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DEVELOPMENT OF AN AUTOMATIC CONTROL SYSTEM FOR A PUMPING UNIT BASED ON A FREQUENCY-CONTROLLED ELECTRIC DRIVE

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Abstract: This paper considers the development of an automatic control system for a pumping unit based on a frequency-controlled electric drive. The feasibility of using frequency converters to regulate the performance of centrifugal pumps in water supply systems is substantiated. The main laws of frequency regulation of electric drives are presented, the operating modes of asynchronous and synchronous motors are analyzed, and a structural scheme of the automatic control system for a pumping unit is proposed, ensuring increased energy efficiency and operational reliability.

Keywords: pumping unit, frequency-controlled electric drive, frequency converter, automatic control, energy saving.

Introduction. Pumping stations represent a rather complex electro-hydraulic technical system of facilities and equipment in which electrical energy is converted into the mechanical energy of a fluid flow, and this process is controlled. The main purpose of pumping stations (PS) in water supply systems is to provide [1]:

- the required water supply schedule in normal operating modes of the pump units;
- the required level of reliability and a certain degree of uninterrupted operation;
- minimal costs for equipment and operation;
- durability corresponding to the technological importance of the facilities to which they belong;
- ease of operation (widespread use of automatic control of pump units with adjustable electric drives).

At the current stage of development of adjustable electric drive systems for general industrial mechanisms, frequency regulation has become a serious alternative. A widely recognized method of their regulation is the frequency control method, whose main tasks are:

- stabilization and optimization of technological parameters dependent on the operation of the electric drive;
- smooth acceleration and braking of the drive load;
- saving electrical energy by reducing consumed power;
- automation of technological processes by creating closed-loop systems capable of precisely maintaining set technological parameters;
- coordinated control of multiple drive motors from a single frequency converter;
- increasing the service life of the electric drive and equipment.

Methods and Materials. From an energy perspective, the most effective method of regulating centrifugal pump delivery modes is by controlling the rotational speed of their impellers. The rotational speed can be adjusted in various ways; however, for building automatic control systems for pump units, the most convenient and efficient method is an adjustable electric drive, which typically consists of a drive motor, a transmission mechanism, and a control system. In practice, water supply systems exclusively use asynchronous (induction) and synchronous motors as drive motors for pump units. Small and medium-power pumping units are usually equipped with squirrel-cage asynchronous motors. High-power pumping units often use synchronous motors.

It is known that the angular velocity of an asynchronous motor is determined by the expression:

$$\omega = \frac{2\ \pi\ f_1\left(1-s\right)}{p_n}\ , \qquad (1)$$

where
f – supply network frequency;
s– slip of the asynchronous motor;
p – number of pole pairs of the motor.

Expression (1) clearly defines the methods of controlling the angular speed (rotational frequency) of an asynchronous electric motor:

- by changing the frequency of the current in the stator circuit of the asynchronous motor, for which frequency converters are used;
- by changing the slip of the asynchronous motor, for which cascade circuits with counter-EMF in the rotor circuit are used;
- by changing the number of pole pairs, for which schemes of switching the stator windings of the asynchronous motor are used, allowing the number of pole pairs to be altered.

Speed regulation of asynchronous and synchronous motors by changing the supply voltage frequency is the most economical and efficient method. In frequency regulation, the slip of the induction motor, regardless of the regulation range, remains relatively small, and the losses in the motor are minimal.

When using a frequency converter together with an asynchronous or synchronous motor, in addition to frequency regulation, it is necessary to regulate the voltage in the stator circuit. This is because, when the frequency changes, the magnetic flux of the electrical machine varies inversely with the supply frequency. Therefore, when the frequency drops below the nominal value, the magnetic flux of the motor increases, which, in turn, leads to saturation of its magnetic core and a sharp rise in magnetizing current. Conversely, increasing the frequency in the electrical machine while keeping the applied voltage constant leads to underutilization of the motor.

Academician M.P. Kostenko formulated the law of frequency regulation:

$$\frac{U}{U_н} = \frac{f}{f_н}\sqrt{\frac{M}{M_н}} \qquad (2)$$

If the relationship (2) is strictly followed, the drive motor of the pump unit will operate with an almost constant stability factor, unchanged power factor (cosφ), constant absolute slip, and efficiency depending only on the frequency change and not on the change in torque on the motor shaft, provided that the saturation of its magnetic system is not too high.

