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doi:10.15199/48.2019.12.32

The operation modes of a power-efficient system of control of a pumping plant variable-frequency electric drive

***Abstract**. The possibility of using two-parameter regulation in the system of a variable-frequency electric drive of a pumping plant, taking into account changes in the current parameters of the hydraulic network, is demonstrated. The characteristics of the pump and the pipeline network during adjusting the capacity and changing the position of the stopcock at the output of the pump unit in the pressure stabilization system at the consumer are given. A block diagram of the system of power-efficient pumping unit control is proposed. It allows adjusting the reference signal in accordance with the deviation of the parameters of the hydraulic network. The curves of changes in the technological and power characteristics of the pump with one-parameter and two-parameter regulation with variable water consumption are considered. The possibility of improving the power efficiency of a pumping plant by using two-parameter control with increased water consumption is shown. It is obtained that reducing the accuracy of pressure maintenance at the consumer makes it possible to improve the efficiency of the pumping plant.*

***Streszczenie:** W artykule wykazano możliwość zastosowania w pompowni regulacji dwuparametrowej w systemie napędu elektrycznego o zmiennej częstotliwości, z uwzględnieniem zmian aktualnych parametrów sieci hydraulicznej. Podano charakterystykę pompy i sieci rurociągów podczas dostosowywania wydajności i zmiany położenia zaworu odcinającego na wyjściu zespołu pompowego w układzie stabilizacji ciśnienia u odbiorcy. Zaproponowano schemat blokowy układu sterowania energooszczędną jednostką pompującą. Wykazano możliwość regulacji sygnału odniesienia zgodnie z odchyleniem parametrów sieci hydraulicznej. Uwzględniono krzywe zmian charakterystyki technologicznej i mocy pompy z regulacją jednoparametrową i dwuparametrową ze zmiennym zużyciem wody. Wykazano możliwość poprawy efektywności energetycznej pompowni poprzez zastosowanie sterowania dwuparametrowego ze zwiększonym zużyciem wody. Zmniejszenie dokładności utrzymania ciśnienia u konsumenta umożliwia poprawę wydajności pompowni.(**Sposoby działania energooszczędnego systemu kontroli napędu elektrycznego o zmiennej częstotliwości w pompowni**)*

Keywords: power-efficient control, variable-frequency electric drive, pumping plant, parameters of the hydraulic system.
Słowa kluczowe: sterowanie energooszczędne, napęd elektryczny o zmiennej częstotliwości, pompownia, parametry układu hydraulicznego.

Introduction

When regulating pumping plant (PP) parameters, the most efficient method consists in the variation of the rotation frequency of the pumping unit (PU) impeller by using a variable-frequency electric drive (VFED), built based on electrical devices with semiconductor elements [1]. It allows saving up to 30% of the consumed electricity [2] and up to 10% of the pumped liquid [3].

Automatic control systems (ACS) of PP VFED are actively introduced to solve the basic technological problem – maintenance of the required value of the head or discharge at the consumer. Extreme ACS providing the power-efficient operation of PU with the maximum possible efficiency of the pump have been widely used recently [4].

During operation, due to PP work under unsteady conditions (cavitation, surge), the head and discharge signals vary in time [5]. This results in the deviation of the parameters of the PU and the hydraulic network from their rated values, and, consequently, in the shift of the PC operating mode point, a decrease in PU efficiency, leading to premature wear of the pumping and pipeline equipment.

Therefore, when developing the PP VFED ACS, the search for power-efficient modes of operation of pumping units with changing water consumption and current parameters of the hydraulic system, is topical.

Research method

It is expedient to consider the possibility of using two-parameter regulation in PP ACS, where the required technological mode (for example, stabilization of pressure at the consumer) is provided by varying the rotation frequency of the pump motor, and power-efficient control – by correcting the hydraulic characteristic of the pipeline network via changing the resistance of the stopcock at PU output. Fig. 1 shows the head-discharge and power characteristics of the PU when the system of automatic control of parameters operates in the mode of pressure stabilization at the consumer. At the initial time moment PP operates at rotation frequency n_1, the values of head H_1 and discharge Q_1 at the pump output (Fig. 1, a, curve n_1, p. 1) and maximum possible efficiency η_1 (Fig. 1, b, curve n_1). In this case, the required value of pressure $H_{con} = const$ is maintained at the consumer (Fig.1, a, p. 1`).

