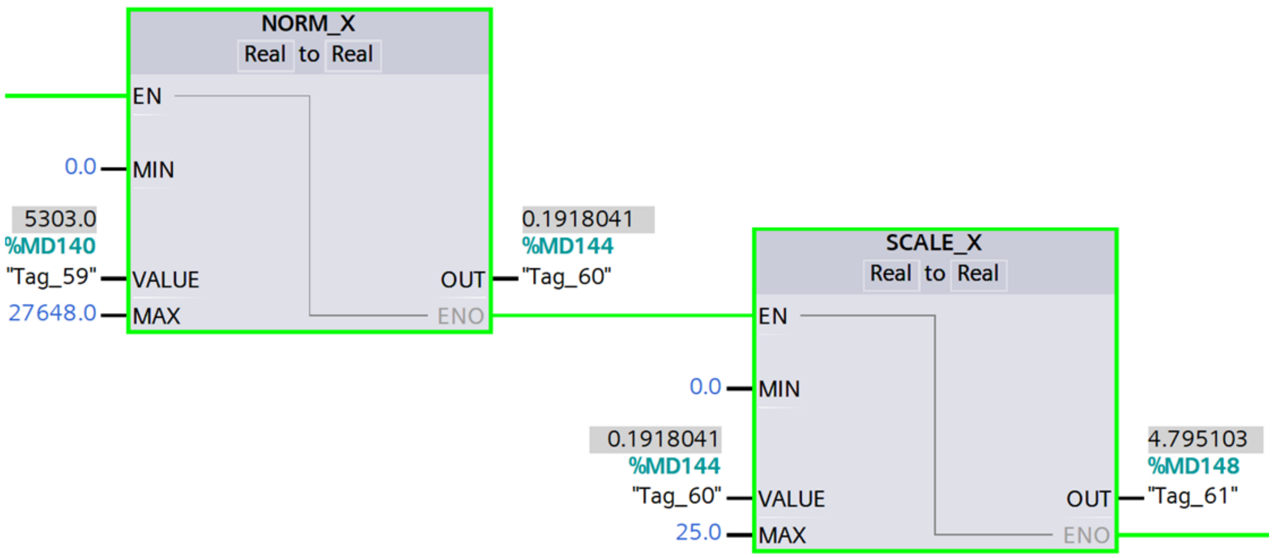

Fig. 4. Processing the measuring signal TP "2" "Water pressure at the output of BPS" (functional blocks of normalization "NORM_X" and scaling "SCALA_X") under the "on-line" mode

5. 3. Development and implementation of control algorithms for pumping units at water pumping stations

The algorithm for controlling BPS pumping units at the PLC S7-1200 level is implemented in the FBD (Function Block Diagram) programming language of the IEC 61131-3 standard [23] in connection with the dispatcher interface at the SCADA level in the following order:

1) TP "77" – analysis of permissible electrical parameters of the input power network (absence of damage and permissible values of phase voltage) – a bit signal is generated – "Input three-phase network is normal";

2) TP "76" – testing the "Emergency STOP" switch – a bit signal is generated – "Emergency STOP is normal";

3) analysis of TP "4" – the bit signal "Absence of minimum water pressure at the BPS inlet" or "Minimum water pressure at the BPS inlet is normal" is generated;

4) if the parameters TP "4", TP "76", and TP "77" are in an acceptable state, the status of activated PUs No. 1, No. 2, and No. 3 is checked and authorization for the operation of PUs No. 1, No. 2, and No. 3 is carried out – TP " 51–53":

– PU No. 1 – activated (TP "51");

– PU No. 2 – activated (TP "52");

– PU No. 3 – activated (TP "53");

5) TP "3" "Set water pressure at the BPS outlet" and TP "2" "Water pressure at the BPS outlet" are read (see Fig. 4);

6) checking for the absence of other accidents:

– TP "68" "Interruption of the phase of the electric motor PU No. 1;

– TP "69" "Interruption of the phase of the electric motor PU No. 2;

– TP "70" "Interruption of the phase of the electric motor PU No. 3";

– TP "5" "Maximum permissible water pressure at the BPS outlet" – bit signals TP "78-80" are generated:

– TP "78" "Permit to operate electric motor PU No. 1";

– TP "79" "Permit to operate electric motor PU No. 2";

– TP "80" "Electric motor operation permit PU No. 3";

7) TP "56-58" "START/STOP" electric motor PU No. 1–3" are performed from the local operator interface on the system control panel or from the control room;

8) TP "55" "Period of operation of activated PUs" is performed from the operator interface on the system control panel or from the control room;

9) after completing points (1–8), the "MAIN PU" is started through the Sinamics G120C PN frequency converter for the specified period of operation "Period of operation of activated PU " – TP "55";

10) switching between PUs is carried out alternately from No. 1 to No. 3, taking into account activated PU TP "51-53" and allowed PU TP "78-80";

11) the system carries out PID regulation [24, 25] by the frequency converter Sinamics G120C PN (3.0 kW) [26] to enable the specified water pressure at the output of BPS TP "2" in accordance with the specified TP "3" (Fig. 5).

12) when the water pressure in the output pipeline of BPS TP "2" decreases compared to the specified TP "3", the PID controller automatically increases the FC output frequency. As a result, the frequency of revolutions of the electric drive increases and, accordingly, the water pressure at the output of the BPS TP "2" increases. If the water pressure in the output pipeline of TP "2" is higher than the set TP "3", the PID controller reduces the FC output frequency. As a result, the rotation frequency of the PU electric drive decreases and, accordingly, the water pressure in the output pipeline of the BPS TP "2" decreases.

