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FREQUENCY ADJUSTMENT OF WELL PUMPING EQUIPMENT

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Abstract:

Objective. improve energy efficiency by adjusting the frequency of well pumping equipment.

Methods. Frequency adjustment, thermal image management, analytical analysis, energy-efficient operating modes of pumps, reliability indicators.

Results. Based on equations (1) - (42) in the MatLab/Simulink program, the simulation model of the "Autonomous voltage inverter - asynchronous electric motor with a short-circuited rotor - centrifugal pump" system was developed.

Conclusion. This computer model confirmed the hypothesis that it is possible to reduce the energy consumption of the well pumping system by adjusting the rotation frequency of the electric motor rotor by adjusting the supply frequency in scalar systems of frequency converters at the same mains frequency..

Keywords: Frequency adjustment, asynchronous motor, water supply system, well pumping equipment, electric drive, computer model, MatLab/Simulink.

Introduction. It is effective to use frequency-adjustable electric drives in automated control systems (ACS) of well pumping equipment to adjust the operating mode of the well pump to the operating mode of the delivered liquid supply system, for example, the network of an industrial enterprise.

Industrial water consumption is constantly changing depending on process requirements. Water consumption is determined by the laws of random-probability. Constantly adjusting the operating mode of the pumping equipment to monitor such changes increases efficiency.

The adjustment process is complicated by the imbalance between well pumps connected directly to the network and water consumption. The characteristics of well pumps are that as water consumption increases, the pressure developed by the pump in pipelines decreases. On the contrary, with a decrease in water consumption, the pressure in pipelines increases. Therefore, in periods of reduced water consumption, water supply systems create excess pressure. To keep the pressure in the supply systems at the same level, it was done by changing the number of pump units, changing the opening level of the valves in the pipelines, or adjusting the speed of the pump unit. The most effective of these is adjusting the speed of the pump unit [1].

The development of the water supply system includes the use of frequency converters and specialized control algorithms that can maintain the pressure level set in the supply network within certain limits [2]. In addition, by adjusting the "asynchronous motor - pump - pipe" system based on electric drive with a frequency converter, it helps to optimize the pressure in the water network and reduce the probability of pipe breaks [3].

The purpose of this research work is to develop a method for evaluating the energy saving potential by reducing excess water pressure and electrical losses when adjusting the operation modes of the pump equipment based on the frequency converter.

Methods. According to the information in the article [4], 58.9% of the produced water is consumed due to the demand of the technological process, and the remaining 41.1% is wasted (Fig. 1). In this regard, the average amount of water produced per day is 65.5 m3·h, of which 38.6 m^3·h is used for consumption, and the remaining 26.9 m^3·h is discharged into the sewage pipeline. The reason for the waste of produced water is the unevenness of the water consumption regime, and this method is used to adjust the pressure in the pipe.

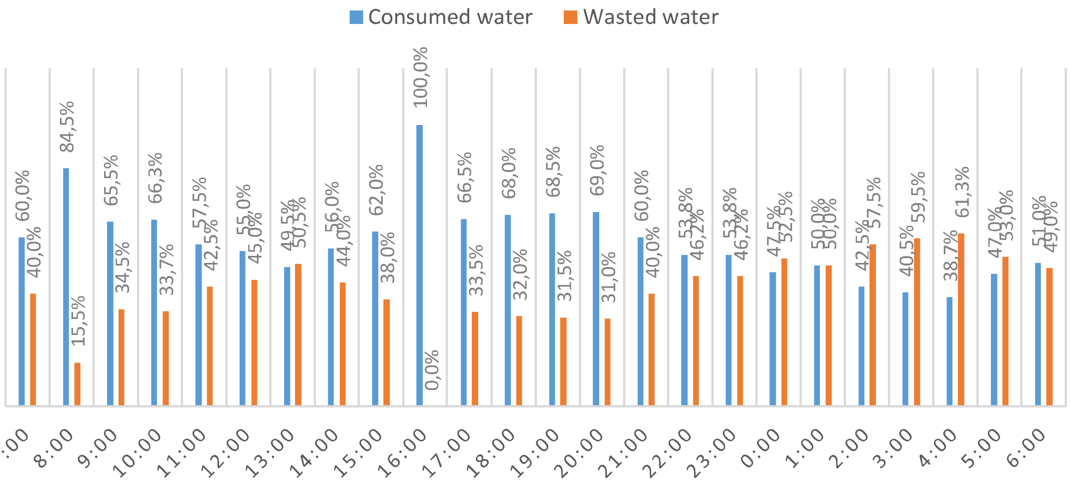

Figure 1. Consumption of produced water for 1 day

One of the ways to increase the energy efficiency of well pumps is to maintain optimal pressure in the pipeline. To determine the required pressure created by the pump, the depth of the pump in the well in the working state, the diameter of the pipe, the static H_{st} and dynamic H_{d} water level in the well and the geometric height of the water rise H_g are determined as follows:

$$H = \left(H_g - H_d\right) + \Delta H, \tag{1}$$

The energy efficiency of well pump equipment is realized due to adjustment of their operating modes based on automation, frequency converter and specialized control algorithms. When adjusting the rotation speed of the system, the pressure characteristics of the pump are described by the quadratic parabola equation [5]:

$$H(Q) = H_x \cdot (\omega/\omega_{nom})^2 - S_x Q^2, \tag{2}$$

where: H_x – imaginary head of the pump at zero efficiency, m, in the absence of data for clean water $H_x = 1{,}25 \cdot H_{nom}$; ω, ω_{nom} – variable and nominal angular velocity of the pump drive, rad/s; S_x – is the imaginary hydraulic resistance of the pump, $m \cdot (h/m^3)$.

The imaginary resistance of the pump can be determined according to the formula (2) at the nominal capacity, pressure and pump speed:

$$S_x = \frac{H_{nom} - H_x}{Q_{nom}^2} = \frac{H_{nom} - 1{,}25 \cdot H_x}{Q_{nom}^2}, \qquad (3)$$

where: Q_{nom} – nominal flow of the pump, $m^3/soat$.

The pressure characteristic of the pipeline network is described by the quadratic parabola equation using the following formula[6]:

$$H(Q) = H_g + S_q Q^2 \qquad (4)$$

where: S_q – hydraulic resistance of the pipeline network, $m \cdot (h/m^3)$:

$$S_q = \frac{H_g - H_{nom}}{Q_{nom}^2} \qquad (5)$$

At the intersection of the pressure characteristics of the pump and the pipeline network, a steady state is formed, which determines the actual operation and pressure of the pump unit. The solution of the system of equations (2) and (4) allows obtaining the hydraulic characteristics related to the angular velocity of the electric drive. The real roots of the equation determine the working area of the pump:

$$H(\omega) = \frac{S_x H_g + (\omega/\omega_{nom})^2 S_q H_x}{S_x + S_q}, \qquad Q(\omega) = \sqrt{\frac{H_g - (\omega/\omega_{nom})^2 H_x}{S_x + S_q}}. \qquad (6)$$

The entire range of the angular speed change of the electric motor $\mu_{m.nom}$ and the efficiency of the frequency converter μ_{VFD} remains close to the nominal, and the hydraulic efficiency of the pump varies according to Moody's formula [7]:

$$\mu_n(\omega) = 1 - \frac{1 - \mu_{n.nom}}{(\omega/\omega_{nom})^{0.36}}. \qquad 7)$$

where: $\mu_{n.nom}$ – nominal hydraulic efficiency of the pump.

Energy efficiency to reduce excess pressure in water lifting

Nominal pressure $H_{nom} = 150\,m$, productivity $Q_{nom} = 63\,m^3/soat$, efficiency $\mu_{n.nom} = 0.84$ and rotation speed $n_{nom} = 2919\,ayl/min$ ($\omega_{nom} = 305{,}522\,rad/s$) Consider the operation of a well pump in a direct supply system. Nominal parameters of the electric motor: power $P_{nom} = 45\,kW$; efficiency $\mu_{m.nom} = 0.84$; overload volume $\lambda = M_{max}/M_{nom} = 2.2$; moment of inertia $J = 0.1\,kg/m^2$. Annual water consumption – $Q_{yil} = 109090\,m^3$, maximum hourly water consumption $Q_{max} = 68\,m^3$.

As a result of the hydraulic calculation, the required water pressure $H_g = 65\,m$ according to (1) was determined, which reduces the excess pressure of the water rising into the pipe system: $\Delta h = \Delta H_1 - \Delta H_2$. An explanatory diagram of the water supply network is shown in Fig. 2.

Reducing the pressure (points 1 to 2 in the diagram in Fig. 2) reduces the head from Q_{nom} to Q_r by changing the speed of rotation of the pump wheel in accordance with the pressure characteristic (2) and therefore it is set in the hours of maximum water consumption 'indicators must be observed:

$$Q_r \geq Q_{max}. \qquad (8)$$

The angular velocity of the motor can be obtained by solving equation (6) with a known thrust or pump supply:

$$\omega_r = \frac{\omega_{nom}\sqrt{S_q H_x (S_q H_r - S_x H_g + S_x H_r}}{S_q H_x} \qquad (9)$$

The limiting angular velocity Q(ω), which determines the stable operation of the pump, is found by solving (6) equation [6, 7, 8]:

$$\omega_b = \omega_{nom}\sqrt{H_g/H_x}. \qquad (10)$$

Thus, it follows from the possible control ranges that the frequency control conditions can be met:

$$\omega_r \geq \omega_b \text{ va } \omega_r \geq \frac{2\pi f_{min}(1-s)}{p}, \qquad (11)$$

where: f_{min} – minimum permissible power frequency during pump operation, Hz; s, p– the number of slips and pairs of poles of the motor.

