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Control of energy-efficient electric drive of pumping stations

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Abstract. The principles of pumping station control, providing the most efficient modes of operation are discussed in the article. To perform calculations of energy-efficient operation modes, a mathematical description of the system has been proposed. It is shown that the increase of energy efficiency in the system is achieved by choosing a power circuit, splitting up sections of the pumping station, selecting the appropriate operation algorithms for each of the sections. An electrical equivalent circuit of the control object is proposed. Comparison of the energy consumption of the pumping station was carried out for the following cases: in the first, the cascade did not work, and in the second, the flow was controlled in a cascade over the entire range of flow variation. It is established that the proposed control algorithms can significantly reduce energy consumption from the mains supply by about 30%.

1. Analysis of electric drive operating modes

At the booster pumping station, which provides water supply to the residential area of the city, two identical pumping units of the D2000-100s type work in parallel. The centrifugal pump of the first unit is driven by an asynchronous closed-loop motor (AI-450x6), the stator circuits of which are fed directly from the industrial network. The pump of the second unit is driven by an asynchronous motor with a phase rotor included in the scheme of the valve stage [1].

The functional diagram of the valve cascade (figure 1) includes an asynchronous motor with a phase-rotor M, an unmanaged rectifier R, a smoothing choke L, a network-driven inverter I, and a transformer T.

To assess the energy efficiency of the valve stage in the pumping unit, the values of the monthly electricity consumption of the pumping station, measured in different years, were compared, but so that in the first year the valve stage did not work, and the value of the flow of both pumps was regulated only by valves [2, 3], in the second year the cascade was included, the flow was regulated both by the valve of the first pump, and by changing the speed of the asynchronous motor in the valve stage scheme with the fully open hydraulic path of the second pump [4, 5].

To evaluate the energy performance of the electric pump station with the selected method of flow control at its output give pressure-flow characteristics with separate inclusion of each of the pumps (curve 1 in figure 2) and their parallel operation (curve 2 in figure 2). Characteristics of the hydraulic network is represented by curve 3, static head $H_{ST} = 30$ m.

The maximum possible flow rate at fully open valves of both pumps connected in parallel corresponds to point a, while $Q_A = 4250$ m³/h. One pump operating on a fully open hydraulic network is able to provide a flow rate $Q_B = 3000$ m³/h (point b of intersection of curves 1 and 3 in figure 2). In the process, the flow rate varies in the range from $Q_{min} = 1500$ m³/h at night to $Q_{max} = 3500$ m³/h in peak hours.



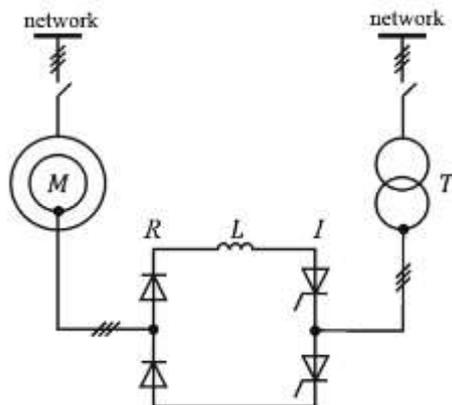


Figure 1. Functional diagram of the valve cascade.

The flow from Q_{min} to Q_b possible to implement one pump, moving along the curve 3 in the interval c-b. This is energetically the best way, when the losses in the hydraulic network is minimal [6, 7]. It can be provided by adjusting the angular velocity of the pump shaft valve stage [8]. You can adjust the flow within the same limits, moving along curve 2 on the segment d-e-h, which is realized by means of valves. This is the energetically most disadvantageous method, which entails the greatest losses in the hydraulic network [9, 10]. The value of additional losses due to the operation of the valves is proportional to the vertical distance between the curves 1 (or 2) and 3 at a fixed flow rate [11].

To ensure flow rates from Q_b to Q_{max} , both pumps must be turned on [12]. Energetically the most favorable mode is achieved with fully open valves. When the flow rate is maximum (i.e. $Q_f = Q_{max}$), the first pump provides the flow Q_g , and the flow rate of the second corresponds to the segment g-f. As the flow rate decreases with fully open valves, it is necessary to move along curve 3 on segment f-b, reducing the angular velocity of the shaft of the second pump by means of a valve cascade [13, 14]. At point b, the flow rate of the second pump will drop to zero and the check valve will operate [15, 16].

Regulation of the flow rate in the range from Q_b to Q_{max} can be done without reducing the angular velocity of the shaft of the second pump [17, 18]. In this case it is necessary to work only with latches, moving on a curve 2 on a segment of e-h. It is energetically unprofitable way, it should be avoided [19].