Thus, the specified water pressure in the output pipeline of TP "3" is maintained at the output of the BPS TP "2";

13) when the water flow increases and reaches the maximum speed of the electric drive (up to 2850 rpm) of the "MAIN PU", as well as a decrease in the water output pressure, the "MAIN PU" is shunted to the input three-phase network 380 V. At the same time, the next one starts (taking into account the activated PU TP "51–53" and allowed PU TP "78–80") PU with hysteresis by water pressure at the output of BPS TP "82" "Hysteresis of pressure at the output of the BPS". Next, PID regulation takes place to achieve the specified water pressure at the output of BPS TP "2" in accordance with TP "3";

14) thus, under the cascade mode of operation of BPS, the total number of simultaneously functioning PUs is determined by the necessary water pressure at the BPS outlet of TP "2" in accordance with the specified water pressure at the outlet of BPS TP "3";

15) reducing the water flow leads to the switching of the corresponding PUs in the reverse order in the cascade mode. This enables the set water pressure at the output of the BPS TP "2" in accordance with the set water pressure at the output of the BPS TP "3". In addition, activated PU TP "51–53" and permitted PU TP "78-80" with the hysteresis function of PU based on the water pressure at the output of BPS TP "82" are additionally taken into account;

16) when developing the PU control algorithm, the functionality of the system was expanded by controlling and taking into account the main technological parameters of PU electric drive. The following parameters are calculated and directly read from the corresponding FC Sinamics G120C PN (3.0 kW) registers [26]:

– TP "11–13" "Temperature of electric motor PU No. 1–3", °C;

– TP "15" "Constant voltage of the rectifier of the frequency converter No. 1", V;

– TP "19" "Output alternating voltage of frequency converter No. 1", V;

– TP "23–25" "Electric motor current PU No. 1–No";

– TP "27–29" "Power of the electric motor PU No. 1–3", kW;

– TP "31–33" "Moment on the shaft of the electric motor PU No. 1–3", Nm;

– TP "43–45" "Frequency of rotation of electric motor PU No. 1–3", Hz;

– TP "47–49" "Speed of rotation of the electric motor PU No. 1–3", rev/min.

Fig. 6 shows the process of controlling the main technological parameters of the PU electric drive, which are calculated and read directly from FC Sinamics G120C PN.

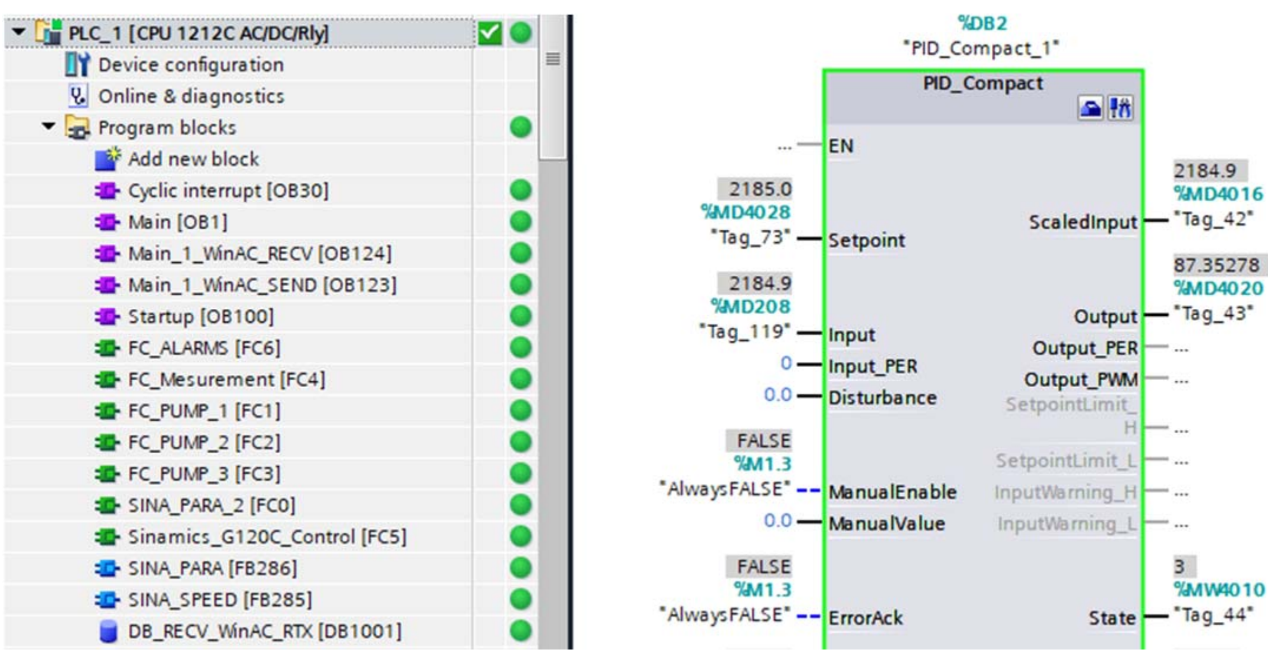

Fig. 5. The structure of the project and the process of PID regulation of TP "2" "Water pressure at the output of BPS" (functional module "PID_Compact"), under the «on-line» mode