The actual power, kW, used for the rise of water at a certain angular speed of the pump is determined by the following formula[6]:

$$P(\omega) = \frac{\rho \cdot Q(\omega) \cdot H(\omega)}{3600 \cdot 102 \cdot \mu_n(\omega) \cdot \mu_{n.nom} \cdot \mu_{VFD}} \qquad (12)$$

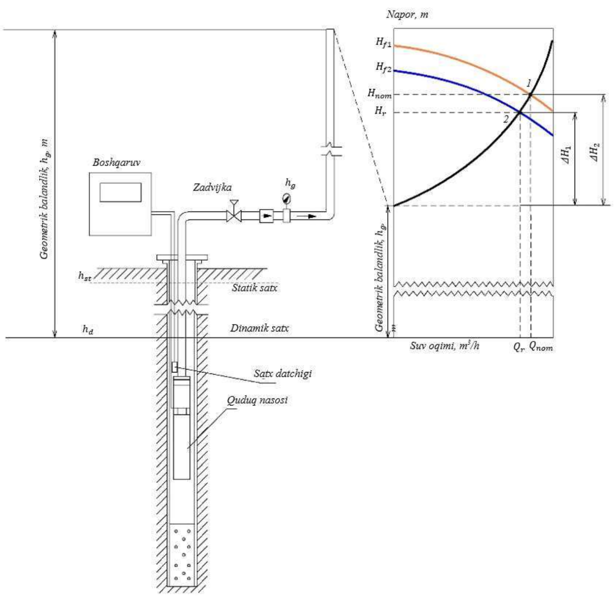

Figure 2. Adjusting the operating mode of the well pump by adjusting the speed of the electric motor

Reducing the annual cost of electricity by reducing the excess pressure of the raised water at a certain volume of water consumption can be determined by the value of the specific power consumption of the pump at a certain indicator:

$$\Delta W = \left(\frac{P(\omega_{nom})}{Q_{nom}} - \frac{P(\omega_r)}{Q_r}\right) Q_{yil} = (w_d(\omega_{nom}) - w_d(\omega_r)) Q_{yil}, \qquad (13)$$

where: w_d – specific power of liquid transport, $kVt \cdot soat/m^3$.

Frequency adjustment of the speed of an asynchronous electric motor

Variable speed control technology changes the pump speed and adapts to the load demand. When using Variable Speed Drives (VSD) technology, energy consumption is significantly reduced, allowing the same output to be used with significantly less energy. This, in turn, makes it possible to avoid complex transient processes in electrical networks, ensures the operation of the equipment in the most economical mode [9,10].

The main element of the adjustable frequency drive is the frequency converter, through which the practically constant network parameters of voltage U_1 and frequency f_1 are converted into variable parameters U_2 and f_2 needed for the control system of the pumping equipment. The speed of the electric motor connected to the output of the converter changes proportionally to the frequency f_2. The "Frequency converter - asynchronous motor" system is characterized by the following mathematical equations:

Three-phase voltage system

$$\begin{cases} U_A = U_{max} \cdot \sin(\omega \cdot t), \\ U_B = U_{max} \cdot \sin\left(\omega \cdot t + \frac{2 \cdot \pi}{3}\right), \\ U_C = U_{max} \cdot \sin\left(\omega \cdot t - \frac{2 \cdot \pi}{3}\right). \end{cases} \tag{14}$$

where:

U_{max} – maximum voltage, V;

ω – angular speed of rotation, rad/sec.

Three-phase rectifier

Average rectified voltage:

$$U_d = 2{,}34 \cdot U_0, \tag{15}$$

where: U_0 – phase voltage of the secondary winding of the transformer.

Average rectified current:

$$I_d = \frac{U_d}{R_n}, \tag{16}$$

where: R_n– nominal load resistance.

