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Construction of an Electric Drive System for Borehole Pumps with Frequency Control

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Abstract. Variable speed drive (VSD) can provide reliable dynamic systems and essential savings in energy usage and costs of the electrical motors. A variable speed drive (VSD) is a device that regulates the rotational force and speed of mechanical equipment. VSDs are effective in energy savers in fan and pump applications; they strengthen process operations, especially where flow control is involved. VSDs provide accurate soft-start capabilities, which decrease line voltage sags and electrical stresses associated with complete voltage motor start-ups, particularly when driving high-inertia loads. Variable speed drive technology and the significance of controlling the speed of existing electrical motors have attracted many attentions in the recent years with the advent of new magnetic materials and power devices. Thus, this paper highlights a comprehensive review on applications of VSD in electrical motors energy savings and energy use. The purpose is to identify incorporated costs of applying variable speed drives and energy saving opportunities to the existing applications of electrical motors. Author hopes to provide convenient information for future variable speed drive applications like pumps, chillers, fans, heaters and ventilators.

INTRODUCTION

Electrical motor drive systems, which are supplied directly from alternating cutting (AC) line power, have a massive potential for energy saving, when they are operated at variable-speed by using variable speed drives (VSDs). Energy consumption in centrifugal load applications vary in accordance with the affinity laws [1], which means that torque is proportional to the square of speed, and power is proportional to the cube of speed. This variation helps reduce high energy losses compared to throttling devices or fixed-speed controllers for a relatively small decrease in speed.

VSD can provide reliable dynamic systems and simultaneously contribute significantly to the energy usage and costs of electrical motor drives. These drive systems are perfect class of the general adjustable speed drives (ASDs) [2] because they permit fine-tuning processes while reducing costs for motor maintenance and energy [3]. Moreover, to energy savings, they can offer continuous speed control according to the specific requirements of the work being performed.

However, the most of motors operate only at full speed 100% for short periods of time. This frequently results in many systems operating inefficiently during long periods of time. Therefore, there are significant energy losses during the operation time. System loss reduction can be achieved by installing VSD systems to match the speed of the motor with the related load. VSD has been raising popularity due to their advantages over traditional control methods. The speed of a generator or motor can be adjusted and controlled to any desired speed by using VSD. Besides adjusting the speed of an electrical motor, VSD is able to keep an electric motor speed at an invariable level where the load is variable [4].

VSDs along with VFDs are electronic devices, which match motor speed to the required speed of the application. The output voltage and frequency are determined by input power of the motor. Majority of motors can benefit from

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VSD to provide different frequency outputs, whether the speed of the drive is set manually by an operator or automatically by a control system [5].
VSDs are an economical and efficient contemporary option that should be considered for all variable speed systems. VSDs allow the motor speed to vary depending on actual operating conditions, rather than operating continuously at full speed. Varying speed allows matching changing load requirements more closely, and because the power draw is proportional to the cube of its speed, reducing speed can save a lot of energy. For instance, reducing a fan's speed by 20% can reduce its energy requirements by about 50% [6]. Installing a VSD on the fan motor permits the fan to automatically match this reduced capacity, slowing down in response to reduced demand, thus saving energy.

METHODS

When frequency control of the speed of asynchronous borehole water pumping motors occurs, a number of problems arise related both to the behavior of the motor and to the choice of the law of frequency control. In this case, the asynchronous short-circuited motor is controlled by changing the amplitude and frequency of the supply voltage. When developing a system for frequency control of an asynchronous motor of a downhole pump and taking into account the main dependences of the motor operation and its parameters, it is necessary to choose a control law that, under the conditions of a downhole pump drive, will allow providing stable operation of the engine in the specified control range, as far as possible with the lowest possible losses.
In accordance with the chosen law, you should define the simplest scheme that allows you to implement this law.
To obtain the basic ratios of an asynchronous motor for frequency control, we use the T-shaped substitution scheme (Figure 1). The following well-known assumptions should be made: steel saturation is not taken into account; the effect of current displacement and the active resistance of the magnetization circuit are not taken into account; the phase windings of the machine are considered symmetrical; a symmetrical sinusoidal voltage is applied to the stator. These assumptions do not change the general nature of the regularities obtained for a frequency-controlled asynchronous motor.

