IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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To cite this article: V V Platonov and T Fedorov 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **315** 032040

IOP Conf. Series: Earth and Environmental Science **315** (2019) 032040 doi:10.1088/1755-1315/315/3/032040

Energy-efficient pumping installations at agricultural production facilities

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Abstract. The article presents the method of the feasibility study of various methods of regulation on pumping installations of agricultural objects. It was found that the best results are observed in electric drives with frequency converters and valve cascade: here the total losses Q_{min} mode are only about 10% of the base value, which is explained by minimal losses in pipelines. There is no need to use valves at all. It is shown that with parametric control of the speed of an asynchronous electric drive with a phase-rotor, the loss in hydraulic elements (pump and network) has the same value as with frequency control (about 10% of the base value), but slip losses increase by 12%

1. Introduction

Pumping installations are widely used in agriculture. The share of electric drives in such objects is more than 50%. Therefore, the task of reducing energy usage in such installations is important and relevant [1]. To date, speed control at such facilities is performed in a throttle manner. In this case, it is necessary to overestimate the installed capacity of the electrical installation, the load on the hydraulic system increases, and the reliability of the object decreases. The most optimal way to reduce loads is to switch to an adjustable electric drive, when the pressure in the hydraulic system does not change due to the valve but by changing the speed of the electric machine [2, 3]. However, choosing an adjustable drive requires a feasibility study. In some cases, when the schedule of water consumption is not of an alternating nature under the terms of reliability, it is more profitable to leave an unregulated electric drive [4]. With this in mind, the problem of choosing a calculation method for substantiating the use of an adjustable electric drive at agricultural objects of pumping plants is relevant and requiring its solution.

2. Research problem statement

In order to improve the energy performance of the electric drive, the urgent task is to search for calculation methods, which requires solving the following subtasks:

- analysis of the reasons for the overestimation of the installed capacity of the electric drive;
- analysis of the effect of uneven load curve;
- the choice of calculation methods and the results of the comparison of electricity losses with different methods of flow control.

3. Causes of excessive energy consumption in unregulated electric drives of pumping units

The overwhelming part of the electric drives of pumping units is made according to the open (without feedback) principle [5]. The inability to control the angular speed of the pump unit, the discrete power range of the pumps and electric motors lead to an excessive consumption of electricity when the working conditions change [6, 7].

If conditionally all the costs of operating the pump for its entire service life are taken as 100%, then according to [8] approximately 3% is spent on its maintenance, 3% on initial investments, and 94% on electricity costs. This shows the important role of energy saving in electric pumps.

The joint operation of a centrifugal pump on a hydraulic network is illustrated in figure 1, where the pressure-flow characteristic of the pump is shown - the dependence of the generated head H on the flow rate Q (curve 1) - and the characteristic of the hydraulic network - the dependence of the pressure loss in the pipeline on the flow rate (curve 2). The abscissa of the point a at the intersection of these curves corresponds to the flow of water that is provided by the pump. The ordinate of the point a corresponds to the pressure loss in the pipeline and is equal to the pressure created by the pump. In this mode, the pump power required for pumping fluid is minimal [9].

We indicate the main cases of over-consumption of electricity with the "right" choice of electrical and hydraulic equipment.

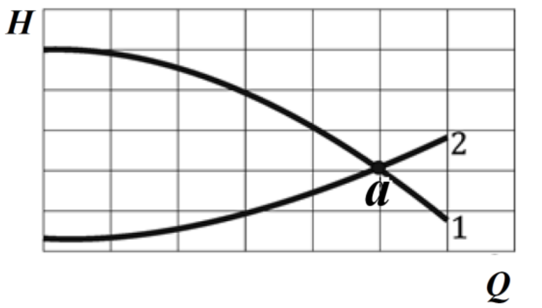

Figure 1. Pressure head pump characteristic and characteristic hydraulic network.