The autonomous voltage inverter and its control system are described mathematically as follows [11]:

Phase A output voltage for 6-zone Pulse Width Modulation (IPWM) is described as follows:

$$U_a = \begin{cases} \frac{1}{3} U_n, 0 \le t \le \frac{T}{6} \\ \frac{2}{3} U_n, \frac{T}{6} < t \le \frac{T}{3} \\ \frac{1}{3} U_n, \frac{T}{3} < t \le \frac{T}{2} \\ -\frac{1}{3} U_n, \frac{T}{2} < t \le \frac{2T}{3} . \\ -\frac{2}{3} U_n, \frac{2T}{3} < t \le \frac{5T}{6} \\ -\frac{1}{3} U_n, \frac{5T}{6} < t \le T \end{cases} \tag{17}$$

A three-phase sinusoidal waveform is described as follows:

$$\begin{cases} U_A = q \cdot U_{max} \cdot \sin(\omega \cdot t), \\ U_B = q \cdot U_{max} \cdot \sin\left(\omega \cdot t + \frac{2 \cdot \pi}{3}\right) \\ U_C = q \cdot U_{max} \cdot \sin\left(\omega \cdot t - \frac{2 \cdot \pi}{3}\right). \end{cases} \tag{18}$$

where: q– pulse fill factor.

The output frequency of the analog signal generated by PWM is calculated using the following formula

$$f = \frac{F_{clk}}{N \cdot 512 \cdot Z}, \tag{19}$$

where: F_{clk}– clock frequency of the microcontroller (quartz resonator);

Z– number of pulses;

N– number of inverter switches.

Asynchronous electric motor with a short-circuited rotor

We write the mathematical description of the asynchronous motor in the d-q system in the following form[12,13]:

$$\begin{cases} V_{qs} = R_s \cdot i_{qs} + \dfrac{d\Psi_{qs}}{dt} + \omega \cdot \varphi_{qs} \\ V_{ds} = R_s \cdot i_{ds} + \dfrac{d\Psi_{ds}}{dt} + \omega \cdot \varphi_{ds} \\ V'_{qr} = R'_r \cdot i'_{qr} + \dfrac{d\Psi'_{qr}}{dt} + (\omega - \omega_r) \cdot \varphi'_{dr}, \\ V'_{dr} = R'_r \cdot i'_{dr} + \dfrac{d\Psi'_{dr}}{dt} + (\omega - \omega_r) \cdot \varphi'_{qr} \\ T_e = 1{,}5 \cdot p \cdot (\Psi_{ds} \cdot i_{qs} - \Psi_{qs} \cdot i_{ds} \end{cases} \tag{20}$$

where: $\Psi_{qs} = L_s \cdot i_{qs} + L_m \cdot i'_{qr}$– the projection of the stator current connection on the q axis;

$\Psi_{ds} = L_s \cdot i_{ds} + L_m \cdot i'_{dr}$– the projection of the stator current connection on the d axis;

$\Psi'_{qr} = L'_r \cdot i'_{qr} + L_m \cdot i_{qs}$– the projection of the rotor current connection on the q axis;

$\Psi'_{dr} = L'_r \cdot i'_{dr} + L_m \cdot i_{qs}$– projection of the reduced rotor current connection along the d axis;

$L_s = L_{1s} + L_m$– stator inductance;

$L'_r \cdot L'_{1r} + L_m$– given rotor inductance.

Electric motor torque is determined by the Kloss formula:

$$M_m = \frac{M_k \cdot (2+q)}{\frac{s_k}{s} + \frac{s}{s_k} + q}, \text{ N·m}, \tag{21}$$

where: M_k– critical moment, N·m;

s– slip;

s_k– critical slip.

Critical slippage:

$$s_k = \frac{r_2}{\sqrt{r_1^2 + x_k^2}}. \tag{22}$$

where: r_1– active resistance of the stator, Om;

r_2– active resistance of the rotor, Om;

x_k– inductive resistance of the stator.

Critical moment:

$$M_k = \frac{3 \cdot U_f^2}{2 \cdot \omega \cdot (\sqrt{r_2^2 + x_k^2} + r_2)}, N \cdot m \tag{23}$$

where: U_f– phase voltage, V;

ω– rotational angular frequency of the electric motor rotor, rad/s.

$$q = \frac{r_1}{\sqrt{r_1^2 + x_k^2}}. \tag{24}$$

Electric motor current:

$$I = \sqrt{\frac{U^2 \cdot 1{,}2}{(r_1 + \frac{r_2}{S})^2 + x_k}}, \text{ A}. \tag{25}$$

The parameters of the T-shaped equivalent circuit are calculated according to the following formulas:

Angular velocity of magnetic field rotation

$$\omega_0 = \frac{2 \cdot \pi \cdot f}{p}, rad/s \tag{26}$$

where: f_1– frequency of the electrical network, Hz;

p– number of pairs of poles.

