UDC 621.316.11:621.67

DOI: 10.29202/nvngu/2018-3/16

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ENERGY EFFICIENT POWER SUPPLY SYSTEM AND AUTOMATIC CONTROL OF MODES OF THE "POWER SUPPLY – PUMPING STATION" COMPLEX

Purpose. Development of technical and algorithmic solutions for complex improvement of electrotechnologic effectiveness indices of "power supply mains – pumping station" ("SM-PS") complex, improvement of its energy efficiency, obtaining its rational structure and operation algorithm of the system of automatic control of modes of pumping over.

Methodology. Circuit design and algorithmic solutions were developed on the basis of liquid pumping efficiency indices analysis for various power supply schemes, power circuits connection diagrams and control methods of centrifugal pumping units, which were acquired using mathematical experiments on the developed digital model of "SM-PS" complex.

Findings. Power supply circuit and centrifugal pump unit connection diagram were developed. A structure and an algorithm for microprocessor system of automatic discrete-continuous control of liquid pumping modes with constant pressure in the pipeline on the full range of the "SM-PS" performance variation were created.

Originality. A mathematical model of synthesis of discrete-continuous control of liquid pumping modes using centrifugal pumping units in the structure of the closed-loop system of the pipeline pressure stabilization was developed.

Practical value. The use of the developed scheme, schematic and algorithmic solutions makes it possible to improve the electrotechnologic efficiency indices of "SM-PM" complex, in particular, to decrease specific cost of active electric energy, to improve the power factor, to decrease circuit voltage deviation as well as to reduce consumption of total and reactive powers, which results in substantial energy saving. The suggested solutions can be applied while designing new and operating working "SM-PS" complexes.

Keywords: *pump station, power supply network, energy efficiency, microprocessor system, control algorithm*

Introduction. One of the topical problems of modern applied science is raising the effectiveness and energy efficiency of high power electrotechnical complexes and optimization of their modes. They include electrical engineering systems of pumping stations for oil and water pipelines.

Pumping stations (PSs) are characterized by high cost of the equipment, large installed capacity of the individual units and relative remoteness of the units from power sources, which imposes the specific requirements to the electricity supply efficiency and their modes' control systems. The large capacity of the units and the fact that they are distant from the power sources cause both the impact of the units on each other and the mutual effect of PS as a whole and the power network (PN). In view of the growing cost of energy, large energy consumption and low energy efficiency of PS, as well as the wide use and importance of high power PS for the national economy, the improvement of the available and creation of new energy-efficient power supply systems and mode control systems for the pumping complexes PN-PS are of topical importance [1].

The PS energy saving depends on many factors, including the hydraulic load of the pumps. In general, the control task consists in maintaining a constant discharge head in a specific unit of the hydraulic network for different values of the hydraulic fluid consumption, while the systems are functioning according to a set optimality criterion. The highest energy efficiency is offered by a hybrid continuous-discrete control of PS performance [2], as in such conditions pumping units operate with reduced energy loss in their elements, and hydraulic shocks in the system are eliminated.

Unsolved aspects of the problem. The analysis of the experimental curves of the PS mode coordinates [1–3] revealed that the current productivity of the centrifugal pumps (CPs) changes over time fairly slowly, except for the cases of starting or shutting down the equipment and in emergencies. For instance, according to the data in the water consumption curve for the water supply network [3], the highest speed of increase or drop in consumption does not exceed 0.1 %/s, and such brief variations of the pressure in the pipeline hardly influence the consumption or other mode coordinates [4]. These circumstances justify the correctness of distinguishing such prolonged modes of PS and give grounds for regarding them as close to steady-state modes. For their analysis, appropriate energy-efficient model solutions should be developed. It is in such quasi steady-state modes that the major volumes of electrical power are consumed and its major losses are sustained, and it is for them that the application of energy-saving structural and circuit design solutions will produce the most significant effect [1].

It is known that selection of this or that method of analysis, mathematical model and degree of its refining are determined by the specific features of the object under study and set research objectives. Modelling of the transients occurring during the operation of high power electrical engineering complexes is, first of all, used for studying the indices of dynamics and energy efficiency of high-speed automatic control systems (ACSs) for controlling their modes, selecting switching equipment, finding the reasons for and predicting failures of the equipment caused by the overloading both in CP [5] and in the pipeline system [6], and others. Despite the universality of dynamic modes modelling, it is not always worth using for the analysis of steady-state modes of multi-unit systems and complexes.

Analysis of the recent research. The generalized mathematical model (MM) of the electrotechnical complex PN-PS (further referred to as PN-PS EC) with centrifugal pump units (CPUs) proposed in [7] allows computations of steady-state modes of such a complex both with non-controlled and controlled units, directly taking into account mutual effect of the parameters and hydraulic and electromagnetic coordinates of the mode [8]. It can be used for selecting an efficient design of the complex structure, for improving the indices of its modes, as well as for developing energy-efficient ACSs for modes control.

Objectives of the article. To solve the task of a comprehensive improvement of the PN-PS EC indices, it is viable to use the approach based on carrying out mathematical experiments on the built MM for different circuit design and algorithmic solutions and disturbing and controlling effects similar to the real ones. Based on the analysis of the obtained results of the mathematical experiments on the digital model, it is necessary to substantiate the CPU rational power and wiring diagram of CPU, as well as the structure and algorithm of the microcontroller ACS for the fluid pumping modes within the whole range of PS productivity and constant pressure in the pipeline.

Presentation of the main research. PN-PS EC being studied is arbitrary divided into two parts: the power network and group of the blocks of CPU and the pipeline (PL), which are electrically connected. The CPU block consists of CP, electric motor (IM or SM), frequency converter (FC) and transformer (T). Such a presentation stems from the fact that the electric motors of the different units (for instance, the booster pump motor and main pump motor) can have equal or different rated power supply voltages. This information is derived from the analysis of the indices and parameters of the PN-PS EC synthesized power supply layout.

The PN-PS EC generalized mathematical model consists of the mathematical models of PN and CPU and PL blocks, which are combined using the equations describing electrical connections and hydraulic couplings between its elements. Let us present the equations of the mathematical models of the static condition of some most important elements of the complex.