Results. The conditions for regulating the rotational frequencies of asynchronous and synchronous electric motors, which must be strictly observed when changing the frequency of their supply voltage, are presented in Table 1.
Table 1

Law of Frequency Regulation	$\frac{M}{M_{н}}$	$\frac{U}{U_{н}}$	$\frac{P}{P_{н}}$	$\frac{Ф}{Ф_{н}}$	$\frac{I}{I_{н}}$
At constant power: $M = M_{н} (f_{н}/f)$	$\frac{f_{н}}{f}$	$\sqrt{\frac{f}{f_{н}}}$	const	$\sqrt{\frac{f_{н}}{f}}$	$\sqrt{\frac{f_{н}}{f}}$
At constant torque: $M = M_{н} = const$	const	$\frac{f}{f_{н}}$	$\frac{f}{f_{н}}$	const	const
At constant torque:	${\frac{f}{f_{н}}}^{2}$	${\frac{f}{f_{н}}}^{2}$	${\frac{f}{f_{н}}}^{3}$	$\frac{f}{f_{н}}$	$\frac{f}{f_{н}}$

At present, thyristor and transistor frequency converters are used in adjustable electric drives with asynchronous (AD) and synchronous (SD) motors. These converters can be divided into the following three groups:

- Direct frequency converters (DFC);
- Two-stage frequency converters with an autonomous voltage inverter (FC with AVI);
- Two-stage frequency converters with an autonomous current inverter (FC with ACI).

Two-stage frequency converters have an intermediate DC link.

For small- and medium-power pumping units, asynchronous frequency-controlled drives are used, while high-power units typically use synchronous frequency-controlled drives. The development of semiconductor technology and microelectronics has enabled the electrical engineering industry to create frequency converters for asynchronous and synchronous drives (FC–AD and FC–SD systems) with control quality comparable to DC drives. Modern frequency-controlled electric drive systems feature high energy efficiency, a wide control range, and can be used with various control structures [2]. The most widely used frequency converters are those with a DC link (two-stage frequency converters), which contain a controlled or uncontrolled rectifier (first stage) and an autonomous inverter (second stage). When a controlled rectifier is used as the first stage, it performs the function of forming the output voltage of the frequency converter or provides protective functions. If an uncontrolled rectifier is used, the function of forming the output voltage is assigned to the autonomous inverter. In addition, the autonomous inverter generates the output frequency of the frequency converter, whether a controlled or uncontrolled rectifier is used. Voltage and frequency control in frequency converters enables the formation of various frequency regulation laws. Pumps have a mechanical characteristic described by a quadratic parabola. Therefore, according to M.P. Kostenko's law of frequency regulation (Table 1), the frequency-controlled electric drive must ensure the regulation of the drive motor of the pump unit according to the fan law**.**

$$\frac{U}{f^2} = const \quad \text{или} \quad \frac{E}{f^2} = const$$

where
U – voltage of the stator circuit;
f – frequency of the current in the stator circuit;
E – EMF of the stator circuit.

The law (3) of frequency regulation is widely used in frequency converters with an autonomous voltage inverter. The mechanical characteristics of an asynchronous motor under the fan law of frequency regulation for a pump unit are as shown in Figure 1.

Figure 1. Mechanical characteristics of a frequency-controlled electric drive of a pump unit in the FC–AD scheme with an autonomous voltage inverter (AVI)

Figure 1 shows a typical mechanical characteristic of a centrifugal pump, as well as the main operating section of the family of mechanical characteristics of an asynchronous motor at various stator current frequencies. In this case, the torque and angular speeds of the frequency-controlled electric drive of the pump unit are determined by the operating points at the intersections of the motor and centrifugal pump mechanical characteristics. During the operation of drive motors in pumping units at frequencies up to 50 Hz, the frequency regulation law in accordance with expression (3) is applied. However, when operating at frequencies above 50 Hz, a different frequency regulation law must be used. This is due to the fact that the drive motor of the pump unit has limited power, determined by its rated parameters. Achieving higher values of angular velocity and electromagnetic torque as the stator frequency increases becomes impossible; therefore, at frequencies above 50 Hz, the torque must be limited. This can be implemented through the frequency regulation law at constant power (P=const). This law of frequency regulation can be realized using a control system for a frequency converter with an autonomous voltage and current inverter, by weakening the magnetic field of the pump drive motor. Since the maximum torque of the asynchronous motor decreases as the frequency rises (above 50 Hz), a limit on angular velocity is reached, as shown in Figure 1. The upper angular velocity limit defines the maximum range of speed regulation and depends on the mechanical characteristic of the centrifugal pump. As practice with pumping units and water supply systems shows, the vast majority of operated pump units work at angular speeds lower than their rated values; therefore, the upper angular velocity limit does not prevent the use of frequency-controlled drives in pumping stations. Control systems for hydraulically intensive water supply equipment, with pump units working together in pumping units, can be classified as multivariable parametric automatic control systems [3]. The construction of closed-loop automatic control systems (ACS) for individual regulation loops belongs to classical automatic control theory, whose foundations were laid by I.A. Vyshnegradsky, A. Stodola, and J.C. Maxwell. This theory features relatively simple control objectives: maintaining or changing controlled variables according to a set law, generating deviation signals, etc. A rigid control algorithm is used, primarily implementing the principle of feedback. All features of this approach are applied in building ACS for pumping units based on frequency-controlled pump drives, implementing smooth start, stop, and the water supply process. Feedback signals are taken from pressure sensors installed on the discharge pipelines, and by smoothly regulating the pump unit performance, equality is maintained between the required water supply schedule and its delivery (Figure 1). The proposed scheme of a frequency-controlled pump drive, through automatic smooth start and management of the water supply process, operates as follows: Sequential smooth starting of the water-lifting pump units equipped with squirrel-cage asynchronous motors and connected for parallel operation in a common discharge pipeline network, prevents sharp dynamic impacts on their hydraulic mechanisms. This is carried out with open discharge valves V3 and V4 and a closed discharge valve V2. When connecting the pumping unit to the power network and closing contact KM-1.2, the drive motor (M1) of pump unit H-1 starts smoothly, powered by a regulated-frequency voltage (f=var Hzf = \text{var Hz}f=var Hz) from the frequency converter (FC). Upon reaching the nominal FC frequency, the control system (CS), by measuring and processing signals from pressure sensors (DDS and DD1), ensures the smooth loading of pump H1 by closing the bypass valve V4 to prevent idle water discharge, based on a signal from the motorized valve control unit (BUMZ).