The nominal angular velocity of the rotor is determined based on the slip expression

$$s_{nom} = \frac{\omega_0 - \omega_{nom}}{\omega_0}, \tag{27}$$

where: ω_{nom}– nominal angular frequency of the electric motor rotor,

$$\omega_{nom} = \omega_0 \cdot (1 - S_{nom}), rad/s \tag{28}$$

Rated motor torque:

$$M_{nom} = \frac{P_{nom}}{\omega_{nom}}, Nm. \tag{29}$$

Nominal phase current of the motor:

$$I_{f.nom} = \frac{P_1}{3 \cdot U_{nom.F} \cdot \cos\varphi_{nom}}, A, \tag{30}$$

where: $U_{f.nom}$– nominal phase voltage, V;
$\cos\varphi_{nom}$– nominal power factor.

Motor power consumption:

$$P_1 = \frac{P_{nom}}{\eta_{nom}}, \tag{31}$$

where: P_{nom}– nominal active power, W;
η_{nom}– nominal efficiency of the electric motor.

The nominal resistance of an electric motor (Om), which must be multiplied by the active and inductive resistances in relative units, to obtain the motor parameters in absolute units:

$$Z_{nom} = \frac{U_{f.nom}}{I_{f.nom}}, \tag{32}$$

where: $I_{f.nom}$– phase nominal current, A.

To recalculate the parameters of the T-shaped equivalent circuit of the motor from relative units to absolute units, we use the following expressions:

active resistance of the stator winding, Om:

$$R_s = R_s^* \cdot Z_{nom}, \tag{33}$$

where: R_s^*– the active resistance of the stator winding,

- inductive resistance of the stator winding, Om:

$$X_s = X_s^* \cdot Z_{nom}, \tag{34}$$

where: X_s^*– active resistance of the stator winding,

- decrease in the active resistance of the rotor coil, Om

$$R_r' = R_r'^* \cdot Z_{nom}, \tag{35}$$

where: $R_r'^*$– active resistance of the rotor winding,

- reduction of the leakage inductance of the rotor coil, Om

$$X_r' = X_r'^* \cdot Z_{nom}, \tag{36}$$

where: $X_r'^*$– dispersion inductive resistance of the rotor coil, Om
bu yerda: $X_r'^*$- rotor chulg‘amining tarqalish induktiv qarshiligi, Om

- inductive resistance of the magnetization circuit, Om

$$X_\mu = X_\mu^* \cdot Z_{nom}, \tag{37}$$

where: X_μ^*– inductive resistance of the magnetization circuit, Om

- specific inductance of the stator

$$L_{\sigma s} = \frac{X_s}{\omega_0}, Gn \tag{38}$$

- specific inductance of the rotor

$$L_{\sigma r} = \frac{X_r'}{\omega_0}, Gn \tag{39}$$

- mutual inductance

$$L_m = \frac{X_\mu}{\omega_0}, Gn \tag{40}$$

- stator coil inductance

$$L_1 = L_m + L_{\sigma s}, Gn \tag{41}$$

- rotor coil inductance

$$L_2 = L_m + L_{\sigma r}, Gn \tag{42}$$

According to the U and f matrix of the linear control law used to start the electric motor, U is determined for the calculated value of f and substituted into the formula to calculate the current and torque of the electric motor. Then, in order to find the current minimum point at which the pump unit supplies water to the water supply system with a certain pressure, the system automatically reduces the voltage by one step without changing the frequency and calculates the motor current. As the voltage decreases, the system decreases by another step until the current increases. After that, the system returns to the previous voltage value at a certain frequency and continues to work, realizing the required pressure in the water supply system.

Since solving the equations of the mathematical model of frequency converter with short-circuited rotor induction motor and centrifugal pump is an analytically demanding task, a computer model was developed to test the formulated hypothesis.

Results. Based on equations (1) - (42) in the MatLab/Simulink program, the simulation model of the "Autonomous voltage inverter - asynchronous electric motor with a short-circuited rotor - centrifugal pump" system was developed.

This model includes the frequency converter's PWM pulse shaper output (voltage) and f (frequency) as control variables. In this model, the data of the stator current is transferred to the workflow and statistically processed, then the maximum value of the stator current is found, and then the input parameters are changed. As the stator current increases, the duty cycle of the pulses changes so that the current is minimal. As a result, we can choose energy-saving modes for any pump and study the laws of frequency converter control.

The data of the simulated machine ПЭДВ 45-219 type short-circuited rotor asynchronous electric motor are presented in Table 1.

Table 1.