The CP improved mathematical model is developed based on the principle of electrohydrodynamic analogy and makes it possible to take into account the effect of the physical properties of the hydraulic fluid and rotation speed of the pump impeller on its internal parameters, which significantly enhances the accuracy of modelling the CP steady-state modes [9]

$$\left(\underline{Z}_{1*}+\underline{Z}_{0*}\right)\dot{Q}_{\Sigma*}-\underline{Z}_{0*}\dot{Q}_{CP*}-\dot{H}_{0*}=0;$$
$$-\underline{Z}_{0*}\dot{Q}_{\Sigma*}+\left(\underline{Z}_{0*}+\underline{Z}_{2*}\right)\dot{Q}_{CP*}-\dot{H}_{CP*}=0;$$
$$H_{CP*}-R_{dr*}Q_{RE*}-H_{RE*}=0;$$
$$Q_{CP*}-H_{RE*}\big/R_{bp*}-Q_{RE*}=0;$$
$$\mathrm{Re}\left(\dot{Q}_{CP*}\right)\mathrm{Im}\left(\dot{H}_{CP*}\right)-\mathrm{Im}\left(\dot{Q}_{CP*}\right)\mathrm{Re}\left(\dot{H}_{CP*}\right)=0;$$
$$\dot{H}_{0*}-\dot{H}_{0nom*}\omega_{r*}^{2}=0,$$

where, in the relative units, $\underline{Z}_{0*}=\underline{Z}_{0*}\left(k_{v*},\omega_{r*}\right)$, $\underline{Z}_{1*}=\underline{Z}_{1*}\left(k_{v*},\omega_{r*}\right)$, $\underline{Z}_{2*}=\underline{Z}_{2*}\left(k_{v*},\omega_{r*}\right)$ are complex equivalent hydro resistances of CPs, which are complex functions of the kinematic viscosity k_{v*} of the hydraulic fluid and rotation speed ω_{r*} of the CP impeller; R_{dr*}, R_{bp*} are relative equivalent hydro resistances of the flow-regulating valve and by-pass; $\dot{H}_{0*}, \dot{Q}_{\Sigma*}, \dot{H}_{CP*}, \dot{Q}_{CP*}, \dot{H}_{RE*}, \dot{Q}_{RE*}$ are complex discharge heads and volume flow rates of the idealized CP, real CP and real CP with the flow-regulating valve and by-pass taken into account; $\dot{H}_{0nom*}$ is the rated discharge head of the idealized CP.

The model of the steady-state mode of the induction motor was built in d-q coordinates taking into consideration the non-linear static resistance of its main magnetic circuit and skin effect. The equations of the IM model are also written in relative units (all the notations in the equations are conventional

$$r_{s*}I_{sd*}-\omega_{s*}\left(L_{s*}I_{sq*}+\Psi_{\delta q*}\right)-U_{sd*}=0;$$
$$r_{s*}I_{sq*}+\omega_{s*}\left(L_{s*}I_{sd*}+\Psi_{\delta d*}\right)-U_{sq*}=0;$$
$$\omega_{s*}r_{1r*}I_{1rd*}-\left(\omega_{s*}-\omega_{r*}\right)\left(L_{1r*}I_{1rq*}-\Psi_{\delta q*}\right)=0;$$
$$\omega_{s*}r_{1r*}I_{1rq*}+\left(\omega_{s*}-\omega_{r*}\right)\left(L_{1r*}I_{1rd*}-\Psi_{\delta d*}\right)=0;$$

$$\omega_{s_*} r_{2r_*} I_{2rd_*} - \left(\omega_{s_*} - \omega_{r_*}\right)\left(L_{2r_*} I_{2rq_*} - \Psi_{\delta q_*}\right) = 0;$$

$$\omega_{s_*} r_{2r_*} I_{2rq_*} + \left(\omega_{s_*} - \omega_{r_*}\right)\left(L_{2r_*} I_{2rd_*} - \Psi_{\delta d_*}\right) = 0;$$

$$I_{sd_*} - \left(I_{1rd_*} + I_{2rd_*}\right) - R_{mn_*} \Psi_{\delta d_*} + \omega_{s_*} \Psi_{\delta q_*} / R_{a_*} = 0;$$

$$I_{sq_*} - \left(I_{1rq_*} + I_{2rq_*}\right) - R_{mn_*} \Psi_{\delta q_*} - \omega_{s_*} \Psi_{\delta d_*} / R_{a_*} = 0,$$

where

$$R_{mn_*} = I_{mn_*}\left(a_0 + a_2\left(\psi_{\delta d_*}^2 + \psi_{\delta q_*}^2\right) + a_4\left(\psi_{\delta d_*}^2 + \psi_{\delta q_*}^2\right)^4\right).$$

The similar approach was used for building the MM of the steady-state modes of the double-wound transformer

$$k_t U_{ld_*} + R_{l_*} I_{ld_*} - \omega_* \left(L_{l_*} I_{lq_*} + \Psi_{1q_*}\right) = 0;$$

$$k_t U_{lq_*} + R_{l_*} I_{lq_*} + \omega_* \left(L_{l_*} I_{ld_*} - \Psi_{1d_*}\right) = 0;$$

$$U_{hd_*} - R_{h_*} I_{hd_*} + \omega_* \left(L_{h_*} I_{hq_*} + \Psi_{1q_*}\right) = 0;$$

$$U_{hq_*} - R_{h_*} I_{hq_*} - \omega_* \left(L_{h_*} I_{hd_*} + \Psi_{1d_*}\right) = 0;$$

$$I_{hd_*} - R_{m_*} \Psi_{1d_*} + \omega_* G_* \Psi_{1q_*} - I_{ld_*} = 0;$$

$$I_{hq_*} - R_{m_*} \Psi_{1q_*} - \omega_* G_* \Psi_{1d_*} - I_{lq_*} = 0,$$

where $R_{m_*} = I_{m_*}\left(b_0 \Psi_{1_*} + b_6 \Psi_{1_*}^3 + b_{10} \Psi_{1_*}^5\right)$.