In reality, the entire operating range of flow control from Q_{min} to Q_{max} was divided into three zones [20]: at low flow rates, only the second pump worked according to the valve stage scheme with the first pump switched off (the valve is closed); at large water consumption, the flow was also regulated by changing the angular velocity of the second pump by the electric valve stage, but the valve of the first pump was completely open; the second zone is intermediate, in this zone regulation is carried out both by the valve and valve stage. Work in the second zone is provided for smooth switching of pumps from the first zone to the third and back [21, 22].

2. Mathematical description of the system

The peculiarity of the booster pump station is that the water consumption is regulated directly by the population of the residential area. At night consumption is falling, and during peak hours morning and evening increases dramatically. The decrease in consumption corresponds to the increase in resistance at the outlet of the hydraulic network, as shown in figure 3 taken into account by characteristic 4. In order to reduce water losses from leaks in the hydraulic network, the service personnel of the pumping station controls not only the flow rate, but also the pressure at the outlet of the pumping station [23].

Work in the first zone is carried out at night (from 1 to 5 hours) in order to maintain the pressure in the network within the range of 35 to 45 meters [24, 25]. Work in the third zone is carried out in the morning, afternoon and evening hours (from 6 to 24 hours), when the pressure in the network is maintained in the range from 65 to 75 meters [26].

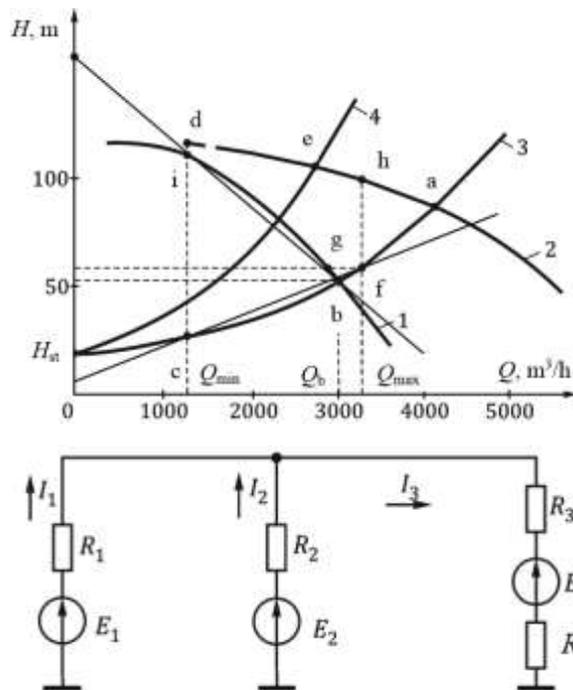


Figure 2. Pressure-flow characteristics the separate inclusion of each of the pumps.

Figure 3. Electrical circuit replacement.

The modes of operation of the hydraulic network when changing the flow rate is conveniently shown using its electrical equivalent circuit (figure 3). In the diagram, the EMF values E_1 and E_2 correspond to the maximum values of pressure that are created by the first and second pumps at zero water flow [27, 28]. In this case, $E_1 = \text{const}$, since the angular velocity of the first pump is not adjustable; $E_2 = \text{var}$, since the angular velocity of the second pump is governed by a valve stage. Resistances R_1 and R_2 take into account the pressure drop at the outlet of each of the pumps, due to losses in the pump and valve. In the hydraulic network, the EMF E_3 corresponds to a static head, the resistance $R_3 = \text{const}$ takes into account losses in the pipeline, and the resistance $R_H = \text{var}$, takes into account the unevenness of consumption by consumers. The supplies Q_1 and Q_2 of pumps in the diagram are taken into account by currents I_1 and I_2 , and the flow rate Q_3 in the network is taken by currents I_3 .

It is more convenient to make calculations in relative units [29, 30]. Before selecting the basic values of the variables, linearization of the static characteristics of the pumps and the hydraulic network was performed [31]. The slope of the rectified characteristics corresponded to the range of flow changes in the hydraulic network in the range from Q_{\min} to Q_{\max} : the real characteristic of each of the pumps was replaced by a direct b-i, and the static characteristic of the hydraulic network direct c-f (see figure 2). The numerical values of the basic values of the variables are shown in table 1.

In table 1 the following notation for base values is taken:

- Q_N – nominal pump flow, respectively I_n – nominal current;
- H_0 – pump head with the valve closed (at zero flow), respectively, E_0 is the current source voltage;
- $h_0 = H_0/Q_N$ - loss of pressure in the pipeline, when the pressure H_0 creates a flow Q_N ; $R_0 = E_0/I_N$ - resistance in the electric circuit, when the EMF E_0 creates a current I_N .