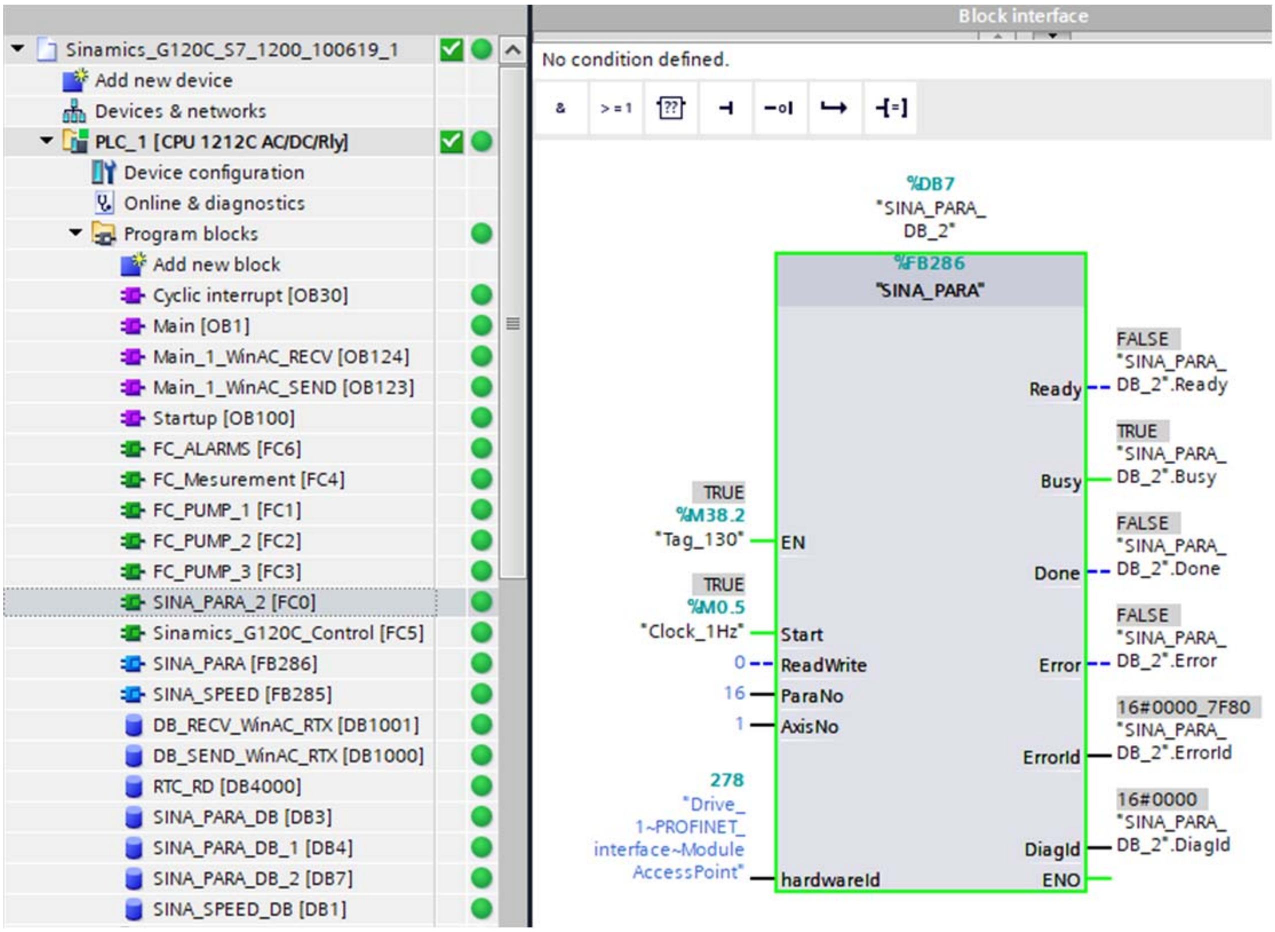

Fig. 6. The process of controlling the main technological parameters of the electric drive of pumping units, which are calculated and read directly from FC Sinamics G120C PN (functional module "SINA_PARA"), under the «on-line» mode

17) in addition, the PU control algorithm must provide protection of the power components by blocking the operation of the electric motors of PU TP "78–80" "Permit to operate the electric motor PU No. 1–3" in the event of the following accidents:

– TP "64–66" "Overcurrent of electric motor PU No. 1–3";

– TP "68–70" "Interruption of the phase of the electric motor PU No. 1–3";

– TP "72-74" "Exceeded temperature of the electric motor PU No. 1–3";

18) additional protection functions are provided directly by FC Sinamics G120C PN (3.0 kW) [27];

19) to unlock the generated errors and accidents of FC Sinamics G120C PN (3.0 kW), the TP command "60–62" "ACCEPTANCE of electric motor accident PU No. 1–3" is used from the local operator interface on the control panel or remotely from the control room.

The designed system provides communication between PLC Simatic S7-1200, operator panel Simatic KTP X00 PN, and FC Sinamics G120C PN through the local "Industrial Ethernet" bus. In addition, VPN communication with a remote control center is carried out based on the GRE (Generic Routing Encapsulation) tunnel protocol [28].

The system performs the function of archiving technological parameters and carries out automatic start-up after an accident or interruptions in the power supply network.

The system provides scaling and can be expanded and supplemented with additional control and management components, operating modes, and functionality during further operation.

5. 4. Design of the dispatcher interface in the control system for pumping units at water pumping stations

The dispatcher interface of the pumping unit control system has been designed on the basis of SCADA WinCC Professional, which is integrated into the software platform TIA Portal "Siemens" [29, 30].