The frequency converter is represented in a general form on the basis of the balance between the active and reactive powers with their losses taken into account (higher-order harmonics were not considered in the model)

$$U_{ind_*} I_{ind_*} + U_{inxq_*} I_{inq_*} - \Delta P_* - U_{outd_*} I_{outd_*} + U_{outq_*} I_{outq_*} = 0;$$

$$U_{inq_i} I_{ind_i} - U_{ind_i} I_{inq_i} - \Delta Q_* - U_{outq_i} I_{outd_i} - U_{outd_i} I_{outq_i} = 0,$$

where, in relative units, U_{in}, I_{in}, U_{out}, I_{out} are input and output voltages and currents of FC; ΔP_*, ΔQ_* are losses of the active and reactive powers in FC.

Development of the rational power supply diagram and structure of the energy-efficient ACS for the modes of the generalized PN-PS EC [7] was performed based on the results of modelling the steady-state modes of the diagram of its electrical connections and hydraulic couplings presented in Fig. 1. The analysis of the applica-

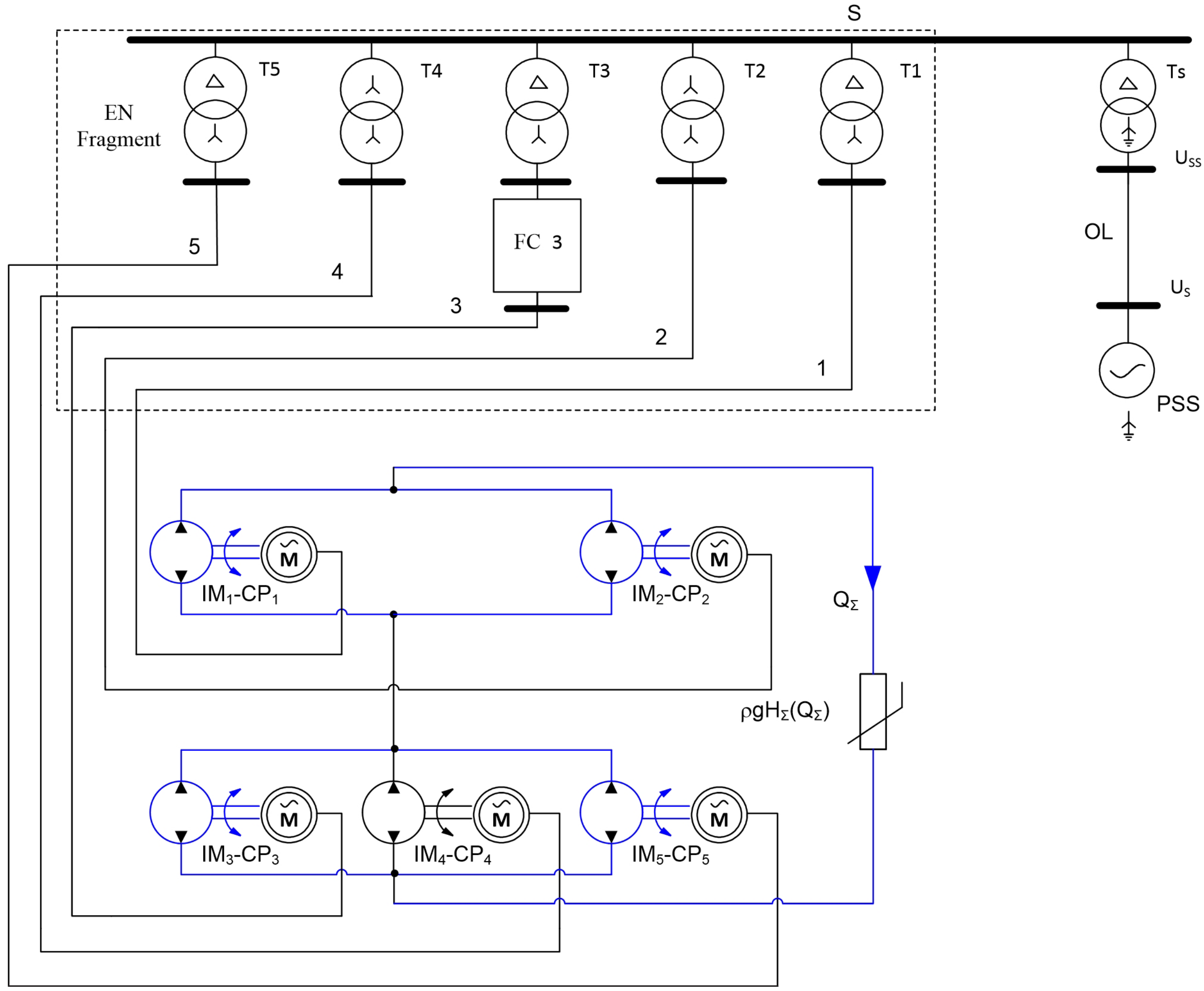

Fig. 1. Hydraulic couplings and electrical connections of PN-PS EC (Variant V0)

tion of different functions of scalar frequency control of the IM pump revealed the viability of implementing the control model

$$U_{s1}/U_{s2}=\left(f_{s1}/f_{s2}\right)\sqrt{T_{em1}/T_{em2}},$$

where U_{s1}, U_{s2}, f_{s1}, f_{s2} are the voltage and voltage frequency on the stator; T_{em1}, T_{em2} are electromagnetic torques for different speeds. Unit 3 is frequency-controlled. Other units are directly controlled by their switching on or off according to the synthesized algorithm.

PN-PS EC is powered from the line with voltage $U_c = 110$ кV, $S_{kc}^{(3)}=160$ MV·A via the transformer T_s ТДН-16000/110. The list of other pieces of the PS equipment is presented in Table 1.

PN-PS EC operation is controlled according to the mode of maintaining the constant value of the discharge head of $H_\Sigma = 370$ m of the hydraulic fluid, which is achieved by varying the number of the switched non-controlled CPUs and by implementing speed frequency control of the Unit 3 IM rotor, depending on the current value of the inlet productivity Q_Σ, as well as on the selected optimality criterion (for instance, electrical power specific loss minimization criterion).