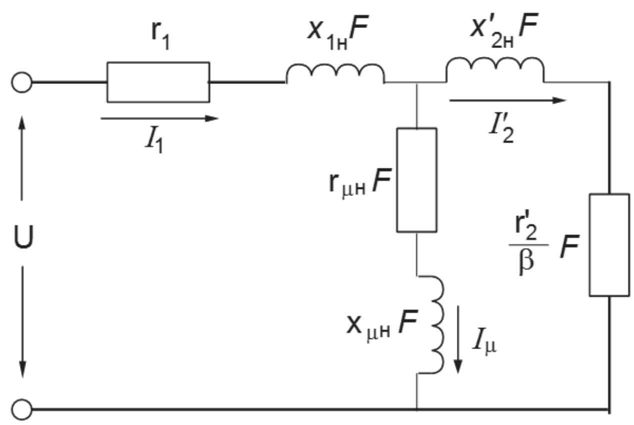

FIGURE 1. Asynchronous motor phase replacement scheme

In the equivalent circuit of induction motor the following notation: r_1 and r_2' active resistance of the stator winding and given the resistance of the phase winding of the rotor; x_{1H}, $x_{2\text{H}}'$ and $x_{\mu H}$ –nominal inductive reactance of the stator winding, the resistance of the winding rotor, and magnetizing circuit; $\sigma = 1 + \frac{x_{\mu\text{H}}^2}{x_s x_r}$ the scattering coefficient at nominal frequency, $x_r = x_{2\text{H}}' + x_{\mu\text{H}}$- the inductive loop resistance of the stator at rated speed; $x_s = x_{1\text{H}} + x_{\mu\text{H}}$- the inductive reactance of the circuit of the rotor at rated speed; f and f_{H}- current and rated frequency of the stator; U and U_H- the current and the nominal value of the voltage supplied to the stator; I and I_1 - the current and the nominal value of the stator current; $I_2'$and $I\mu$- given the rotor current and the magnetizing current; $F=f/f_H$ - relative frequency management; $\gamma=U/U_H$ - relative voltage applied to the stator; $i=I/I_1$- relative current of the stator; β - the absolute slip; S - relative slip; p - the number of pairs of poles of the motor; m- number of phases of the stator of the motor.
The parameters of the substitution scheme (Figure 1) given with the index "n" correspond to the nominal value, without the index-to the current value for frequency control.

Based on Figure 1, the primary relations of coordinates and engine parameters can be determined, with the help of which it is possible to identify rational methods of frequency control. Such relations are the dependences of the E_1 - electromotive force, Ψ - the magnetic flux in the air gap, I_1- the stator current, the rotor current, M -the magnetization current and the electromagnetic moment as a function of the parameters of the substitution circuit (F) and the controlled parameters and β.
An asynchronous motor with frequency control is a multi-connected control system that has several adjustable parameters, the relationship between which is determined by the internal properties of the machine and the external control effect. In this case, the amplitude and frequency of the supply voltage are input control parameters, the angular velocity of the rotor ω and some generalized indicator of motor utilization are output parameters, and the load moment is a disturbing effect.
The relationship between the frequency and amplitude of the supply voltage when changing the speed of rotation and the load moment determines the main characteristics of an asynchronous electric motor in the control system: overload capacity, temperature excess, efficiency,$\cos\varphi$, etc. This ratio should be chosen so that the main parameters of the asynchronous electric motor in the speed control modes and during transients are rational (close to the nominal value). One of the important tasks of optimal frequency control is to ensure a minimum of losses in the electric motor when limiting its heating.
The laws of frequency control differ from each other in what relationships are chosen between the input, output and internal parameters of the motor when changing the disturbing effect. In this regard, we will consider the rational laws of frequency control of an asynchronous electric drive of a pumping unit, taking into account the features of the latter's operating modes.
In order to construct a model of an asynchronous motor of a borehole pumping unit, we will use the well-known mathematical model of an asynchronous electric motor obtained in a fixed orthogonal coordinate system $\alpha,\ \beta$. In accordance with this, this model of the "Asynchronous motor – borehole pump" system can be implemented in the Matlab environment.
For a stationary relative stator coordinate system $\alpha,\ \beta\ (\omega_k = 0)$, the differential equations of the electrical equilibrium of stresses in the stator and rotor windings of the machine take the following form [7, 8].