The dispatcher interface of the pump unit control system includes the following components:

1) buttons for selecting the BPS operating mode: "AUTOMATIC-RELAY MODE, MANUAL MODE, AUTOMATIC-FREQUENCY MODE";

2) dynamic scale of indication TP "2" "Water pressure at the BPS outlet" in the range (from 0 to 10 kgf/cm^2);

3) TP input field "3" "Set water pressure at the BPS outlet" P_out, kgf/cm^2 "SET" with the input confirmation button "OK";

4) input field TP "55" "Period of operation of activated PUs" (from 1 hour) with an input confirmation button "OK" and a countdown counter of activated PUs in seconds;

5) output field TP "2" "Water pressure at the BPS outlet" R_out, kgf/cm^2;

6) a mnemonic diagram with functions to dynamize the state of pumping units (H-1, H-2, and H-3) with the corresponding technological parameters;

7) control buttons with dynamization functions: "START", "STOP", "CONTROL GLOBAL", "CONTROL LOCAL", and "RECEPTION";

8) field of archives (trends) of individual technological parameters over time:

– "P_out", kgf/cm^2 corresponds to TP "2" "Water pressure at the BPS outlet";

– "I", A corresponds to TP "23–25" "Electric motor current PU No. 1–3";

– "f", Hz corresponds to TP "23–25" "Frequency of rotation of electric motor PU No. 1-3";

9) buttons for controlling the dispatcher interface and detailing the main interface mnemonic: "MAP", "MAIN", "PUMP #1", "PUMP #2", "PUMP #3", "ALARMS", "WATER CONSUMPTION", and "QUICK INQUIRY DATA".

10) a field indicating the current date and time.

Fig. 7–9 show the result of the operation of the designed dispatching interface of the pump unit control system according to the cascade algorithm under «on-line» mode based on SCADA.

Thus, the operation of the BPS pump unit control system recorded under «on-line» mode in accordance with the developed topology, algorithmic and application software clearly demonstrates the effectiveness of the control process. At the same time, the stability of maintaining the water pressure at BPS output is ensured up to tenths of units during switching transient processes and up to hundredths of kgf/cm^2 under the stabilization mode for the BPS cascade control scheme.

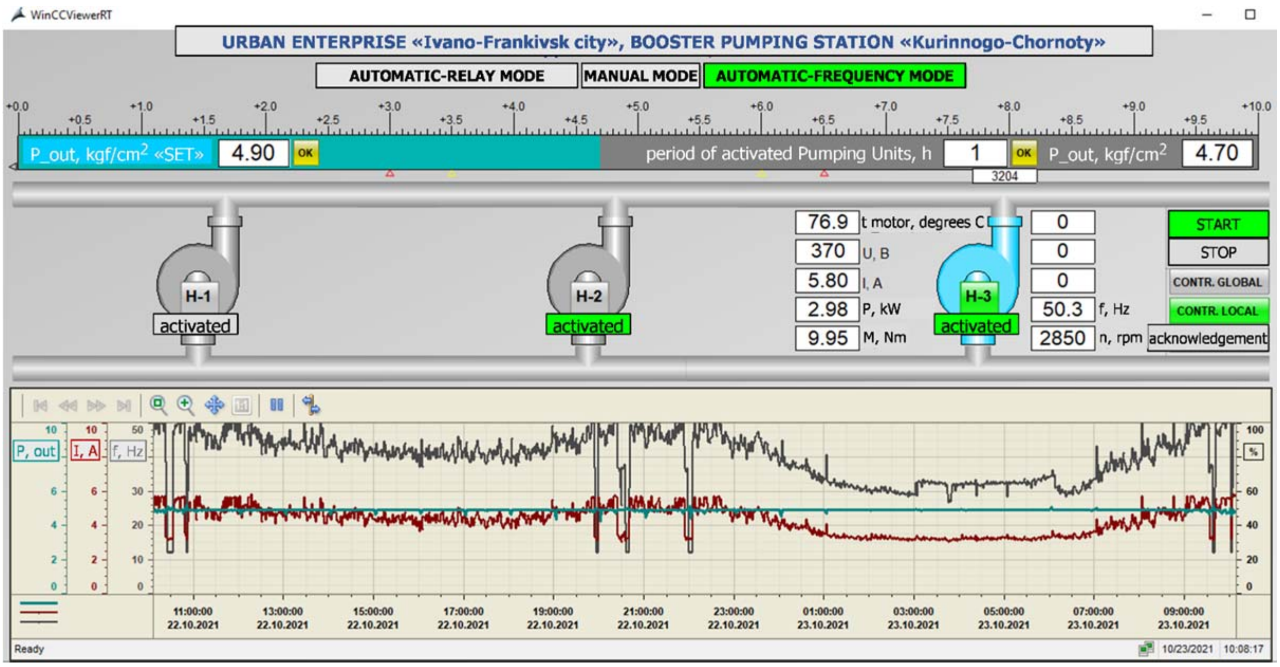

Fig. 7. The H-3 pump unit operates at a maximum speed of 2850 rpm from the Sinamics G120C frequency converter, the water pressure at the outlet of BPS P_out drops to 4.70 kgf/cm^2 compared to the "SET" P_ex equal to 4.90 kgf/cm^2