The PS under study can maintain a set value of the discharge head within the whole range of the productivity – from 0 to 7130 m^3/h. This value being exceeded will cause a reduced head at the pipeline inlet; all CPUs will be switched on and will run at the maximum speed.

The obtained results of the simulation studies (without taking into account the reactive power compensation) showed that efficient operation of PN-PS EC being studied with specified mode parameters is possible when four combinations of concurrently switched CPUs are used. The list and numbers of concurrently switched CPUs within different ranges of the hydraulic fluid consumption (PS productivity) are presented in Table 2.

It was found that the control of the steady-state operation modes of the PN-PS EC design being studied can be implemented by switching on or off Units 2, 4, 5 on condition that CPU1 is constantly on and subject to the frequency control of the CPU3 motor depending on the variation of the inlet volume flow rate.

Table 1

Pumping Station Equipment

Unit	Transformer	Induction Motor	Centrifugal Pump
Booster Pump	ТМ-1600/35	ДАЗО4-550У-6У1	20 НДсН (а)
Main Pump	ТМ-4000/35	4АЗМ-3150/6000УХЛ4	НМ 3600-230 (с1)

Table 2

PS Productivity for Different Combinations of Switched on CPUs

CPU quantity	2	3	4	5
CPU number	1, 3	1, 3, 4	1, 2, 3, 4	1, 2, 3, 4, 5
Variation range of Q_Σ, m^3/h	0... 2620	2620... 4300	4300... 5210	over 5210

The units should be switched on or off, when the volume flow rate passes through the values $Q_{\Sigma1} = 2620$, $Q_{\Sigma2} = 4300$ and $Q_{\Sigma3} = 5210$ m^3/h, as it is shown in Table 3.

The pumping productivity exceeding 7130 m^3/h will cause a drop in the discharge head at the PS outlet. If the volume flow rate drops below the value equal to 10 % of the rated productivity of PN-PS EC, this will result in multiple increases in the electrical power consumption. Such load modes occur quite rarely and are non-typical. Therefore, we will not discuss the PN-PS EC performance indices in these modes.

The diagram of the PN-PS EC power supply shown in Fig. 1 (variant V0) is not the best from the point of view of the quantity and rated power of the electrical equipment. To find out the rational configuration of the PS power supply layout, let us compare the two variants of its implementation that differ in the quantity and rated power of the power supply transformers. Schematic changes will be made in the PN fragment outlined with dashes. Further on, only the figure showing the finally selected variant will be presented.

In the first variant of PN-PS EC power supply layout (further on referred to as V1), the boosters CPU1 and CPU2 are powered from one and the same transformer T12 TM-4000/35. The main non-controlled CPU4 and CPU5 are also powered from one transformer, which is T45 TM-6300/35. The power supply of the controlled CPU3 is implemented using the transformer TMH-4000/35, as in the initial variant V0 (Fig. 1). The total rated power of the five transformers in variant V0 amounts to 15.2 MVA, while for variant V1 the total rated power of the three transformers is 14.3 MVA.

In another variant, which is further on referred to as V2, the boosters CPU1 and CPU2 are powered similarly to V1. The power supply of all the main CPUs (non-controlled CPU4 and CPU5 and controlled CPU3) is implemented using the transformer T345 ТДНС-10000/35. The rated power of the two transformers in V2 is 14.0 MVA.

The computations carried out on the model showed that due to the changeover from V0 to V1, all the indices improve significantly: the power factor and voltage Uss on the high-voltage buses of the transformer Ts of PN-PS EC rise; specific consumption of electrical pow-

Table 3

Reactive Power Compensation

CPU quantity		2	3	4	5
CPU number		1, 3	1, 3, 4	1, 2, 3, 4	1, 2, 3, 4, 5
Rated reactive power of RSC, kVAr	RSC_{12}	390	540	980	1160
	RSC_{345}	0	650	1260	2700
	RSC_3	1080	1190	1440	1440
Variation range of Q_Σ, m^3/h		0... 2620	262... 4300	430... 5210	over 5210

er for fluid pumping, reactive and total power decrease. When switching from V0 to V2, these indices improve even more.

Comparison of the variants V1 and V2 finalizes the selection of the variant V2 as the best one, as its implementation requires the lowest amount of equipment with the minimum possible rated power of the power supply transformers.

Therefore, the study confirms the viability of using the variant V2 of implementing the electrical power supply layout, which enables reducing the quantity of transformers from five to two and, respectively, their rated power from 15.2 to 14.0 MVA (i.e., by 7.9 %) with simultaneous enhancement of the PN-PS EC operation modes in general.

On the selected base variant V2 of the implementation of the PN-PS EC power supply layout, we will determine viable points of connecting the reactive shunt compensation (RSC) devices, evaluate their necessary parameters and verify the efficiency of reactive power (RP) modes compensation.

When determining the viable points of RSC devices connection, the volumes of the consumed RP, required degree of its compensation and dependence of its value upon the hydraulic fluid consumption were taken into consideration. These factors being accounted for, three viable points of RSC devices connection in the power supply layout were distinguished:

- RSC_{12} with the voltage of 6 kV on the low-voltage (LV) buses of the transformer T12 that powers the boosters CPU1 and CPU2 (the viability of switching on this RSC needs a separate technical and economic substantiation, as the effect of the low-power booster CPU on the total electrical power consumption is insignificant);
- RSC_{345} with the voltage of 6 kV on the LV buses of the transformer T345 that powers all the main CPUs, namely non-controlled CPU4 and CPU5 and non-controlled CPU3);
- RSC_3 with the voltage of 6 kV at the output of the FC of the main controlled CPU3 (in this case, the advantage is the regulating effect of the capacitance, due to which RP generation will decline as the voltage and frequency at the RSC connection point decrease) [10].

Taking into account the fact that the viability of using RSC_{12} needs additional substantiation, we considered two options. In the first variant, which is further on referred to as V2.1, RSC_{12} zero RP is generated. In the second variant V2.2, RSC_{12} generates non-zero RP.

Selection of the necessary RSC parameters aimed at avoiding the RP overcompensation within the whole range of productivity variation during the PN-PS EC operation according to the developed control algorithm. The list and numbers of the concurrently switched on CPUs and calculated required rated reactive power of RSC for different ranges of the hydraulic fluid consumption are presented in Table 3.