4. The deviation of the real resistance of the hydraulic network from the calculated value

This is possible for a number of reasons that cannot be accurately taken into account at the hydraulic equipment selection stage: changes in the pipeline route [10], clarification of the estimated number of bends in the pipeline [11], reduction of the pipeline section due to the appearance of a crust of dirt on the inner surface of the pipe [12]. In this case, instead of the calculated curve 2 (in figure 1 and 2.) We get the curve 3 in figure 2. Comparing curves 1 and 3, we see that in this case the water consumption will decrease (point b in figure 2). In order to return to the previous flow rate, a higher power pump is necessary, having a pressure-flow characteristic corresponding to curve 4 [13]. Point c corresponds to a new overestimated head value at the same pump capacity. The length of a-c is proportional to the overestimation of pump power [14, 15].

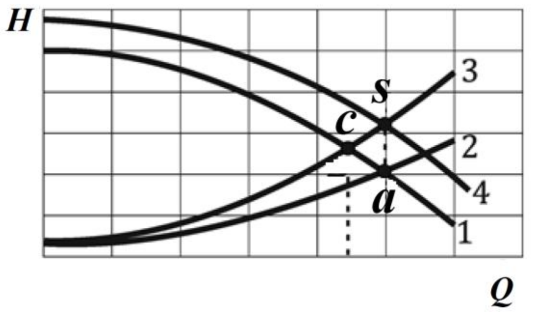

Figure 2. Effect of magnification hydraulic resistance network to choose pressure head pump characteristics.

5. Discrete series of nominal powers of pumps and electric motors.

Unfortunately, we have to choose a pump whose pressure-flow characteristic corresponds exactly to curve 4 in figure 2 and 3, in most cases, fails, as the number of nominal pump powers is discrete [16, 17]. For this reason, the developer, in order not to risk, chooses a pump of the nearest greater power, which has a pressure-flow characteristic lying above curve 4 (see curve 5 in figure 3) [18, 19]. In this case, the “discharge flow” combination corresponds to point e *d*. The excess of the resulting pressure has to be extinguished by a valve, i.e. additionally increase the losses in the hydraulic network [20].

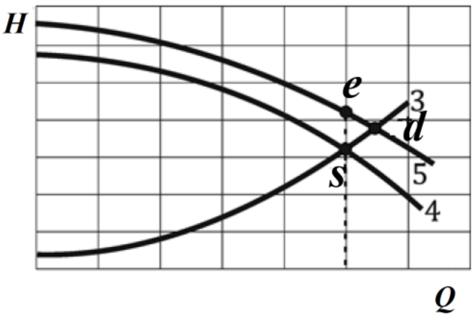

Figure 3. Influence of discrete power range on pressure head pump characteristic.

Electric motors also have a discrete series of nominal powers and angular speeds of rotation of the shaft, which often do not coincide with a discrete range of powers and angular velocities of rotation of the shaft of the pump wheel [21]. This causes a further overestimation of the overall power of the electric drive and, consequently, leads to an increase in losses [22].

6. Uneven schedule of water consumption

Here it is necessary to reckon with the obligatory condition of guaranteeing the operability of the hydraulic system with maximum water consumption, i.e. choose the hydraulic and electrical equipment of the pump for maximum performance. However, as experience shows, even in the nominal mode, pumping units are loaded no more than 80% [23, 24], and during periods of consumption failure (night hours), the required capacity decreases even more [25]. The entire excess of the installed capacity of the hydraulic unit has to be “blown off” by the gate valves.

Taking into account the above circumstances, even in the most favorable case and with an unmistakable choice of pump and electric equipment, the installed capacity is overestimated, and in the working range of water consumption values, the pump’s discharge flow characteristic is significantly higher than the network’s hydraulic characteristics, which entails large unjustified losses [26].

In order to minimize the losses in the electric drive and hydraulic aggregate in the process of fluid supply, it is necessary that the operating point a in figure 1 moved along the characteristics of the hydraulic network, but not along the pressure-flow characteristics of the pump [27]. This can be achieved only in the case when the speed of the pump unit is adjusted with minimal losses (for example, in the frequency regulation scheme of the electric drive) [28].

7. The choice of calculation methods and the results of the comparison of electric power losses with different methods of flow control

In solving this problem, the static characteristics of the hydraulic network elements (figure 4) and the mechanical characteristics of the electric drives and pumps (figure 5) were used [29]. In order to simplify the active resistances on the electric circuit, the substitutions were assumed to be constant. Their value corresponded to the slope of the static characteristics of the elements of the hydraulic network in the working range of change of water flow Q_3 [30]. In figure 4 this range corresponds to a change in flow rate from Q_{MIN} to Q_{MAX}.