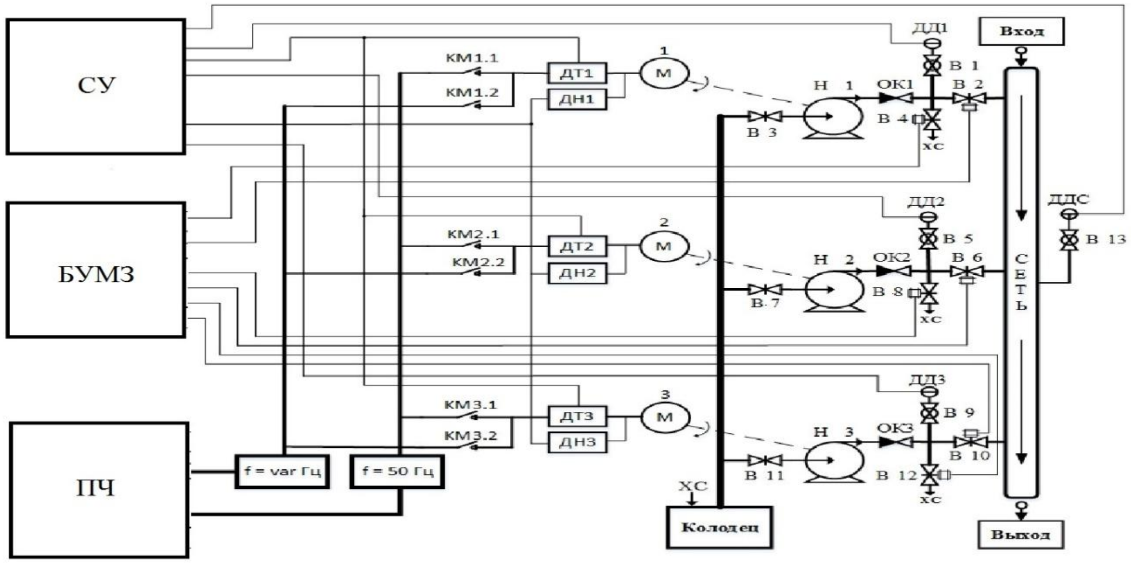

Figure 1. Diagram of the automatic control system for a pumping unit using a frequency-controlled electric drive for the pump units.

When the set nominal pressure value is reached at sensor DD1, installed before the common discharge pipeline network, a signal from the motorized valve control unit (BUMZ) opens valve V2. This allows a smooth, shock-free startup of pump unit H1 within the pumping unit (PU). Subsequently, the performance of H1 is regulated by the control system (CS) through measuring and processing the signal from pressure sensor DDS, installed on the main discharge pipeline of the PU. If the signal from DDS does not reach its preset maximum and the FC frequency equals the supply frequency (f=50 Hz), the CS triggers, sending a command to close contact KM-1.1 and open contact KM-1.2. In this case, similar to the procedure described above, the second pump unit H2 and any subsequent pump unit H3 within the PU are started. Shutdown of the pump units is performed in the reverse order, in a smooth stop mode.

Discussion. As the set pressure value in the main discharge pipeline is reached, the control system, using the feedback signal from sensor DDS, adjusts the supply voltage frequency of the pump drive motors within the specified range of FC frequencies [4]. This ensures changes in the rotational speed of the centrifugal pumps and their required flow rate. For example, when water demand changes in a drinking water supply system, the CS, using feedback from the pressure sensor, will start or stop one of the pump units within the PU and maintain the required water supply automatically via the FC. Automatic control of the PU water supply process, by maintaining the required pressure in the main pipeline and smoothly adjusting pump performance via frequency-controlled drives, allows for rational use of hydraulic energy resources by saving supplied water at each regulation stage. It also reduces the specific electrical energy consumption per unit of pumped water and practically eliminates hydraulic shocks in the "pump–discharge network" system. It should also be noted that to maintain even operating hours among pump units, the smooth start sequence can be set in any order of connecting pump units within the PU.

Conclusion. The main advantages of the proposed scheme are:

- Safe automatic smooth startup of pump units into the common discharge network;
- Increased operational reliability of the pumping installation;
- Improved energy efficiency of the pump drive motors during the regulation of water supply in the technological process.

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