The analysis of the obtained results shows that changing the power supply layout from V2 to V2.1 results in the significant improvement of all the indices: the power factor and voltage Uss on the high-voltage buses of the transformer Ts of PN-PS EC rise; specific consumption of electrical power for fluid pumping and reactive and total power decrease.

The benefit of using RSC_{12} is especially felt in case of the PN-PS EC operation with two concurrently switched CPUs, when the hydraulic fluid volume consumption is below 2620 m^3/h. A significant reduction in RP consumption within the range of low consumption values and improvement of this and other indices in all the consumption ranges occur right when V2 is changed to V2.2. The comparison of the variants V2.1 and V2.2 (Figs. 2, 3) results in selecting V2.2 as the best one.

Therefore, we can arrive at the conclusion about the technical viability of using the variant V2.2 (Table 3) for RP compensation, which brings the value of the power factor the closest to the figure of one for the hydraulic fluid consumption varying within a broad range. Generally, using both variants (V2.1 and V2.2) considerably raises the power factor against the background of the falling RP consumption and voltage U_{ss} on the high-

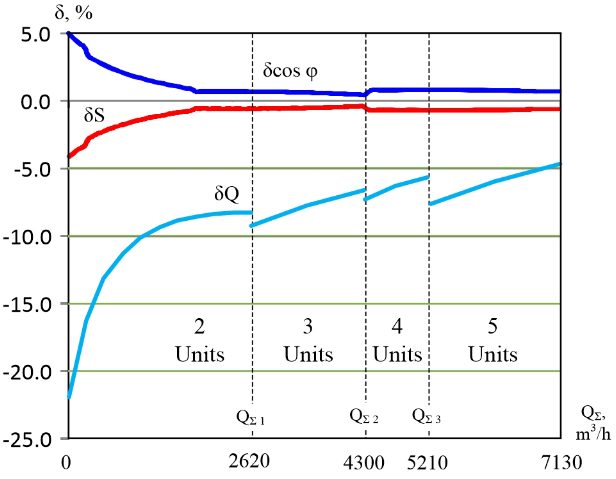

Fig. 2. Percentage change of the total δS and reactive δQ powers and of the power factor δsos φ of PN-PS EC as a result of changing from V2.1 to V2.2

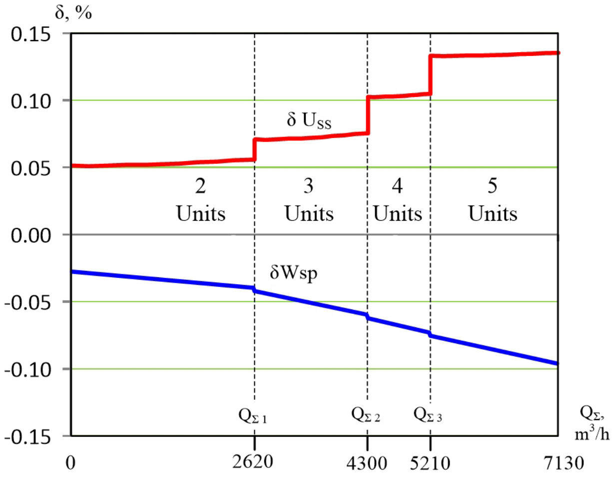

Fig. 3. Percentage change of the specific consumption of electrical power δWsp and voltage deviation δU_{SS} on the high-voltage buses of the transformer Ts as a result of changing from V2.1 to V2.2

voltage buses of the transformer Ts, whereas a decrease in the specific consumption of electrical power used for fluid pumping is insignificant.

The computations on the developed MM for different schemes of the PN-PS EC control and reactive power compensation give grounds for regarding the variant V2.2 as the best one.

Fig. 4 shows the most viable scheme of electrical power supply and reactive power compensation and the developed functional diagram of the feedback ACS for the PN-PS EC hydraulic fluid pumping modes, which were designed based on the simulation study. Following the created control algorithm, the switching devices 2.0...5.2 (V2.2) implement the operating switching of the electrical CPUs and RSCs in the function of current consumption of hydraulic fluid. Table 4 presents the viable law of variation of the electrical switching devices' state as the function of the hydraulic fluid consumption variation, obtained as a result of the computations using the created MM (Off – switched off; On – switched on).

Relying on the developed power supply scheme for the electrical CPUs and the obtained law (algorithm) of switching on/off of these units and RSCs (Table 4), the functional diagram of the feedback system of automatic continuous-discrete control of the hydraulic fluid pumping modes (Fig. 4) and algorithm of its functioning (Fig. 5) have been substantiated. Their use makes it possible to obtain the best indices of the electrical and technological efficiency of PN-PS EC out of all the studied control schemes and algorithms.

It is proposed to implement the developed ACS for fluid pumping on a microcontroller device (MD) (Fig. 4). For indirect operating regulation of the head at the pipeline inlet, a hydraulic fluid consumption sensor (HFCS) is installed. This sensor outputs a mean value of the current productivity on the i-1 interval of the time increment Δt of the system control vector synthesis. This mean value Q_i is fed into the MD analogue input.

At the first two MD outputs in the function of this signal, continuous signals of the control law of the speed (Fig. 6) of the frequency-controlled CPU3 (Fig. 4 marked as IM3-CP3) obtained on MM are formed. These are the signals of setting up the voltage Us and frequency fs of this voltage that are fed onto the input of the frequency converter FC3. Dependencies of the synthesized rational law of scalar frequency control of the induction motor