The main parameters of the electric motor

Name	Symbol	Quantity	Unit
Synchronous speed	n_{nom}	2919	rpm
Rated power	P_{nom}	45	kW
Number of poles	p	2	-
Nominal efficiency	η_{nom}	0,84	%
Rated power factor	$\cos\varphi_{nom}$	0,83	%
Nominal slip	S_{nom}	0,027	-
Nominal frequency	f_1	50	Hz
Nominal phase voltage	$U_{nom.F}$	220	V
Rotor moment of inertia	$J_{m.r.}$	0,1	$kg \cdot m^2$
Active resistance of the stator winding	R_s	0,074	Om
Inductive resistance of the stator winding	X_s	0,255	Om
Active resistance of the rotor coil	$R_r^{'}$	0,072	Om
Inductive resistance of the rotor coil	$X_r^{'}$	0,342	Om

Inductive resistance of the magnetic core	X_μ	5,770	Om

Angular velocity of magnetic field rotation:

$$\omega_0=\frac{2\cdot\pi\cdot f}{p}=\frac{2\cdot 3{,}14\cdot 50}{1}=314\,rad/sek$$

The nominal angular speed of the rotor is determined based on the slip expression:

$$S_{nom}=\frac{\omega_0-\omega_{nom}}{\omega_0},$$

where: $\omega_{nom}=\omega_0\cdot(1-S_{nom})=314\cdot(1-0{,}027)=305{,}522\,rad/sek$

Motor rated torque:

$$M_{nom}=\frac{P_{nom}}{\omega_{nom}}=\frac{45000}{305{,}522}=147{,}289\,Nm.$$

Motor power consumption:

$$P_1=\frac{P_{nom}}{\eta_{nom}}=\frac{45000}{0{,}84}=53{,}571\,kW$$

$$I_{nom.F}=\frac{P_1}{3\cdot U_{nom.F}\cdot\cos\varphi_{nom}}=\frac{53571}{3\cdot 220\cdot 0{,}83}=97{,}793\,A$$

The nominal resistance of an electric motor (Om), which must be multiplied by the active and inductive resistances in relative units, to obtain the motor parameters in absolute units:

$$Z_{nom}=\frac{U_{nom.F}}{I_{nom.F}}=\frac{220}{97{,}793}=2{,}249\,Om$$

Let's recalculate the parameters of the T - figurative equivalent circuit of the motor from relative units to absolute units.

Active resistance of the stator winding:

$$R_s=0{,}074\cdot 2{,}249=0{,}166\,Om$$

The active resistance of the rotor winding decreases according to (35):

$$R_r^{'}=0{,}072\cdot 2{,}249=0{,}162\,Om$$

The internal inductance of the stator according to (38):

$$L_{\sigma s}=\frac{X_s}{2\cdot\pi\cdot f_1}=\frac{0{,}051\cdot 67{,}47}{2\cdot 3{,}14\cdot 50}=0{,}011\,Gn$$

The mutual inductance of the rotor according to (39):

$$L_{\sigma r}=\frac{X_r^{'}}{2\cdot\pi\cdot f_1}=\frac{0{,}049\cdot 67{,}47}{2\cdot 3{,}14\cdot 50}=0{,}017\,Gn$$

According to mutual inductance (40):

$$L_m=\frac{X_\mu}{2\cdot\pi\cdot f_1}=\frac{2{,}5\cdot 67{,}47}{2\cdot 3{,}14\cdot 50}=0{,}537\,Gn$$

Stator winding inductance according to (41):

$$L_1=L_m+L_{\sigma s}=0{,}537+0{,}011=0{,}548\,Gn$$

Rotor winding inductance according to (42):

$$L_2=L_m+L_{\sigma s}=0{,}537+0{,}017=0{,}554\,Gn$$

Discussion. In order to reduce the stator energy consumption by adjusting the supply voltage during speed adjustment, a computer model consisting of a pulse-forming, three-phase voltage inverter connected to a DC network was built in the MatLab/Simulink R2021a program. The computer model before speed adjustment is shown in Figure 5.

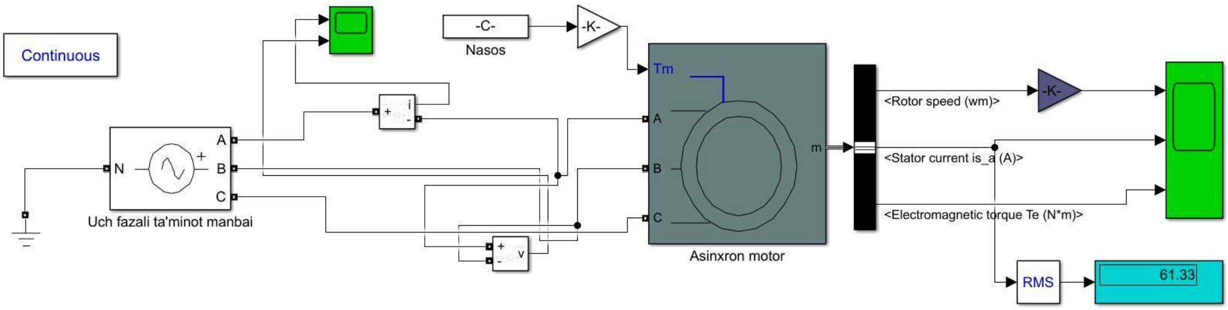

Figure 5. The system "Asynchronous motor-pump" without adjustable speed is a computer model in MatLab/Simulink software