$$\begin{aligned} U_{1\alpha} &= R_1 i_{1\alpha} + \frac{d\Psi_{1\alpha}}{dt}; \\ U_{1\beta} &= R_1 i_{1\beta} + \frac{d\Psi_{1\beta}}{dt}; \\ U_{2\alpha} &= R_2 i_{2\alpha} + \frac{d\Psi_{2\alpha}}{dt} + \omega\Psi_{2\beta}; \\ U_{2\beta} &= R_2 i_{2\beta} + \frac{d\Psi_{2\beta}}{dt} + \omega\Psi_{2\alpha}. \end{aligned} \tag{1}$$

In the system of equations (1), the following notation is used:
$U_{1\alpha},\ i_{1\alpha}$ - stator voltage and current along the axis α; $U_{2\alpha},\ i_{2\alpha}$- rotor voltage and current along the axis β; $R_1,\ R_2$ – active resistances of the stator and rotor windings, respectively; $\Psi_{1\alpha},\ \Psi_{1\beta}$ - flow coupling of the stator windings; $\Psi_{2\alpha},\ \Psi_{2\beta}$- flow coupling of the rotor windings; r_1, L_{l1}- active resistance and inductance of the stator.
The four equations of system (2) contain eight linearly dependent variables. Based on the equations of the relationship between currents and flux links of the stator and rotor windings, we exclude two pairs of variables, that is, we choose the composition of the components of the vector $\vec{\Psi}$ [7]

$$\begin{aligned} \Psi_{1\alpha} &= L_1 i_{1\alpha} + L_{12} i_{2\alpha}; \\ \Psi_{1\beta} &= L_1 i_{1\beta} + L_{12} i_{2\beta}; \\ \Psi_{2\alpha} &= L_2 i_{2\alpha} + L_{12} i_{1\alpha}; \\ \Psi_{2\beta} &= L_2 i_{2\beta} + L_{12} i_{1\beta}, \end{aligned} \tag{2}$$

Where L_1-is the natural inductance of the stator winding; L_2-is the reduced natural inductance of the rotor winding; is the reduced mutual inductance of the stator and rotor windings.
In accordance with the need to determine the structure of a part of the vector without presenting algebraic expressions of the mathematical model of electromechanical energy conversion in an asynchronous motor, as a

result, the block diagram of an asynchronous motor does not include inertia-free circuits. Next, we selected the following structure of a part of the vector:

$$\overrightarrow{\Psi} = \left[i_{1\alpha} i_{1\beta} \Psi_{2\alpha} \Psi_{2\beta}\right] \tag{3}$$

From the rotor flux coupling equation with respect to (2), we determine the rotor currents

$$i_{2\alpha} = \frac{1}{L_2}\Psi_{2\alpha} - \frac{L_{12}}{L_2} i_{1\alpha}$$

$$i_{1\alpha} = \frac{1}{L_2}\Psi_{2\beta} - \frac{L_{12}}{L_2} i_{1\beta} \tag{4}$$

We substitute the obtained equations (4) into expressions for stator flow links (4) [7, 9]

$$\Psi_{1\alpha} = L_1 i_{1\alpha} + \frac{L_{12}}{L_2}\Psi_{2\alpha} - \frac{L_{12}^2}{L_2} i_{1\alpha} = \left(L_1 - \frac{L_{12}^2}{L_2}\right) i_{1\alpha} + \frac{L_{12}}{L_2}\Psi_{2\alpha};$$

$$\Psi_{1\beta} = L_1 i_{1\beta} + \frac{L_{12}}{L_2}\Psi_{1\beta} - \frac{L_{12}^2}{L_2} i_{1\beta} = \left(L_1 - \frac{L_{12}^2}{L_2}\right) i_{1\beta} + \frac{L_{12}}{L_2}\Psi_{2\beta}$$