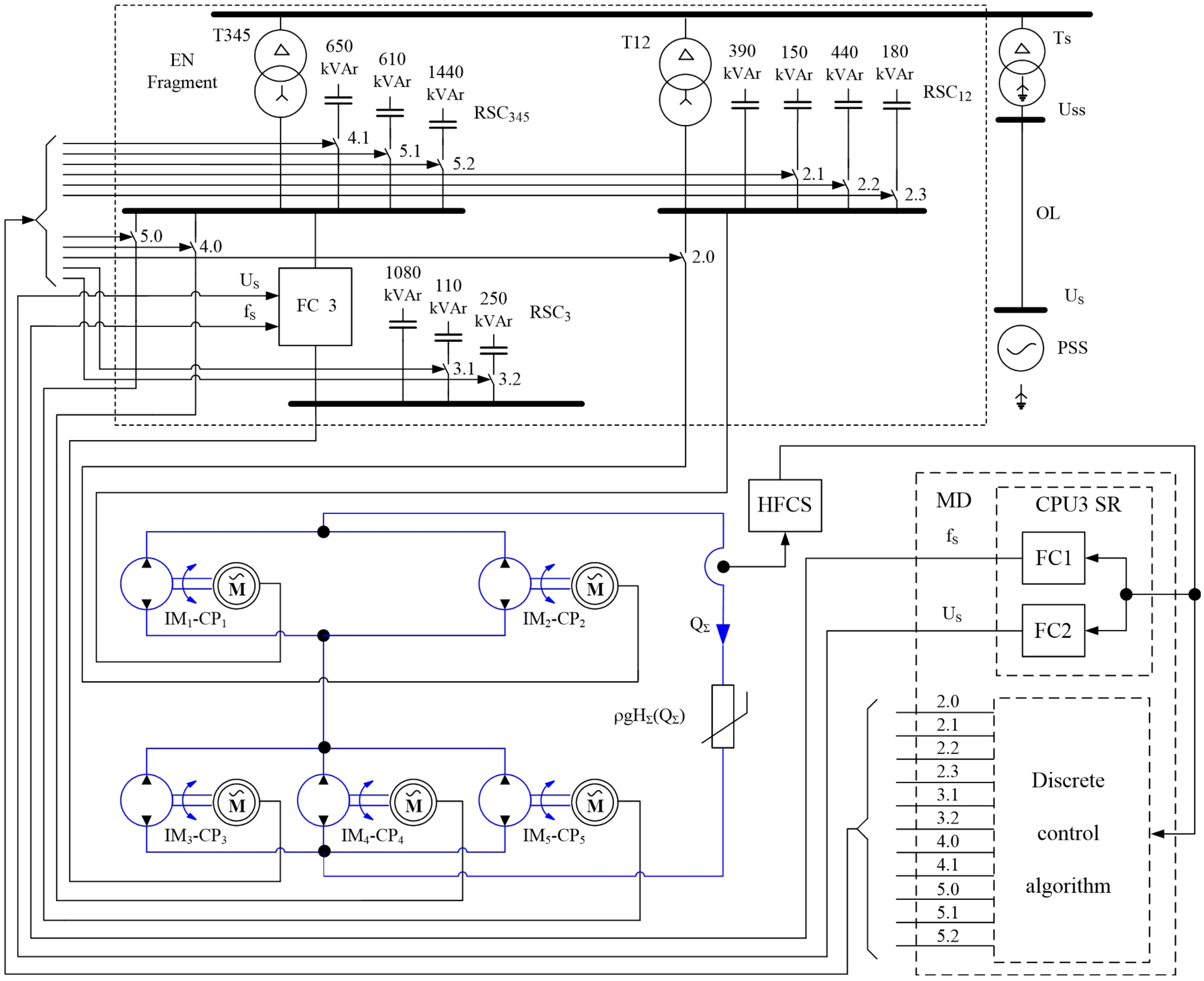

Fig. 4. Electrical power supply and reactive power compensation scheme and flow diagram of ACS for PN-PS EC hydraulic fluid pumping modes (variant B2.2)

Table 4

State of electrical switching devices depending on the PS current productivity Q_Σ

Switch. units Q_Σ,m^3/h	2.0	2.1	2.2	2.3	3.1	3.2	4.0	4.1	5.0	5.1	5.2
0...2620	off	off	off	off	off	off	off	off	off	off	off
2620...4300	off	on	off	off	on	off	on	on	off	off	off
4300...5210	on	on	on	off	on	on	on	on	off	on	off
over 5210	on	on	on	on	on	on	on	on	on	on	on