Due to PU wear its head-discharge (Fig. 1, a, curve n_1') and power characteristics (Fig. 1, b, curve n_1') change, the pressure at the consumer decreases (p. $2'$ on curve $H-Q_{con1}$). To compensate for deviation ΔR_p VFED ACS forms a signal to increase rotation frequency $\omega(t)$ of the pump drive motor with efficiency move to point η_2' (Fig. 1, b, curve n_2').

The increase of water consumption is accompanied by the change of the position of the consumer head-discharge characteristic (Fig. 1, curve $H-Q_{con2}$) and, accordingly, of the total characteristic of the network (Fig. 1, curve $H-Q_{\Sigma 2}$). The operation mode point shifts to position 3 (Fig. 1, a, curve n_2'). To provide the required value of pressure $H_{con}(t)$ and regulation of feed $Q_p(t)$ in accordance with the water consumption diagram $R_{con}(t)$ VFED ACS increases the rotation frequency $\omega(t)$ of the pump drive motor, which results in the efficiency move to point η_3' (Fig. 1, b, curve n_3'). In this case value η_3' is on the right of the maximum possible value of the pump efficiency $\eta_{max} = 0.66$. The above said makes it possible to improve the pump efficiency via the change of the hydraulic characteristic of the pipeline network by regulating the stopcock position (Fig. 1, curve $H-Q_{net}'$). It results in the shift of the total characteristic of the network and, accordingly, of the operating mode point (Fig. 1, curve $H-Q_{\Sigma 2}'$, p. $4''$). In this case the pump efficiency moves to point η_4' (Fig. 1, b, curve n_4'), which provides the improvement of the system power efficiency.

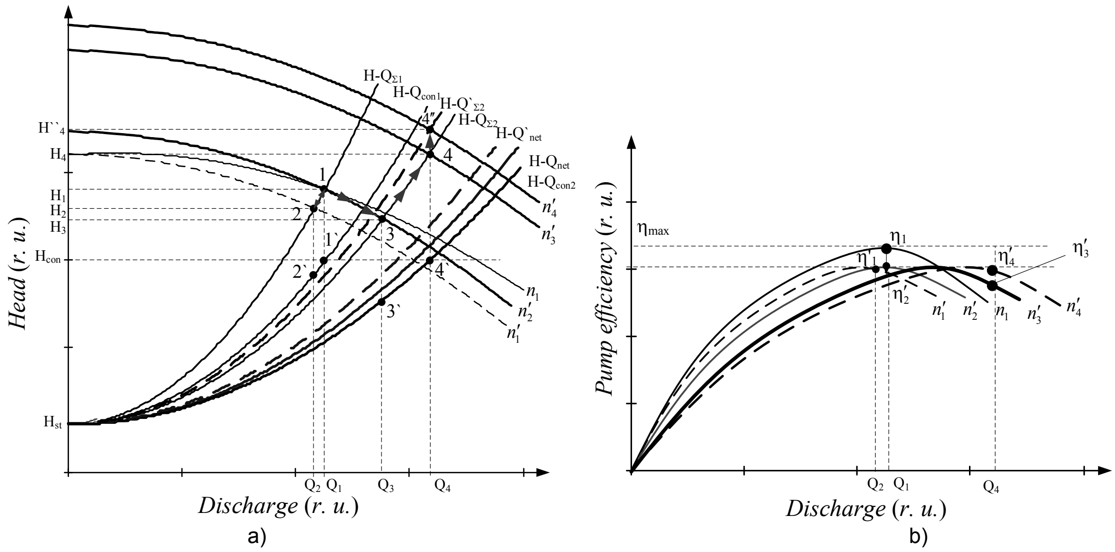

Fig. 1. Head-discharge a) and energy b) characteristics of the pump at two-parameter regulation of PP parameters:
$H-Q_{coni}$, $H-Q_{net}$ – the head-discharge characteristics of the consumer and the pipeline network, respectively; $H-Q_{\Sigma i}$ – the total head-discharge characteristic of the pipeline network; η_{max} – the maximum possible published data of the pump efficiency, respectively; H_{con} – the head at the consumer; H_{st} – the counter pressure in the pipeline network