Meaning $L_1^{\sigma} = \left(L_1 - \frac{L_{12}^2}{L_2}\right)$, further, we present the expression for the flux links of the stator windings:

$$\Psi_{1\alpha} = L_1^{\sigma} i_{1\alpha} + \frac{L_{12}}{L_2}\Psi_{2\alpha}$$

$$\Psi_{1\beta} = L_1^{\sigma} i_{1\beta} + \frac{L_{12}}{L_2}\Psi_{2\beta} \tag{5}$$

Further, using the differentiation symbol $p = \frac{d}{dt}$, the system of equations (1), taking into account formula (5), is obtained in the following form:

$$U_{1\alpha} = R_1 i_{1\alpha} + L_1^{\sigma} p i_{1\alpha} + \frac{L_{12}}{L_2} p\Psi_{2\alpha};$$

$$U_{1\beta} = R_1 i_{1\beta} + L_1^{\sigma} p i_{1\beta} + \frac{L_{12}}{L_2} p\Psi_{2\beta}; \tag{6}$$

$$U_{2\alpha} = \frac{R_2 L_{12}}{L_2} i_{1\alpha} + \frac{R_2}{L_2} p\Psi_{2\alpha} + p\Psi_{2\alpha} + \omega\Psi_{2\beta};$$

$$U_{2\alpha} = \frac{R_2 L_{12}}{L_2} i_{1\beta} + \frac{R_2}{L_2} p\Psi_{2\beta} + p\Psi_{2\beta} + \omega\Psi_{2\alpha}$$

We transform the system of equations (6) to one suitable for constructing a structural model of an asynchronous motor with the following form:

$$i_{1\alpha} = \frac{1}{R_1 + L_1^{\sigma} p}\left(U_{1\alpha} - \frac{L_{12}}{L_2} p\Psi_{2\alpha}\right);$$

$$i_{1\beta} = \frac{1}{R_1 + L_1^{\sigma} p}\left(U_{1\beta} - \frac{L_{12}}{L_2} p\Psi_{2\beta}\right); \tag{7}$$

$$\Psi_{2\alpha} = \frac{1}{p}\left(U_{2\alpha} + \frac{R_2 L_{12}}{L_2} i_{1\alpha} - \frac{R_2}{L_2}\Psi_{2\alpha} - \omega\Psi_{2\beta}\right);$$

$$\Psi_{2\beta} = \frac{1}{p}\left(U_{2\beta} + \frac{R_2 L_{12}}{L_2} i_{1\beta} - \frac{R_2}{L_2}\Psi_{2\beta} - \omega\Psi_{2\alpha}\right)$$

To the obtained expressions (6), we add the electromagnetic moment of the asynchronous motor and the moment of resistance of the borehole pump. The electromagnetic moment of an asynchronous motor can be found by the formula [10]

$$M = p_n \frac{L_{12}}{L_2}\left(i_{1\beta}\Psi_{2\alpha} - i_{1\alpha}\Psi_{2\beta}\right) \tag{8}$$

Where p_n is the number of pairs of motor poles.

The moment of resistance of the borehole pump is determined by the critical moment of load on the shaft of the borehole pump is determined by the expression [11]

$$M_c = M_н \left\{ \begin{array}{l} \left\{ \left[\dfrac{\left(\dfrac{\omega}{\omega_н}\right)^2 - \dfrac{H_n^*}{H_\phi^*}}{1 - \dfrac{H_n^*}{H_\phi^*}} \right] \right\} \left\{ H_n^* + \left(1 + H_n^*\right) \left[\dfrac{\left(\dfrac{\omega}{\omega_н}\right)^2 - \dfrac{H_n^*}{H_\phi^*}}{1 - \dfrac{H_n^*}{H_\phi^*}} \right] \right\}^2 \times \\ \times \dfrac{1}{\dfrac{\omega}{\omega_н} \left\{ 1 - \left[1 - \sqrt{\dfrac{\left(\dfrac{\omega}{\omega_н}\right)^2 - \dfrac{H_n^*}{H_\phi^*}}{1 - \dfrac{H_n^*}{H_\phi^*}}} \right]^{2,3} \right\}} \end{array} \right\}. \tag{9}$$