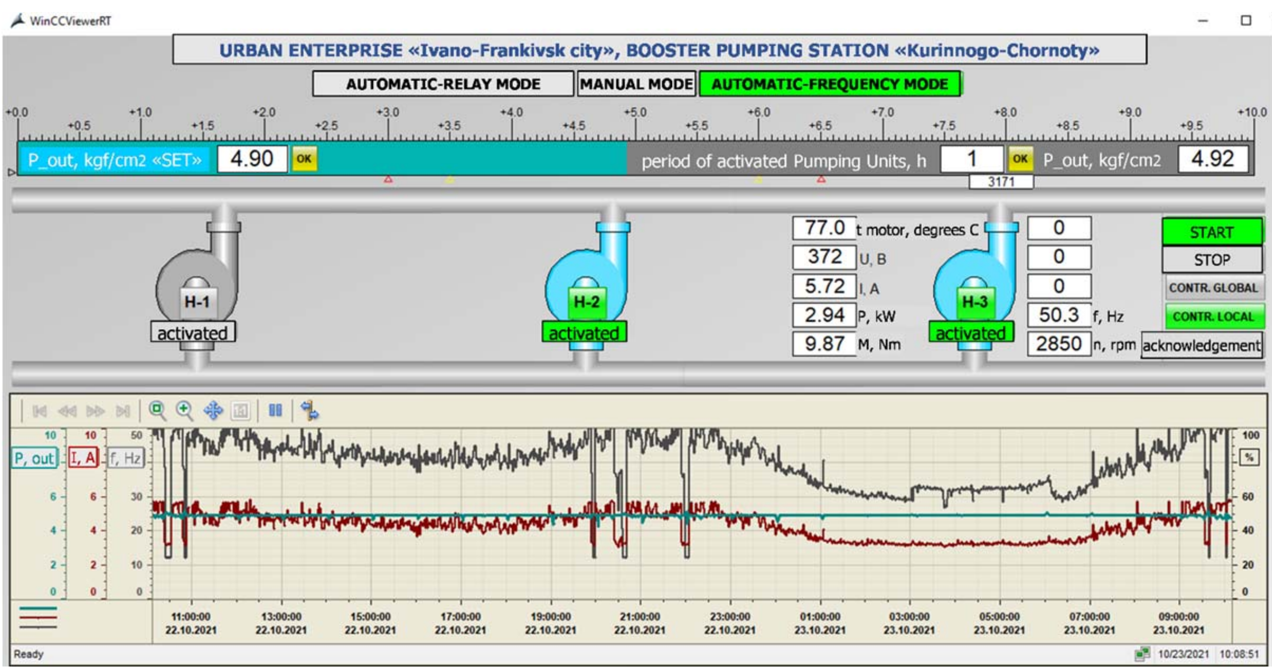

Fig. 8. The H-3 pump unit operates at a maximum speed of 2850 rpm from the Sinamics G120C frequency converter, the process of "shunting" H-2 takes place, the water pressure at the outlet of BPS P_vyh is readjusted to 4.92 kgf/cm^2 compared to the P_out "SET" equal to 4.90 kgf/cm^2

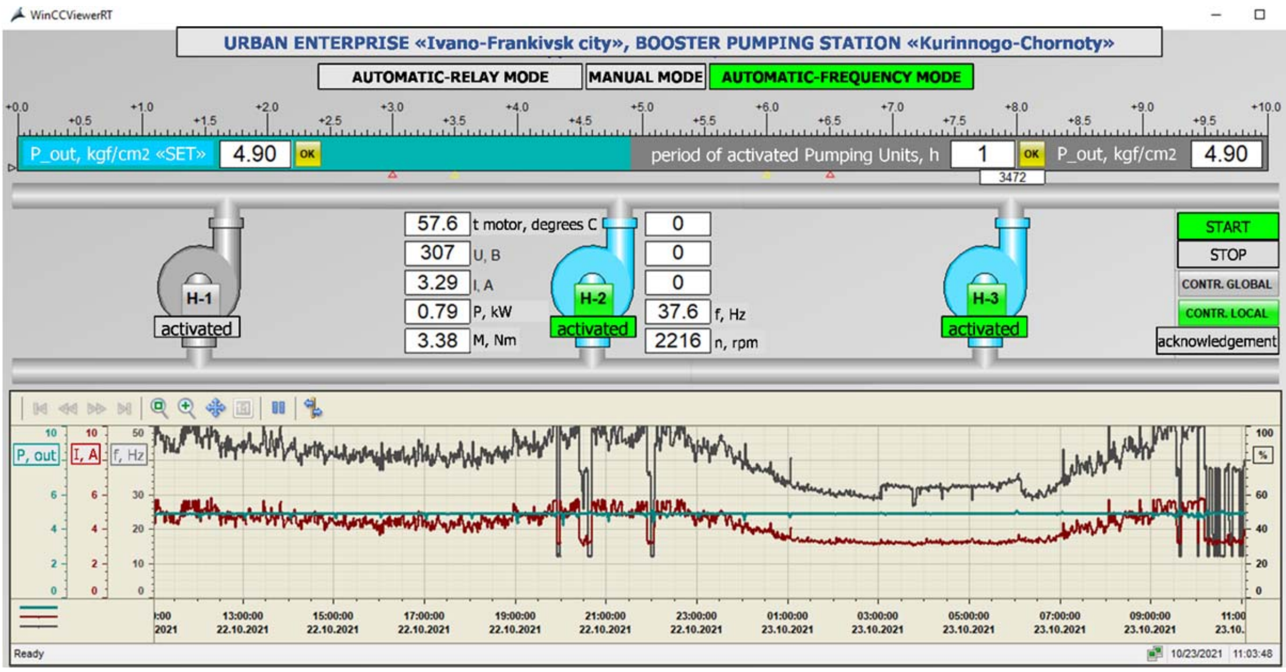

Fig. 9. The pump unit H-2 operates at a current speed of 2216 rpm from the frequency converter Sinamics G120C, the "shunting" process of H-3 takes place, the water pressure at the outlet of the BPS P_ex stabilizes to 4.90 kgf/cm^2 in accordance with the P_out "SET" 4.90 kgf/cm^2

5. 5. Investigating the work modes and information processes in the system of dispatching control over pumping units at water pumping stations

Positive results and valuable experience were obtained as a result of the design, testing, and industrial operation of the dispatching control system for BPS pumping units.