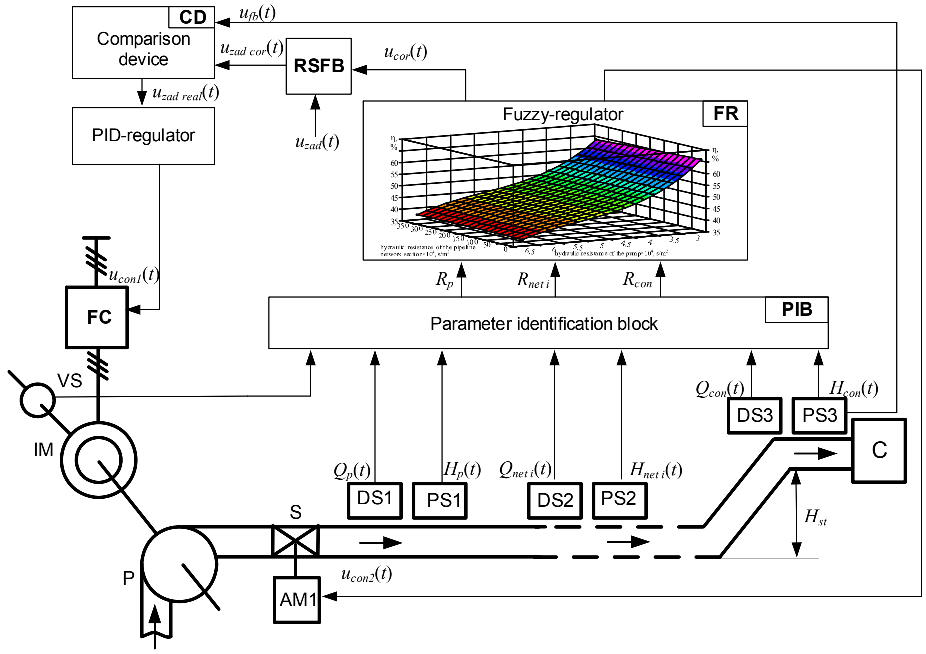

Fig. 2. A block diagram of PP VFED ACS with power-efficient control at the change of the hydraulic system current parameters

A block diagram of PP VFED ACS with power-efficient (two-parameter) regulation at the regulation of the current parameters of the hydraulic network and stabilization of the pressure at the consumer is shown in Fig. 2. It includes: a pump (P) with a drive induction motor (IM), a frequency converter (FC) with a built-in PID-regulator, a controlled stopcock (CS) with an actuating mechanism (AM), pressure sensors (PS1–PS3) and discharge sensors (DS1–DS3), a speed sensor (SS), a reference signal forming block (RSFB), a hydrosystem parameter identification block (PIB), a compare device (CD) and a fuzzy-regulator (FR).

When there are deviations of the parameters of pumping ΔR_p and pipeline $\Delta R_{net\,i}$ equipment from the rated values, a correcting signal $u_{cor}(t)$ is formed at the input of the task unit (TU) of the fuzzy-regulator, aiming to provide the required reference signal $u_{zad}(t)$ as part of ACS with pressure feedback $u_{fb}(t)$. Then reference signal $u_{zad\,real}(t)$ is sent to PID-regulator input and forms control signal $u_{con1}(t)$ at the frequency converter in order to change the rotation frequency of the pump induction motor, aiming at the maintenance of the required pressure at the consumer. In this case, it is possible to improve PU power efficiency by assigning control signal $u_{con2}(t)$ at the stopcock actuating mechanism at the pump output to change its position.

The block identifying the hydrosystem parameters $R_p(t), R_{net\,i}(t), R_{con}(t)$ described in [6], bases on the frequency analysis of the hydraulic power [7, 8], determined by multiplication of the relevant signals of head $H_i(t)$ and discharge $Q_i(t)$ at i – elements of the hydrosystem.