When the pumping stations of the first ascent worked with the maximum water supply (Q_{MAX} = 3000 m³⁄h was taken in the calculations), the state of the hydraulic network was determined by the point *a* of the intersection of characteristics 1 and 3 in figure 4 [31]. If under the terms of the technology it was necessary to reduce the flow to Q_{MIN} (Q_{MIN} = 26,000 m³⁄h was taken), then this could be achieved in two ways: or reduce the angular velocity of the pumps with the same and most favorable pipeline performance (see the intersection point *b* of characteristics 2 and 3) [32], or at a constant angular velocity of the pump motors, change the characteristic of the pipeline by covering the valves (see the point *c* at the intersection of characteristics 1 and 4) [33]. The segment *b*-*c* in is proportional to the additional losses in the pipeline due to flow control by the valve.

On the mechanical characteristics of the units under consideration (figure 5), the maximum feed mode corresponds to the point *a* of intersection of characteristics 1 and 3. The mechanical power developed by the engine is equal to the product of the angular velocity and the moment at that point. When the water supply is reduced, closing the valve, the angular velocity of the pump due to the rigid mechanical characteristics of the engine remains almost unchanged, but the moment decreases slightly (the point *c* at the intersection of characteristics 1 and 4).

When the water supply changes with fully open valves, it doesn't matter for the pump in what way its speed is regulated. But in this case, the energy indicators of the electric drive itself depend on the adopted method of speed control. With frequency regulation of speed or regulation of speed in the asynchronous valve cascade circuit, the mechanical characteristic of the engine is shifted downward, practically not changing in shape (curve 2 in figure 5). The losses in the electric drive are insignificant and are approximately equal to the losses in the electric motor when operating it on the natural mechanical characteristic. It is possible to obtain the operating mode of the electric drive at point *b* in another way, namely: it is possible to introduce additional resistors into the rotor circuit of an induction motor with slip rings and, softening its mechanical characteristic (curve 5 in figure 5), achieve the required reduction in angular velocity. But in this case, slip losses are distinguished in the rotor circuit, the power of which is equal to the product of the difference between the ideal idling speed of the engine and the speed at point *b* at the time of the engine at that point. Since point *b* lies below point *c*, the total losses in the "electric drive-pump" unit turn out to be smaller [34].

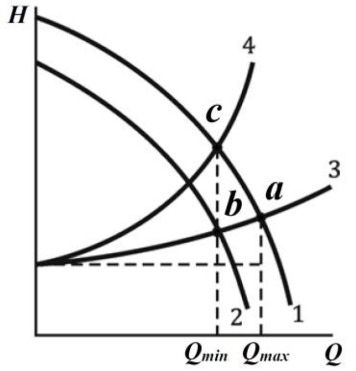

Figure 4. Static characteristics at nominal (1) and low (2) angular wheel speed pump, as well as when open (3) and partially closed (4) pipeline valves.

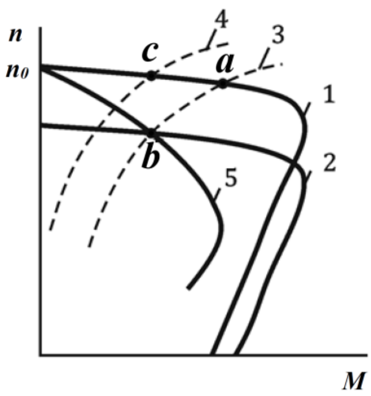

Figure 5. Mechanical asynchronous characteristics electric drive (1 natural, 2 - at frequency or cascade regulation, 5 Areostatnom regulation) and pumping unit (3 - with fully open, 4 – partially closed valve).

Energy calculations in electric drives of pump stations of the first lift were performed in the following sequence. First, for a given value of the maximum flow rate Q_{MAX} = 33000 m^3 (h (point *a* in figure 4 and 5), the value of the useful power of the pump (or group of pumps) was determined:

$$P_{\mathrm{p}} = \rho \cdot g \cdot H \cdot Q,$$

where ρ is the specific density of water; g - gravitational acceleration; Q - supply (consumption) of water; H - head at a given flow rate. According to the characteristics and passport data of pumps [35, 36], electric motors [37] and pipelines known from official reference books, the power at the motor shaft and the magnitude of losses in the unit were determined.