The designed system, in addition to its direct application, is advisable to use as a full-fledged hardware and software complex for researching the modes of operation of pumping units at water pumping stations.

The designed dispatch control system allows analyzing in real-time "on-line" the main technological parameters of the electric drive of BPS pumping units using the appropriate tools of the TIA Portal software platform project [27] (Fig. 10).

When performing research on the operating modes of pumping units, the toolset for adaptive calculation and optimization of the parameters of PID controller in the frequency-controlled electric drive of PU (Fig. 11), which is implemented by the "PID_Compact" functional module (Fig. 5) [27], was used.

Fig. 12 shows the result of the adaptive calculation and optimization of the parameters of PID controller for the frequency-controlled electric drive.

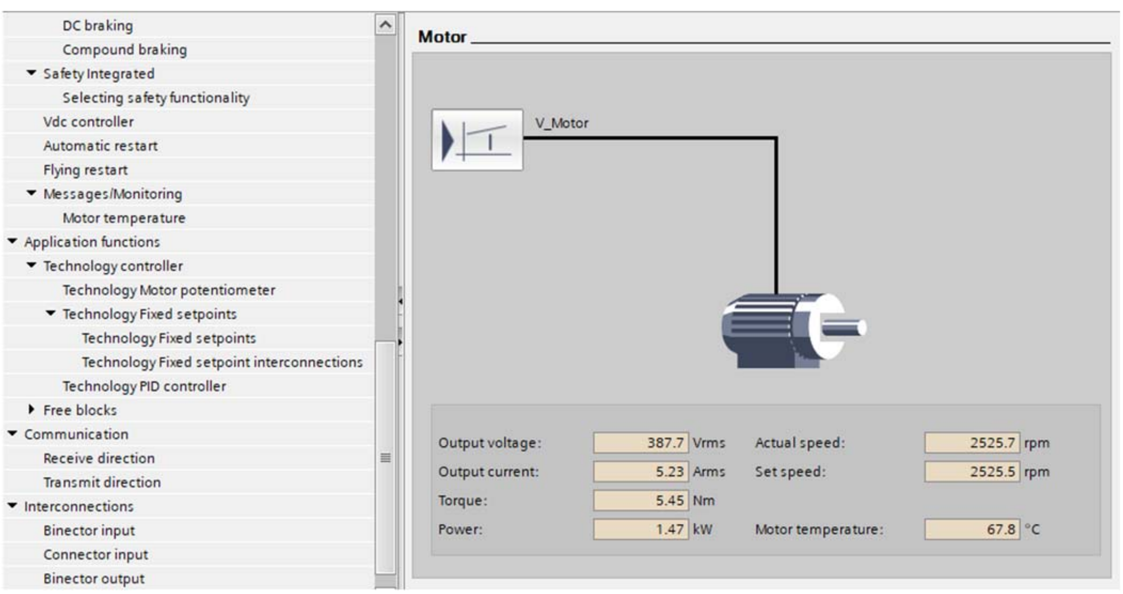

Fig. 10. Toolkit for real-time "on-line" analysis of the main technological parameters of the electric drive of pumping units at booster and pumping stations