Adjusting the voltage and frequency of the supply source, an asynchronous motor with a centrifugal pump located in the resistance torque. The simulation time was chosen to be 1.2 s, which is enough for the electric motor to transition from start-up mode to operation mode.

As a result of the simulation, the dependences of the rotation frequency, electromagnetic torque and phase current a (Fig. 6) were obtained at the phase voltage U=220 V and the frequency of the supply source f=50Hz. Figure 6 shows the time dependence graph of rotor speed, stator α-phase current and electromagnetic torque before adjusting the speed of the motor.

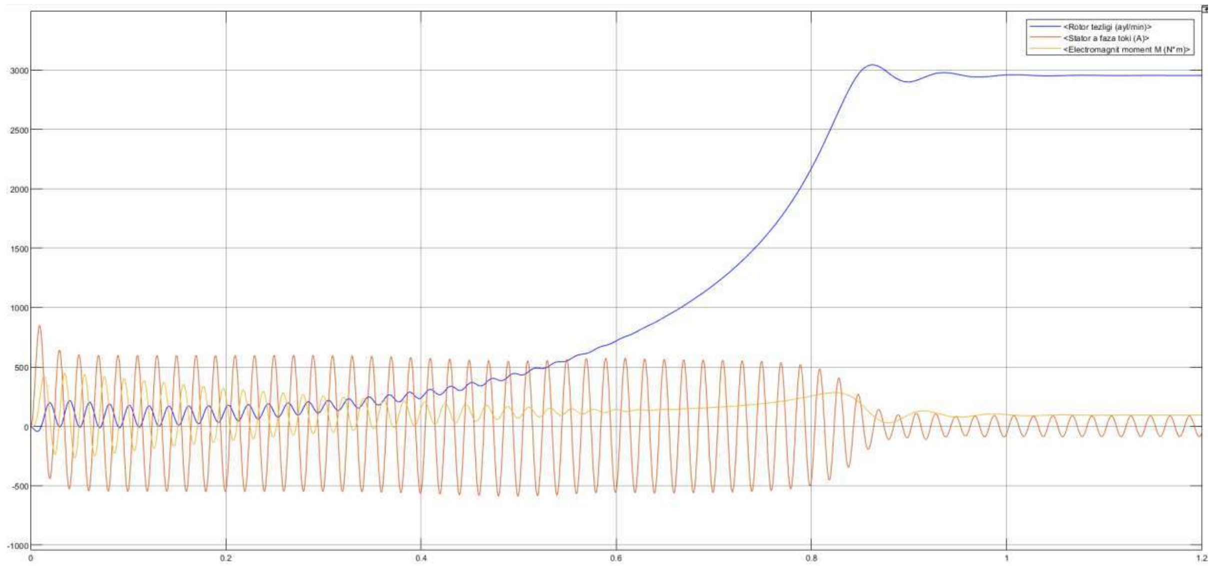

Figure 6. Time dependence graph of rotor speed, stator α-phase current and electromagnetic torque before adjusting the speed of the motor

Analysis of Figure 6 shows that the initialization process takes about 1 s. The maximum value of the starting current reaches 848,702 A.

The maximum value of stator a phase current is 848.721 A, and the minimum value is -589.902 A (Fig. 8).

Similarly, a model is obtained for the case where the speed is frequency adjusted. The computer model in the MatLab system after the frequency adjustment of the asynchronous motor speed is shown in Fig. 7.