Table 1.

1. Hydraulic variables of the network	Q_1, Q_2, Q_3	H_1, H_2, H_3	h_1, h_2, h_3
1.1. Basic unit	Q_N	H_0	h_0
1.2. Numerical value, dimension	2000 m ³ /h	110 m	55 m

2. Variables of an electric network	I_1, I_2, I_3	E_1, E_2, E_3	R_1, R_2, R_3
2.1. Basic unit	I_n	E_0	R_0
2.2. Numerical value, dimension	2000 A	110 kV	55 Ohm

The basic values of all EMF corresponded to the point of intersection of the straight b-i with the vertical axis (the mode of ideal idling of the pump). In this case $E_{1B}=E_{2B}=110$ kV. The basic value of the currents was taken numerically equal to the nominal flow of each of the pumps:

$$I_{1B} = I_{2B} = I_{3B} = 2000 \text{ A.}$$

The relative initial values of the variables and parameters on the equivalent circuit were adopted as follows [32].

The relative values of resistance were determined as follows. Resistance of pipeline section 1 between the first pump and the collector [33]

$$R_1 = \Delta U_{1REL}/\Delta I_{1REL} = \Delta U_{1ABS} \cdot I_{1B}/(U_{BAS} \cdot \Delta I_{1ABS}) = 0,2.$$

When controlling the flow rate with a valve, the resistance value R_1 increases from the specified value (valve is fully open) to infinity (valve is fully closed). Since the pumps are completely identical, and the second valve is fully open, $R_2 = 0.2$. Pipeline resistance hydraulic network

$$R_3 = \Delta U_{3REL}/\Delta I_{3REL} = \Delta U_{3ABS} \cdot I_{3B}/(U_{BAS} \cdot \Delta I_{3ABS}) = 0,1.$$

The load resistance R_N is taken to vary in the range from zero to infinity. Here the first limit corresponds to the maximum water consumption, and the hydraulic resistance of the consumer is related to the pipeline. The second limit corresponds to the ideal case when the pipe at the entrance of the consumer is completely blocked and there are no leaks in the pipeline [34, 35].

Solving Kirchhoff equations for an electrical circuit (look figure 3), we obtain the following expressions for currents:

$$I_1 = \frac{(E_1 - E_2) \cdot (R_3 + R_N) + (E_1 + E_3) \cdot R_2}{R_2 \cdot (R_3 + R_N) + R_1(R_3 + R_N) + R_1 \cdot R_2};$$

Voltage U_1 corresponds to the pressure at the input of the hydraulic network: $U_1 = 6000$ V.

3. Calculation of electricity losses. The choice of laws controlling the pumping station electric drive

Compared with the previous case, the considered pumping station has the following features: firstly, the entire working range of water flow control can be provided by only two pumps, with one pump driven by an unregulated drive, and the speed of the second is changed by means of a valve stage; secondly, the pumping station works for the end user, who himself chooses the amount of water consumption he needs, which is taken into account by the additional resistance R_N (see figure 3). As a result, the energy performance of the electric drive of the entire pumping station is useful to calculate and compare in the following cases:

- Full range flow control from Q_{min} to Q_{max} only be ensured by the valves. There are two possible modes of operation of the valves in the first range changing the flow rate from Q_{min} to Q_b one pump is shut off, and the flow rate in the network regulating valve of the second pump by moving the operating point on the trajectory i-b on the curve 1. At point b, when the valve of the second pump is opened completely to increase the water supply to Q_{max} , it is necessary to open in addition to the second and the first pump, gradually opening its valve and thereby moving to one of the characteristics located between curves 1 and 2.
- The second mode of valve control involves their parallel operation in the entire range of flow control. The working point moves along the d-h curve (see figure 2).

- Full range flow control from Q_{min} to Q_{max} can provide jobs cascade. At the same time on the site c-b (see figure 2) only the stage works, and the valve of the first pump is completely closed. In the section b- f the first pump operates with the maximum possible supply with the valve fully open, and the additional flow is provided by a cascade. This is the most energetically favorable regime, which is characterized by curve 3 (see figure 2).

At the pumping station, the duty officer keeps a log of daily reports, where every hour notes the arrival of water and the water level in the tanks. On the basis of these data, daily schedules of water consumption were constructed (figure 4).

To estimate the electricity consumption from the grid with different flow control methods, curves were constructed (see figure 5), which were calculated according to the following formulas:

- hydraulic power of pumping unit

$$P_{hyd} = \frac{\rho \cdot g}{3600} \cdot \sum_{i=0}^{24} H_i \cdot Q_i,$$

where i is the number of hours of the day on the daily water consumption chart (see figure 4); H_i , Q_i - head and flow values within an hour with the number i ;

where η_{Σ} is the total efficiency taking into account losses in the electric drive, pump and pipeline.