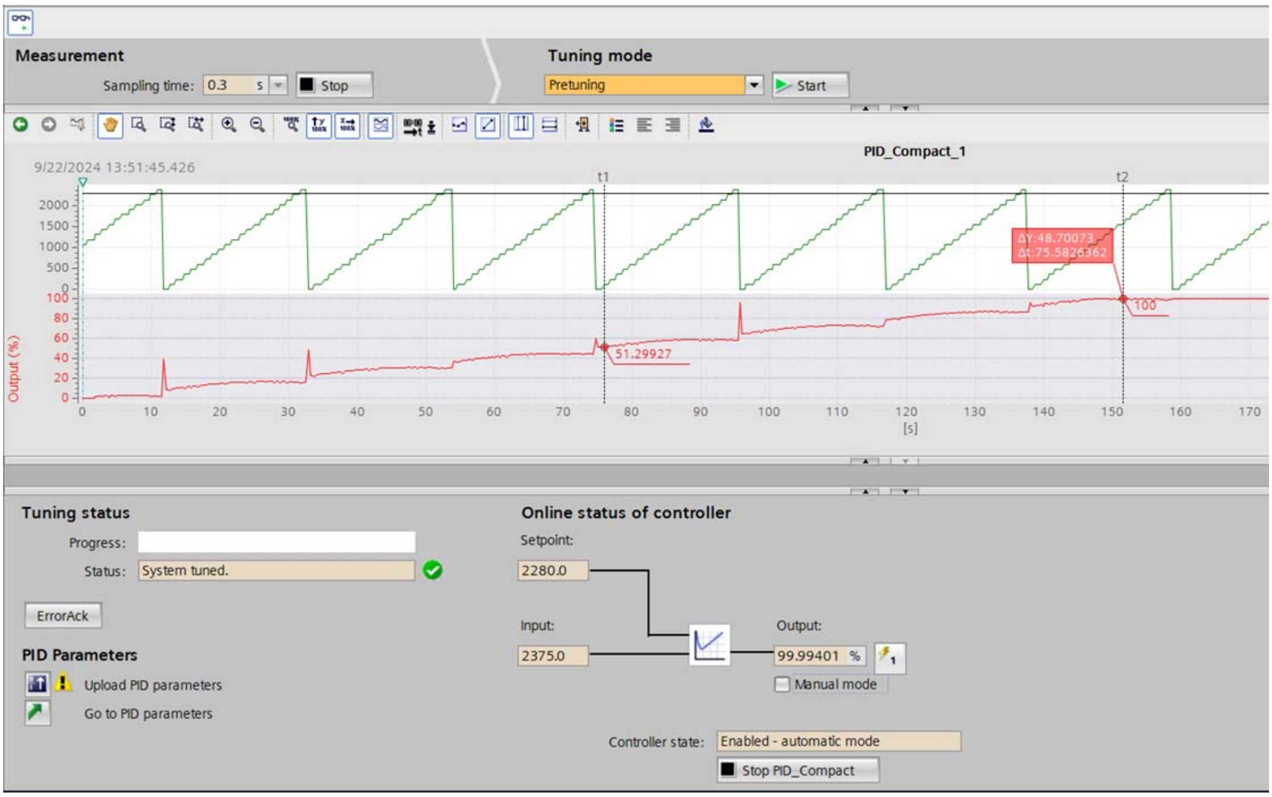

Fig. 11. Toolkit for adaptive calculation and optimization of parameters of the PID controller in the frequency-controlled electric drive of pumping units (transient function of the regulator)

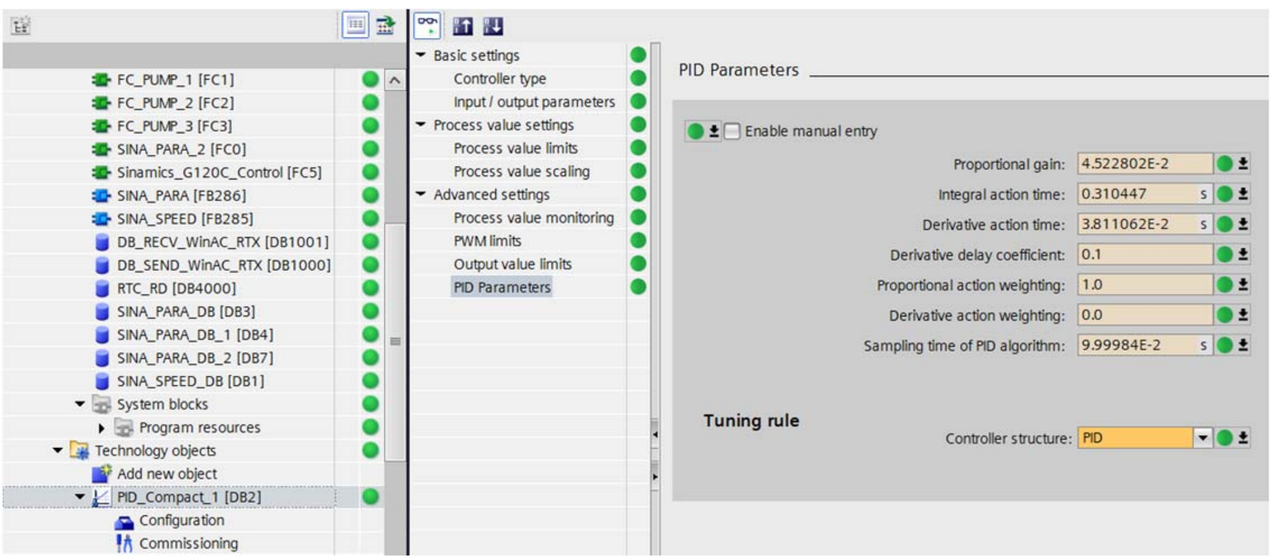

Fig. 12. Result of the adaptive calculation and optimization of parameters of the PID controller in the frequency-controlled electric drive of pumping units

The initial settings of the PID controller are implemented in the "PID_Compact" program instruction for the final proportional control element.

In this case, the following setting modes are possible:

– inactive PID controller;
– rough setting of the PID controller;
– precise setting of the PID controller;
– PID controller automatic setting mode;
– PID controller manual setting mode;
– PID controller output value replacement mode with error monitoring.

In this project, the automatic mode of parameterization of the PID controller and commissioning of the electric drive of pumping units based on the "PID_Compact" program instruction (Fig. 11, 12) is used.

During the commissioning of the electric drive of the pumping units, integrated adjustment algorithms were used in combination with the procedure for correcting and saving the parameters of PID controller.

The program instruction "PID_Compact" is called from the organization module of the cyclic interrupt "Cyclic interrupt [OB30]" with a period of 100 ms (Fig. 5). For a faster response of the regulator to a change in the controlled parameter (water pressure at the BPS outlet), the period of cyclic interruption can be reduced adaptively to the dynamics of water flow.

In addition, the primary settings of PID controller are determined from the current values TP 2 "Water pressure at the BPS outlet" and TP3 "Set water pressure at the BPS outlet", also determined by the parameters of the electric drive of the pump units.

The criteria for optimizing the parameters of PID controller were the minimum time to set the control parameter within the limits of the deviation from the task (no more than 2 %), with over-regulation (no more than 10 %), which is due to the peculiarities of BPS operation regulations.

The special feature and advantage of our technique for calculating the parameters of PID controllers in the frequency-controlled electric drive of PU is the unification and speed of execution of design and test procedures. In this case, the current parameters of the frequency-controlled electric drive of the pumping units, other components of the technological equipment (power wiring, electromagnetic interference filters, chokes), as well as the operating conditions of the electric drive of the pumping units are taken into account.