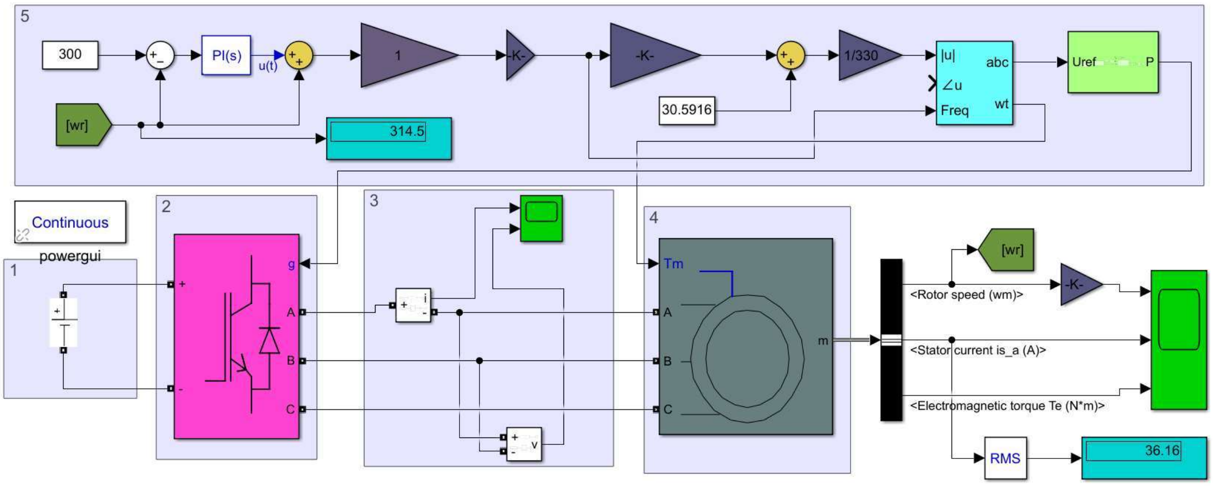

Figure 7. Computer model of frequency adjustment of induction motor speed in MatLab system

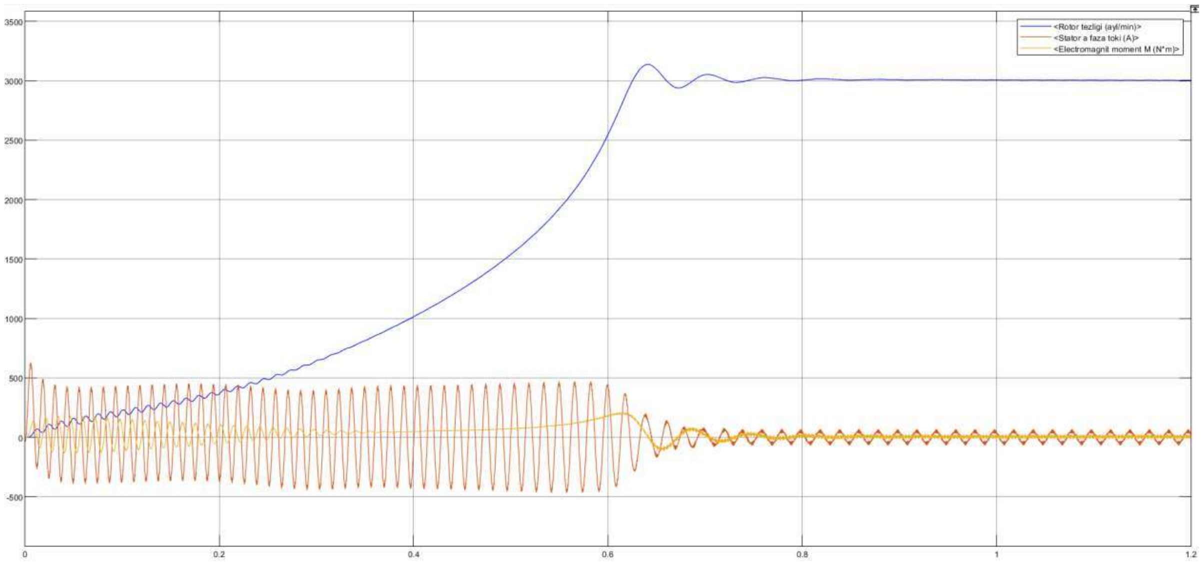

Figure 8. A plot of stator A phase current versus time after speed adjustment

After regulating the voltage at a frequency of 50 Hz, the maximum value of the phase a current of the stator at the start of the electric motor is 631.002 A, and the minimum value is -469.702 A (Fig. 8).

Conclusion. This computer model confirmed the hypothesis that it is possible to reduce the energy consumption of the well pumping system by adjusting the rotation frequency of the electric motor rotor by adjusting the supply frequency in scalar systems of frequency converters at the same mains frequency.

An analysis of the problems of energy efficiency improvement of energy consumption of well pump equipment of water supply systems was carried out. An energy efficiency analysis of frequency regulation was carried out according to the relative parameters of aggregates and water supply networks. The calculation scheme and analytical relations for the integrated method of frequency regulation are presented. Analysis of the obtained results is carried out. The new method makes it possible to significantly simplify the process of energy efficiency assessment at the design stage of well pumping equipment for water supply systems.

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