Since different H_i values were required for each fixed flow rate Q_i depending on the chosen control method, the values of electricity consumption also differed, as shown in figure 5 corresponded to the following curves:

- electric power consumed from the network

$$P_{el} = \frac{P_{hyd}}{\eta_{\Sigma}},$$

- curve 1 corresponded to the ideal case in which only losses in the pipeline were taken into account (curve c-b-f in figure 2), and losses in the electric drive of pumps were accepted equal to zero;
- curve 2 corresponded to the flow regulation according to curve c-b-f (see figure 2), but the losses in the cascade of the asynchronous electric drive and in the pump were taken into account;
- curve 3 corresponds to the case in practice, when on the segment i-b, the valve of the pump, controlled by the cascade, is closed, and the flow control is carried out by the valve of another, unregulated by the speed of the pump. On the b-f segment, both pumps operate with fully open valves, and the flow rate is regulated by a cascade;
- finally, the curve 4 corresponds to the case when both pumps are constantly switched on, and the flow rate is regulated only by valves.

Using curves (figure 5) the monthly consumption of electricity by the electric drive of the pumping station was calculated for different methods of regulating the water supply.

4. Conclusion

The laws governing the pumping station, providing improved energy performance of the system proposed in the article. It is proved that a significant reduction in energy consumption is achieved with separate control of regulated and unregulated electric drives. It is shown that the developed algorithms can reduce energy consumption by about 30%. The proposed effect is achieved both by applying special control laws for an adjustable electric drive and by selecting the operating modes of an unregulated electric drive that connects to the system when the load increases more than half of the nominal one.

The considered control laws were successfully applied at the boost pumping station, installed on the site of Energochel LLC. It was experimentally confirmed that the annual effect of saving electricity in ruble terms was more than 15,000,000 rubles.

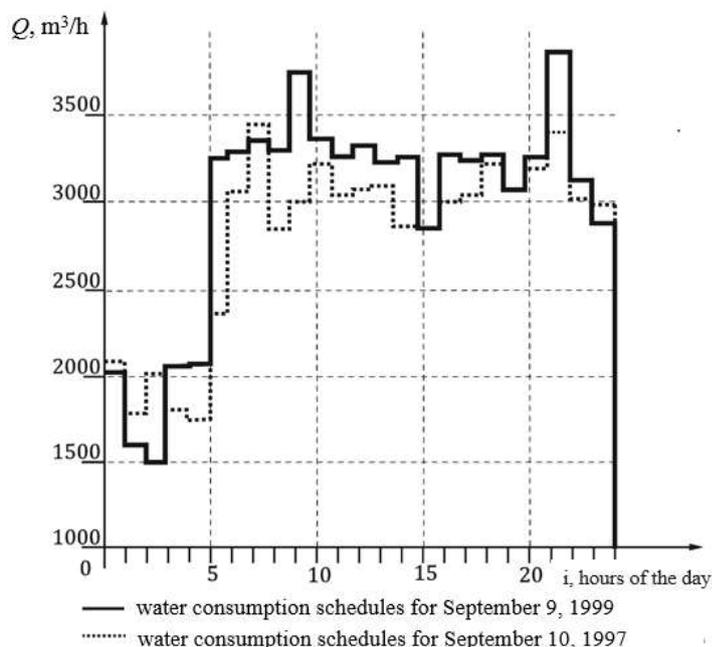


Figure 4. Daily water consumption schedules.

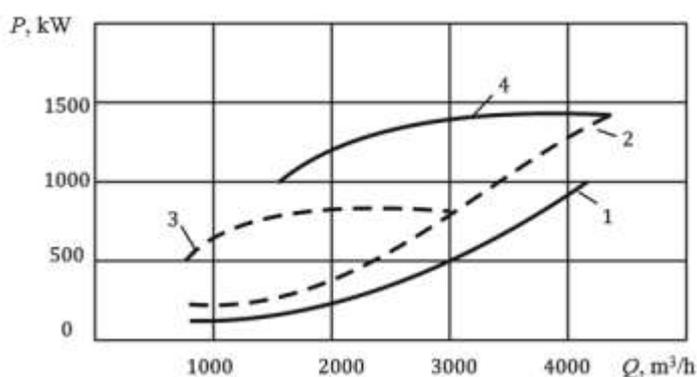


Figure 5. Electricity consumption from the network at different flow control methods:
 1 - perfect way;
 2 - valve cascade throughout range;
 3 - valve on one pump;
 4 - valve on two pumps.

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