The designed WEB-oriented system for dispatching control over pumping units at water pumping stations has passed approval and is operated within the limits of a utility enterprise of critical infrastructure [19].

Due to modularity and uniformity, the system can be expanded and modernized, as well as optimized for work with other types of sensors and actuators.

6. Discussion of results related to the organization of a system of dispatching control over pumping units at water pumping stations

Our results are provided by a specific, different from the typical, topology at the server level (Fig. 2), which includes an additional PLC_1 CPU 1212C. In this way, the task of organizing packet data exchange between an additional PLC at the dispatcher level and a PLC at the level of technological objects by means of the TCP/IP (Open User Communication) protocol is solved [28]. The advantages of such communication are the synchronous exchange of all control and management parameters in one communication package between SCADA and each individual technological object.

The developed algorithm for controlling the operating modes of pump units enables reading (Fig. 6) and taking into account additional parameters of the electric drive (Fig. 7–9) by an indirect method directly from the Sinamics G120C frequency converter by means of the "SINA_PARA" software module.

When designing the hardware and software for the system, unified design procedures for configuration (Fig. 3) and parameterization of PLC hardware, including operations of conversion, normalization, and scaling of measuring signals from sensors, were applied (Fig. 4). Algorithmic PLC software has been developed and structured in the FBD programming language of the IEC 61131-3 standard.

We believe that the main result from investigating the work modes and information processes in the control systems for pumping units at water pumping stations is the comprehensive solution to the formulated scientific and technical tasks. Special attention was paid to the procedures for automated calculation of optimal parameters for adaptive PID controllers "PID_Compact" (Fig. 5) directly at the technological facility (Fig. 10–12). In this way, the current, time-varying electrical parameters of the frequency-controlled electric drive of the pumping units and the operating conditions of the technological equipment were taken into account.

Thus, the improvement of adaptive control algorithms involves devising a set of "PID_Compact" program instructions with automatically calculated control parameters directly at the control object. At the same time, the corresponding "PID_Compact" module is adaptively activated, taking into account the BPS operating modes and the current parameters of the electric drive of the pumping units, including protection functions.

The stated problems have been solved by using the unified software platform TIA Portal "Siemens" [18], which makes it possible to integrate in one project environment the functions of configuration and parameterization of FC, PLC, and SCADA hardware and software tools. In addition, in the process of conducting research, methods and means for simulating control system components integrated into the project based on PID-controllers in the frequency-controlled electric drive of pumping units were applied.

The limitations of our study on information processes in the control systems over pumping units include the relatively small power (up to 10 kW) of the tested frequency-controlled electric drive of pumping units. Therefore, with a significant increase in capacity (from tens of kW), it is necessary to take into account additional features of functioning, modes of operation, and the structure of algorithmic support.

The disadvantage of the research and design works is the relatively significant practical orientation of the work based on methods and means of simulation modeling of system components without the use of analytical apparatus when solving the tasks.

The current research could in the future involve designing new and more advanced dispatch control systems for other industrial facilities. At the same time, there may be improvements in topologies, hardwarem and software, algorithmic and application software of systems for dispatching control over technological objects, including on the basis of experience gained in implementation and operation.

7. Conclusions

1. Based on analysis of methods, means, and requirements for functionality and technical characteristics, the topology of the WEB-oriented dispatching control system for pumping units based on modern hardware and software tools has been designed. In this case, the main requirement for the organization of such systems is round-the-clock uninterrupted supply and distribution of water resources to consumers.

A feature of the designed topology is the use of GRE tunnel protocol for data exchange at VPN level, which provides the possibility of remote programming and maintenance of system components, as well as increases the level of protection against unauthorized access.

2. Research and development work was carried out on designing the hardware and software tools for a dispatching control system for pumping units based on the principles of

standardization, unification, and possibility of expansion and modernization.

The configuration and parameterization of the hardware of PLC-based system has been completed. We have organized and tested the communication environment of the system at the local and global levels in accordance with the designed topology of the system.

3. Algorithms for controlling the operating modes of pumping units have been developed and implemented using the FBD programming language of the IEC 61131-3 standard.

The control algorithm was developed in the form of separate organizational modules, system functions, functional blocks, functions and global data modules that structure the application software for the possibility of its further improvement and support.

The main advantage of the implemented algorithm is the possibility of automated calculation of the parameters of the technological PID controller, taking into account the current electrical parameters of the frequency-controlled electric drive of pumping units and their operating conditions.

4. The WEB-oriented dispatching interface of the SCADA-based pumping unit control system has been developed. Structured by mnemonics, with functions of dynamic visualization, archiving of technological parameters, signaling, administration of access rights to system components and industrial communications support. As a result, the process of dispatching control in real time with a reaction time to events of up to 1 second is ensured.

5. The result of our study on the work modes and information processes in the dispatch control system of pumping units is the unification of design and test procedures, clarification of the type and number of technological control and management parameters. Adaptive control algorithms based on technological PID controllers with automatic calculation functionality have been improved.

The improvement of adaptive control algorithms involves constructing a set of “PID_Compact” program instructions with automatically calculated control parameters directly on the control object. At the same time, the corresponding “PID_Compact” module has been adaptively activated, taking into account the BPS operating modes and the current parameters of the electric drive of the pumping units, including protection functions.

Our results provided an increase in technical and economic indicators during the operation of technological equipment through the efficiency of control and management procedures, effective and energy-saving modes of operation of the frequency-controlled electric drive of pumping units at water pumping stations.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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