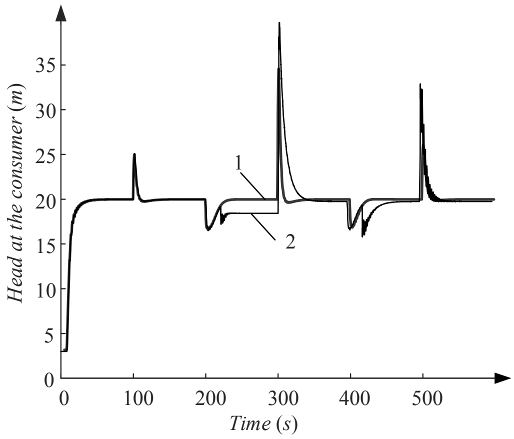

Fig. 3. Curves showing the head variation at the consumer at one-parameter (1) and two-parameter (2) regulation

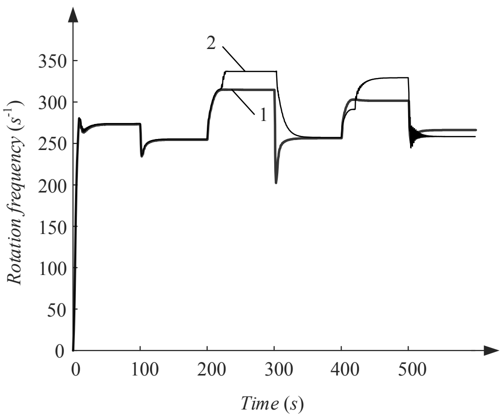

Fig. 4 Curves showing the variation of the drive motor rotation frequency at one-parameter (1) and two-parameter (2) regulation

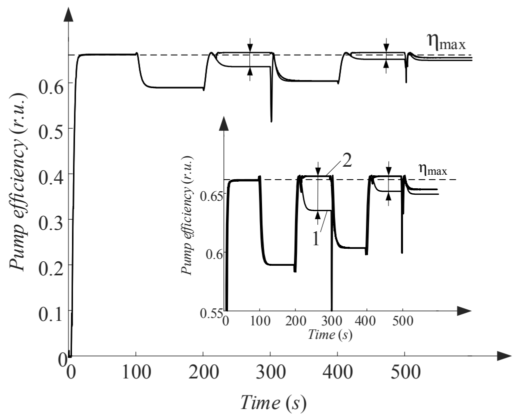

Fig. 5. Curves showing the variation of PU efficiency at the consumer at one-parameter (1) and two-parameter (2) regulation

To study the dynamic processes in PC with one-parameter and two-parameter regulation, a mathematical model is proposed. Its description is given in [9, 10]. To ensure the stabilization of pressure at the consumer, the model is supplemented with a PID-regulator, which generates a control signal on FC to change the rotation frequency of the pump induction motor.

Curves representing the variation of the drive motor rotation frequency $\omega(t)$, head $H_{con}(t)$ at the consumer and pump efficiency $\eta(t)$ in a VFED closed ACS at alternating water consumption are shown in Figs. 3–5. PP with the following parameters was taken for the research: motor $P_n = 7.5$ kW, $\omega_n = 301.6$ s^{-1}, $I_n = 15.12$ A, $M_n = 24.868$ Нм; pump – $Q_n = 0.013$ m^3/s, $H_0 = 32$ m, $H_n = 28$ m; pipeline network – $d = 0.1$ m, $l = 1000$ m.

It is obtained that the increase of water consumption at time moments $t_1 = 200$ s and $t_3 = 400$ s in case of using only one-parameter (frequency) regulation is accompanied by the decrease of the pump efficiency (Fig. 5, curve 1). When two-parameter regulation is used, PU efficiency improves, which is demonstrated by curve 2, Fig. 5.

As mentioned above, during operation, pumping and pipeline equipment is subjected to cavitation, hydraulic and mechanical wear, which results in changes of the parameters of the hydraulic system (resistance and reactance of the pump and pipeline). Therefore, to provide efficient control of PP, VFED ACS is to take into account the variation of the parameters of the electric and hydraulic equipment during the operation process.