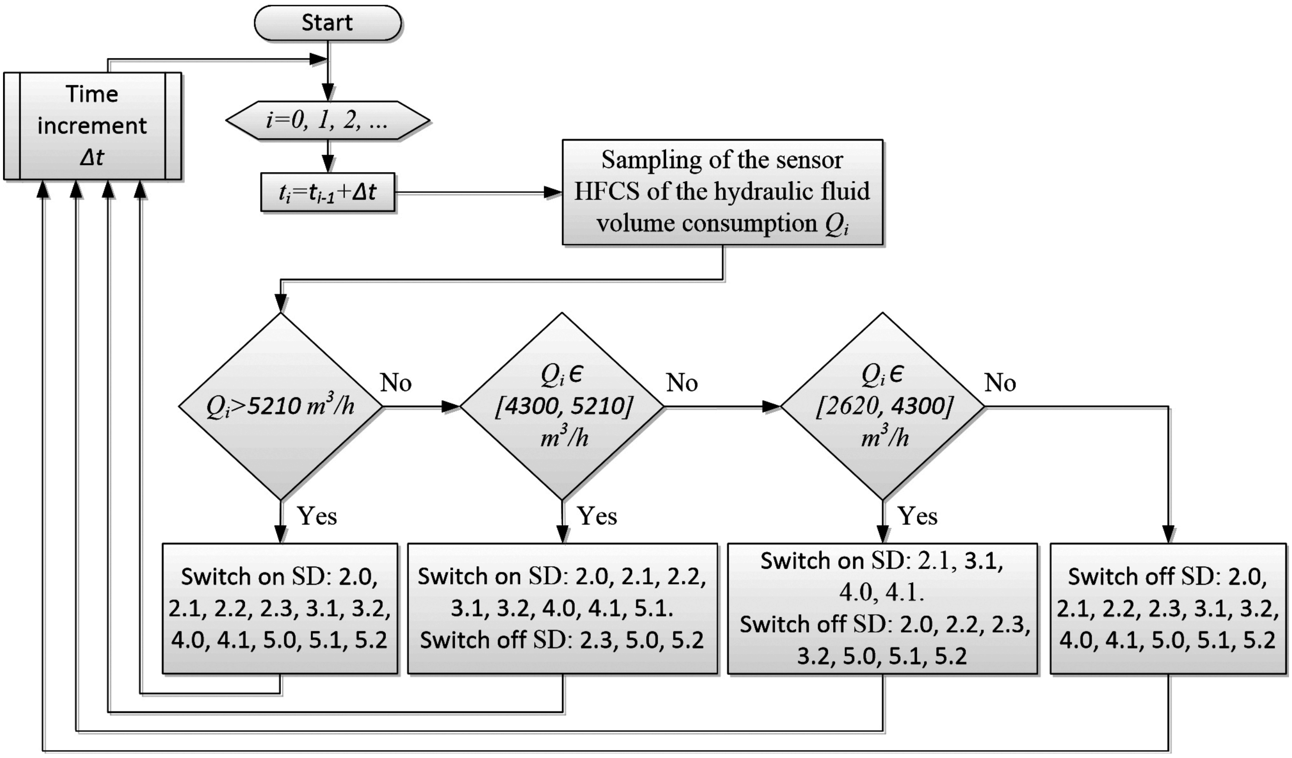

Fig. 5. Flow diagram of the discrete control algorithm for CPU and RSC according to variant V2.2 of PN-PS EC

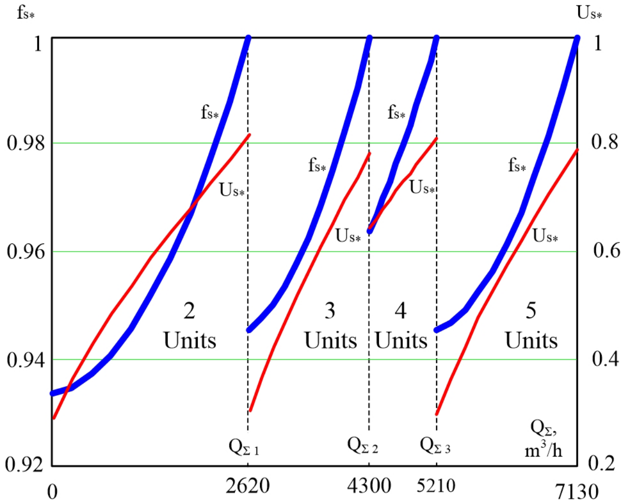

Fig. 6. Continuous signals of the CPU3 speed control law (voltage and voltage frequency of the controlled IM3 stator winding)

IM3 are reproduced in the two functional converters FC1 and FC2 of the speed regulator SR of the controlled CPU3 induction motor drive rotation, software-implemented in the microcontroller device MD. Discrete signals of switching devices' control are formed according to the software-implemented algorithm (Fig. 5) in the function of the hydraulic fluid current productivity Q_i in the logical control block of the microcontroller device MD. The synthesized rational algorithm of switching on and off of PU and RSC implements the obtained law (Table 4) of operating switching in the function of the current fluid consumption (required hydraulic power of PS). The value of the time increment Δt, necessary for uninterrupted operation of the complex, is calculated based on the results of the experimental studies of the actual dynamics of variation of the productivity Q_i of a specific PS.

The electrical and technological viability of the practical use of the developed ACS design for the hydraulic fluid pumping modes of the obtained rational scheme variant V2.2 and the developed algorithm of modes control (Fig. 5) is confirmed by the computed functional curves of the most important indices of the PN-PS EC operational modes presented in Figs. 7, 8.

These figures also show the similar curves for the variant V0 (thin lines), which allows comparing the mode efficiency indices of these two variants of PN-PS EC. The analysis of the obtained curves shown in Figs. 7, 8 leads to a conclusion about the improvement of these indices, especially when approaching the nominal operational mode (subject to full load of all the units). The functional curves presented in these figures suggest that for the scheme variant V2.2 as compared to V0, the specific consumption of electrical power by PN-PS EC decreases on average by 0.3–0.4 %; the power factor rises by 8–10 %; the voltage deviation on HV buses of the transformer Ts is reduced by 39–40 %; the consumed total and reactive powers decrease by 7.8 and 40 %, respectively.

Conclusions and areas of further research.

1. In order to improve the indices of the electrical and technological efficiency of the PN-PS complex modes, the study substantiated the viability of using the approach based on studying the structures and laws of controlling modes on the mathematical model of the steady-state modes of the complex and development of the rational power supply scheme, structure and functioning algorithm of the PN-PS EC automatic control system using the data obtained in the mathematical computer experiments.

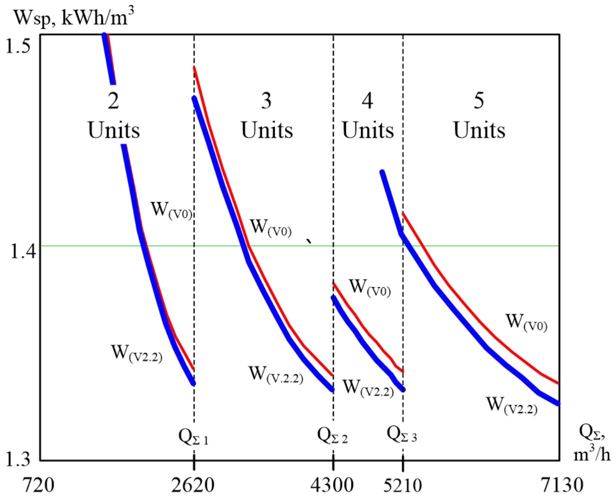

Fig. 7. Specific consumption of electrical power by PN-PS EC

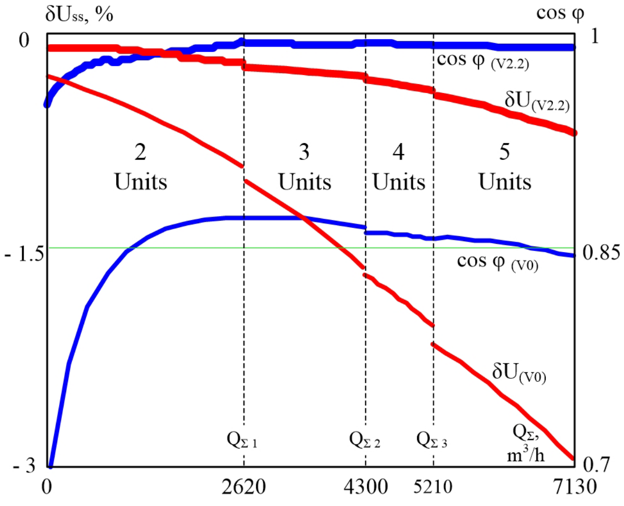

Fig. 8. Deviation of the voltage USS on HV buses of the transformer Ts and power factor of PN-PS EC

2. The mathematical model of PN-PS EC in steady-state modes obtained by combining the mathematical models of its subsystems, offers a broad functionality for a complex study of the indices of electrical and technological efficiency of the complex exposed to various disturbing effects, laws of formation of the controlling effects and ACS structures, and power supply and reactive power compensation schemes.