Where M_H- rated motor torque; ω_H - rated speed of rotation; ω- current speed of rotation; $H_n^* = H_n / H_н$ - relative static pressure; $H_f = H_f / H_H$ - relative fictitious lifting height of the liquid; H_f - fictitious head at zero flow; H_n - back pressure in the liquid supply system; H_h-nominal head.

Based on (1) – (8), taking into account (9), we obtain a block diagram of an asynchronous motor with frequency control, implemented in the Matlab program, shown in Figure 2.

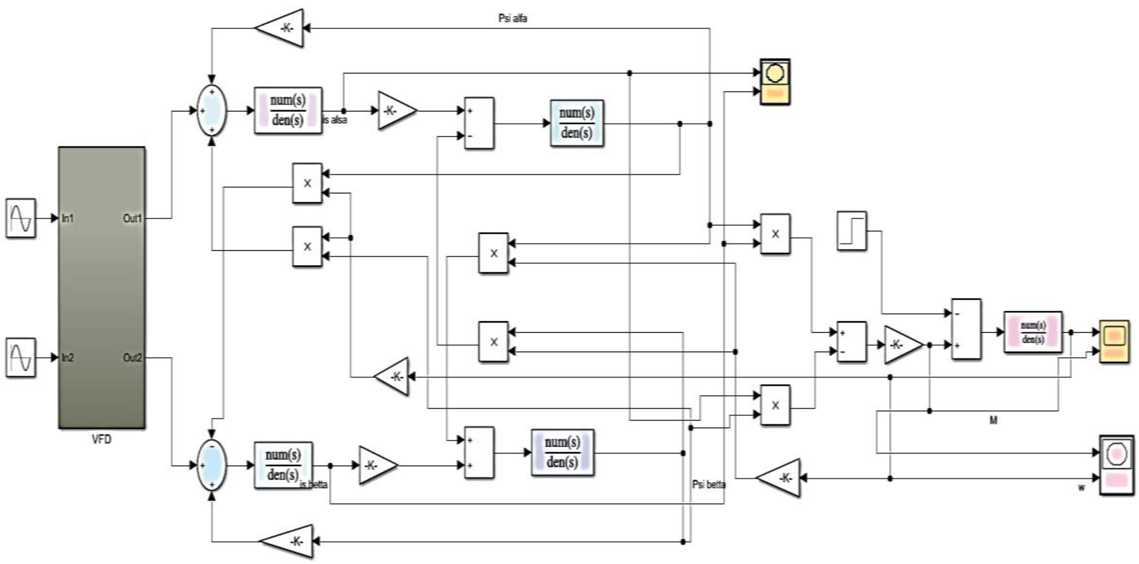

FIGURE 2. Block diagram of a frequency-controlled asynchronous electric drive

RESULTS AND DISCUSSIONS

The results of calculations and simulation of the "frequency-controlled asynchronous motor-borehole pump" system are presented in Fig. 3-5. These figures show the technological modes of operation of a downhole pumping unit with frequency control.

Figure 4 shows the connection of a downhole pump with a frequency converter ω of the moment of the electromagnet M in dynamic and static modes to the rotation frequency ω. (rotation speed ω is a radial second, the position of the transition from dynamic mode to static mode is indicated during pressing).