When changing the flow rate in the network from Q_{MAX} to Q_{MIN} using valves at unregulated speed of the motors of pumping units (point *c* in figure 4 and 5), using characteristic 1, the required values of H and Q were determined, and the effective power of the pump, shaft power and on the stator of the electric motor, which then determined the total amount of losses in the unit.

When changing the flow rate in the network from Q_{MAX} to Q_{MIN}, the speed control of the motors of pumping units (point *b* in figure 4 and 5) has to use characteristic 2, which is not in the reference books. Therefore, for a given value of the flow rate Q_{MIN}, characteristic 1 was recalculated in accordance with the generally accepted methodology [38] based on the known laws of proportionality of the pump:

$$\frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2$$

Here, H_1 and H_2 are the head values at engine speeds n_1 and n_2.

The further course of the calculations depended on the chosen method of controlling the speed of the pump electric drive. When rheostat speed control losses in the drive were determined on the basis of the expression

$$\Delta P_p = (n_0 - n_б) \cdot M_б,$$

where n_0 is the synchronous motor speed; n_b is the motor speed at point *b* (figure 5); M_b is the motor torque at the same point.

When speed regulation is performed using a frequency converter or in a valve cascade circuit, the losses in the electric drive, the same as when working on a natural mechanical characteristic (taken into account approximately the nominal passport efficiency of the engine), were added to the loss in the frequency converter (or the stage inverter) and additional losses in the engine, due to the non-sinusoidal currents of the engine, working complete with a valve converter [39, 40]. They were assumed to be 0.03 of the rated power of the electric drive.

An audit conducted for the pumps and their electric drives, and the subsequent refined analysis of the regimes showed that the pumps with fully open valves were not activated due to excessive head pressure in the pump units. Naturally, the energy performance of the pumping units in this case deteriorated, especially since the value of the excess head was about 14 m (with a maximum head developed by the pumps about 32 m). Since the presence of excess pressure adversely affects the energy of pumping units only when the throttle control flow, and when it is regulated by changing the speed of the engines of pumping units it is irrelevant, the calculations were performed for both conditions.

The calculation results showed the following. As expected, the largest loss is observed with throttle (using a valve) flow control. When the flow rate in the network is equal *to* Q_{MIN}, the relative total value of losses $\Delta P_{ЗАДВ} + \Delta P_{ТРУБ} = 0{,}39 + 0{,}08 = 0{,}47$ of the base power value.

The best results are observed in electric drives with frequency converters and a valve cascade: here the total losses in the Q_{MIN} mode are only about 10% of the base value. This is caused, firstly, by the minimum losses in pipelines, when there is no need to use valves at the flow control, and secondly, the minimum losses in the electric drive, when the engine slip is minimal (in the frequency converter circuit), or the slip energy is recuperated in network (in the circuit of the valve cascade).

It is also interesting to evaluate the energy of the rheostat method of controlling the speed of the electric drive of the pumps. There are no additional losses associated with an increase in the hydraulic resistance of the pipeline due to the impact on the valve. As a result, the rheostatic regulation of the speed of an asynchronous motor with a phase-rotor has a magnitude of losses in the hydraulic elements (pump and network) the same as with frequency regulation (about 10% of the base value). True, this adds a slip loss in an asynchronous motor, which is about 12%. The total losses in the rheostatic regulation of the speed of the motors of the pumps are about 22%. This figure is better than with throttle flow control valve, but inferior to the frequency control and valve stage.

8. Conclusion

It was found that the best results are observed in electric drives with frequency converters and valve cascade: here the total losses in Q_{MIN} mode are only about 10% of the base value, which is explained by minimal losses in pipelines, when there is no need to use valves

It is shown that with parametric control of the speed of an asynchronous electric drive with a phase-rotor, the loss in hydraulic elements (pump and network) has the same value as with frequency control (about 10% of the base value), but slip losses increase by 12%.

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