3. Based on the obtained results of the mathematical experiments, the rational scheme of the CPU power supply and wiring and the structure and algorithm of the microcontroller ACS functioning for fluid pumping in the whole range of the PS productivity at the stabilized inlet pressure were substantiated.

4. It was shown that the use of the developed circuit designs, systems and algorithmic solutions in comparison with the conventional base variant results in the improved indices of the electrical and technological efficiency of the studied PN-PS EC, in particular, in the specific consumption of active electrical power reduced by 0.3–0.4 %, power factor improved by 8–10 %, voltage deviation on the high-voltage buses of the transformer Ts reduced by 39–40 %, as well as consumption of the total and reactive powers reduced by 7.8 and 40 %, respectively. In addition, annual savings of 0.24–0.25 MW·h of the active power and 21.4–21.5 MW·h of the reactive power, respectively, are achieved.

The next stage of the research will consist in making the experimental sample of the developed automatic feedback control system for steady-state modes of PN-PS EC under consideration and in studying the efficiency indices during its testing operation.

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Енергоефективна система живлення та автоматичного керування режимами комплексу „електрична мережа – помпова станція“

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Мета. Розроблення схемотехнічних і алгоритмічних рішень для комплексного поліпшення показників електротехнологічної ефективності комплексу „електрична мережа – насосна станція“ („ЕМ-НС“), підвищення його енергоощадності, отримання раціональної структури та алгоритму роботи системи автоматичного керування режимами перекачування рідини.

Методика. Схемотехнічні та алгоритмічні рішення розроблені на основі порівняльного аналізу показників енергоефективності перекачування рідини за використання різних схем електричного живлення, сполучення силових електричних і гідравлічних кіл і способів керування продуктивністю відцентрових насосних (помпових) агрегатів, що отримані в серії математичних експериментів на розробленій математичній (комп'ютерній) моделі комплексу „ЕМ-НС“.

Результати. Розроблено схему електричного живлення й схему електричних і гідравлічних сполучень відцентрових насосних агрегатів, а також створено структуру та алгоритм роботи мікропроцесорної системи автоматичного неперервно-дискретного керування режимами перекачування рідини зі сталим тиском у трубопроводі на повному діапазоні зміни продуктивності комплексу „ЕМ-НС“.

Наукова новизна. Створена модель синтезу сигналу неперервно-дискретного керування режимами перекачування рідини відцентровими насосними агрегатами у структурі замкненої системи стабілізації тиску у трубопроводі.

Практична значимість. Використання розроблених схемних, системних і алгоритмічних рішень дає змогу поліпшити, у порівнянні із прийнятим базовим варіантом, основні показники електротехнологічної ефективності комплексу „ЕМ-НС“, зокрема, зменшити питомі витрати активної електроенергії, покращити коефіцієнт потужності, зменшити відхилення напруги мережі, а також зменшити споживання повної й реактивної потужностей, що призведе до суттєвого заощадження електричної енергії. Запропоновані рішення можуть бути використані як під час проектування нових, так і у процесі експлуатації діючих комплексів „ЕМ-НС“.

Ключові слова: *насосна станція, електрична мережа, енергоефективність, мікропроцесорна система, алгоритм керування*

Энергоэффективная система питания и автоматического управления режимами комплекса „электрическая сеть – насосная станция“

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Цель. Разработка схемотехнических и алгоритмических решений для комплексного улучшения показателей электротехнологической эффективности комплекса „электрическая сеть – насосная станция“ („ЭС-НС“), повышение его энергосбережения, получение рациональной структуры и алгоритма работы системы автоматического управления режимами перекачивания жидкости.

Методика. Схемотехнические и алгоритмические решения разработаны на основе сравнительного анализа показателей энергоэффективности перекачивания жидкости при использовании разных схем электропитания, соединений силовых электрических и гидравлических цепей, а также способов управления производительностью центробежных насосных агрегатов, которые получены в серии математических экспериментов на разработанной математической (компьютерной) модели комплекса „ЭС-НС“.

Результаты. Разработаны схема электропитания и схема электрических и гидравлических соединений центробежных насосных агрегатов, а также создана структура и алгоритм работы микропроцессорной системы автоматического непрерывно-дискретного управления режимами перекачивания жидкости с постоянным давлением в трубопроводе на полном диапазоне изменения расхода комплекса „ЭС-НС“.

Научная новизна. Создана модель синтеза сигнала непрерывно-дискретного управления режимами перекачивания жидкости центробежными насосными агрегатами в структуре замкнутой системы стабилизации давления в трубопроводе.

Практическая значимость. Использование разработанных схемных, системных и алгоритмических решений позволяет улучшить, по сравнению с принятым базовым вариантом, основные показатели электротехнологической эффективности комплекса „ЭС-НС“, в частности, уменьшить удельные затраты активной электроэнергии, улучшить коэффициент мощности, уменьшить отклонения напряжения сети, а также уменьшить потребление полной и реактивной мощностей, что приводит к существенной экономии электроэнергии. Предлагаемые решения могут быть использованы как при проектировании новых, так и в процессе эксплуатации действующих комплексов „ЭС-НС“.

Ключевые слова: *насосная станция, электрическая сеть, система, энергоэффективность, микропроцессорная система, алгоритм управления*

Рекомендовано до публікації докт. техн. наук О. Ю. Лозинським. Дата надходження рукопису 28.03.17.