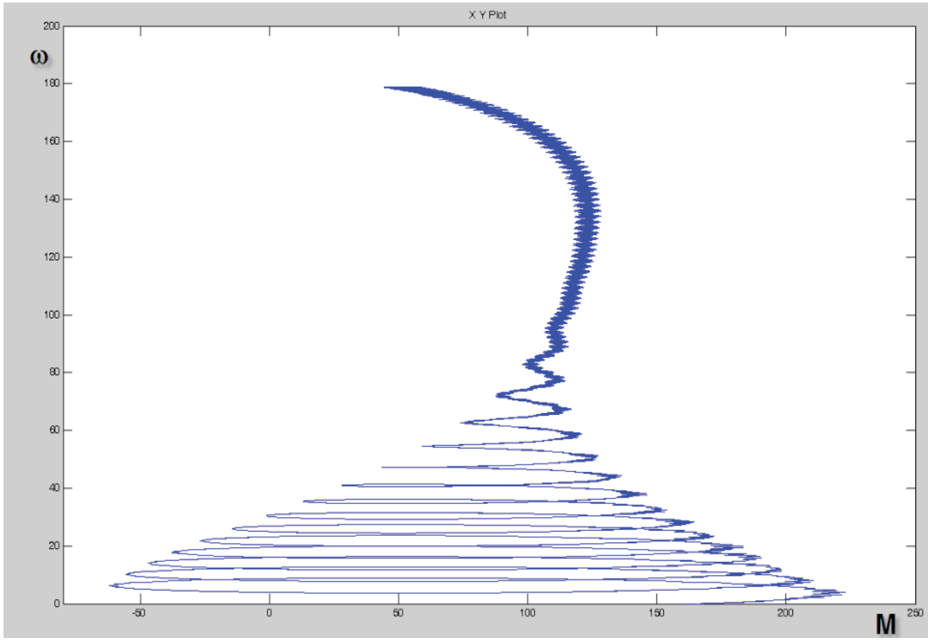

FIGURE 3. Dynamic mechanical response

Figure 5 shows the structural scheme of a Frequency-Controlled asynchronous electric transmission pump. In the Fig. 5 *a* shows the change in the number of turns of the asynchronous material. If we pay attention to this, we can see that the asynchronous motor is running smoothly, and the starting torque is eliminated. In the Fig. 5 *b* shows a graph of the number of turns of the asynchronous material in relation to the torque M.