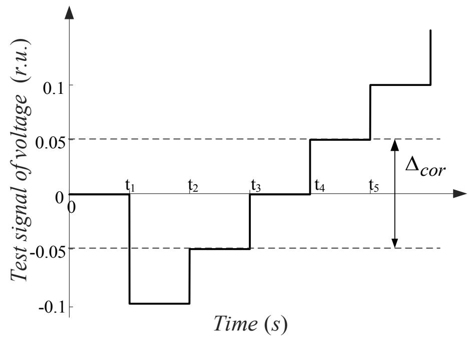

Fig. 6. A curve showing the time-variable test signal of voltage

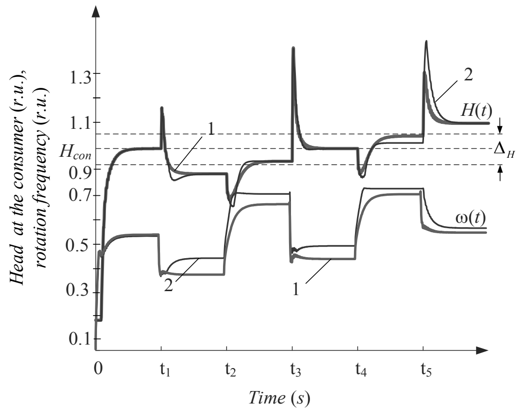

Fig. 7. Curves showing the time variation of head $H_{con}(t)$ at the consumer and drive motor rotation frequency $\omega(t)$: 1 – at one-parameter regulation; 2 – at two-parameter regulation

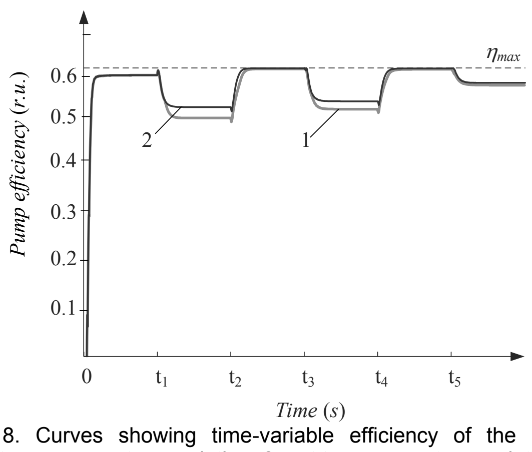

Fig. 8. Curves showing time-variable efficiency of the pump: 1 – at one-parameter regulation; 2 – at two-parameter regulation

Figs. 6–8 show the curves representing the change of the voltage test signal $u_t(t)$, which is equivalent to the deviation of the hydrosystem current parameters $R_p(t), R_{net\,i}(t)$ and curves representing the variation of the head $H_{con}(t)$ at the consumer and the pump efficiency $\eta(t)$ in VFED closed ACS.

The analysis of the obtained curves reveals that at the deviation of the hydrosystem parameters located within Δ_{cor} (Fig. 6), VFED ACS maintains the required value of pressure $H_{con}(t)$ at error $\Delta_H = 10\,\%$ admissible for technological problems of such type. If the parameter deviation exceeds Δ_{cor}, ACS does not operate the reference signal and goes beyond the limits of the admissible pressure change, which causes the necessity of the correction of reference signal $u_{zad\,real}(t)$, formed at the input of PID-regulator of the frequency converter. It allows improving PU efficiency with a certain decrease of accuracy of maintaining the pressure at the consumer.

It is seen in Fig. 8, that water consumption increase at time moments t_1 and t_3 is accompanied by the possibility of the improvement of PU power efficiency by application of two-parameter regulation. This is especially important in the problems of improvement of PP power management in unsteady modes of operation, which are accompanied by the emergence of various wave processes in the pipeline network and result in time variation of the technological parameters (head, discharge and flow rate) of the hydraulic system [11].

Conclusions

The expediency of using two-parameter regulation (by changing the motor rotation frequency and the position of the stopcock at the pump output) in the system of the variable-frequency drive of the pump plant, when the pressure in the pipeline network stabilizes and the hydraulic system parameters are changed during operation, has been substantiated. The structure of the power-efficient automatic control system of the pump electric drive has been proposed. It performs correction of the reference signal to the frequency converter to compensate for deviations of the hydraulic system parameters from the rated values. The possibility of improving the power efficiency of a pumping plant by correcting the characteristic of the pipeline network in the event of an increase in water consumption and a shift in the efficiency of the pump to the area of large feeds has been shown.

Acknowledgements

Some materials were gathered within the NAWA Programme - International scholarship exchange of PhD students and academics, PPI/PRO/2018/1/00010/U/001.

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