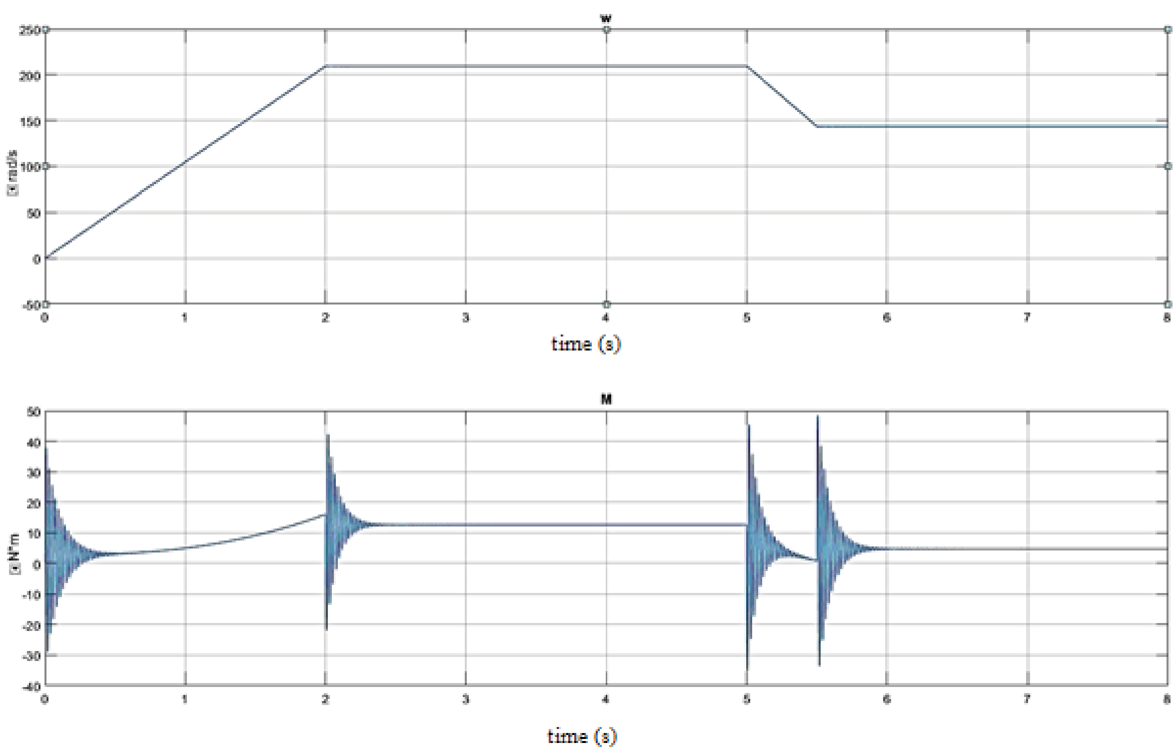

FIGURE 4. Electromagnetic moment M and rotational speed ω as a function of time in the dynamic and static mode of a frequency-controlled borehole pump

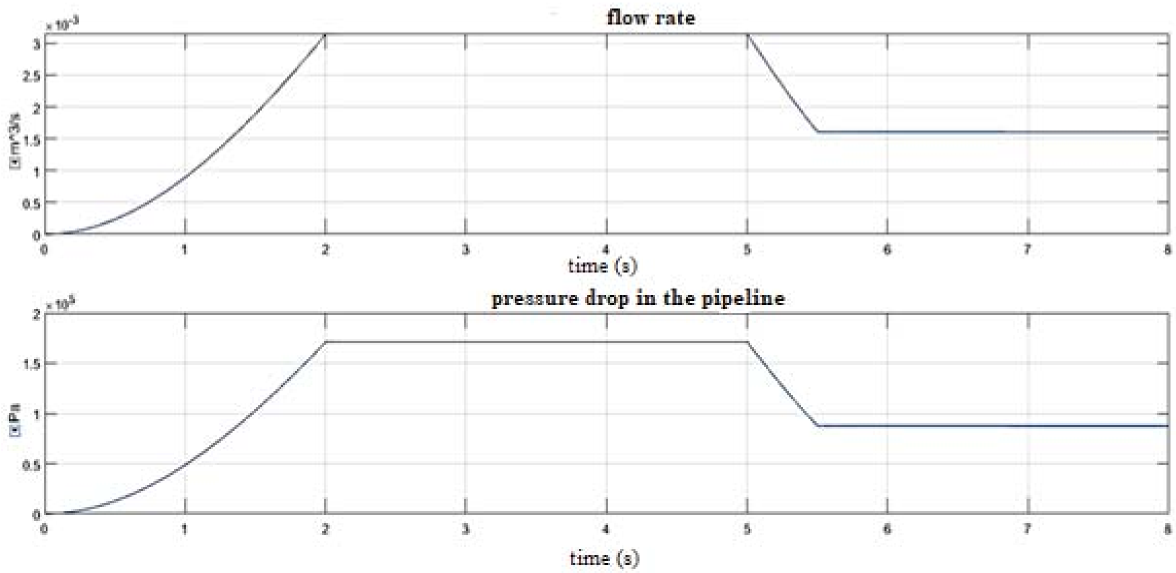

FIGURE 5. Pipeline operation mode with frequency-controlled asynchronous electric drive of the borehole pump

CONCLUSIONS

a) Based on the study and generalization of the general principles of constructing electric drives for borehole pumps, it is shown that in this case the problem of developing and implementing a frequency-controlled asynchronous electric drive is relevant. Regulating the performance of borehole pumps based on changing the opening/closing angle of the valve solves only technological problems. At the same time, this method they do not take into account the energy parameters of the technological process of pumping water (solution) from the well.

b) It is established that adaptation of the "motor - pump" system to the changing parameters of the technological process is a necessary condition for improving the efficiency of the operation mode of borehole pumping units. This method allows you to reduce the consumption of electrical energy and hydraulic losses.

c) A mathematical model of the system "frequency-controlled electric drive – asynchronous motor – downhole pup" has been developed, which allows taking into account the debit of the well and changes in its technological indicators.

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