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Pumping energy consumption in water transportation systems

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ABSTRACT
Selected systems for controlling the operation of water system pump stations are characterised. Dependencies defining the efficiency of a pump set are presented in consideration of pump and motor efficiency variations at variable characteristic curves of distribution. Pump and motor efficiencies at constant and variable rotational speeds are defined. A comparative analysis of water pumping energy consumption is carried out for the control systems under discussion, where the distribution characteristic curves describe irrigation systems.

KEYWORDS: efficiency, water pumping, control system, energy consumption, motor efficiency, pump efficiency

1. Introduction

Ineffective consumption of energy adversely affects the natural environment. An improved energy effectiveness of operation processes limits end users' demand for energy and has beneficial impact on climate effects, restricts harmful emissions, improves health conditions, and limits the energy consumption of the Gross National Product [7], [13].

Significant quantities of energy are necessary to transport water. Water system pump stations in Poland are estimated to consume approximately 2,000 GWh a year. To improve the energy effectiveness of water transportation, it is necessary to reduce the energy consumption of pumping e [kWh/m3]. Unit energy consumption depends on the efficiency of a pump and an induction motor and, to a substantial extent, on a control system of a pump set [13].

The choice of a control system depends on the nature of distribution in a water system, where the given pump set is expected to operate [6], [7], [13]. Irrigation systems in farming, forest management, in sports and leisure facilities are special cases of a water system [3]. As opposed to municipal water mains, a pump unit of an irrigation system may operate at variable pressure in the pump set collector, while the water distribution is known and recurrent. The pump set collector pressure and water station flow rate depend on the number and type of working irrigation equipment. The irrigation equipment has a constant nominal pressure and is combined in so-called sections. The flow rate of a section is the sum total of outputs of irrigation devices making up such a section. Each section is therefore characterised by a pressure and nominal distribution that slightly change over a system's lifecycle as the irrigation equipment experiences wear. Each section operates for a time, which is dependent on the type of irrigated vegetation. The irrigation time may vary in line with weather conditions. Thus, it can be assumed that characteristic curves of an irrigation system's distribution are constant and recurrent in cycles [3].

The nature of distribution in irrigation systems presented in this paper provides an opportunity for developing an energy-saving control system dedicated to these applications. An energy-saving control system for pump operations would be based on the provision of a nominal pressure for irrigation equipment and minimization of unit energy consumption of a pump set, determined on the basis of momentary efficiencies of pump units.

This paper presents a comparative analysis of the energy consumption for water pumping in irrigation systems for selected control systems. A characteristic curve of an irrigation system's distribution is defined with regard to discrete productivity variations and pressure associated with types of the irrigation equipment used.

2. Energy consumption for water pumping

The effectiveness of water pumping depends, among other factors, on momentary efficiency ηc of a pump set.

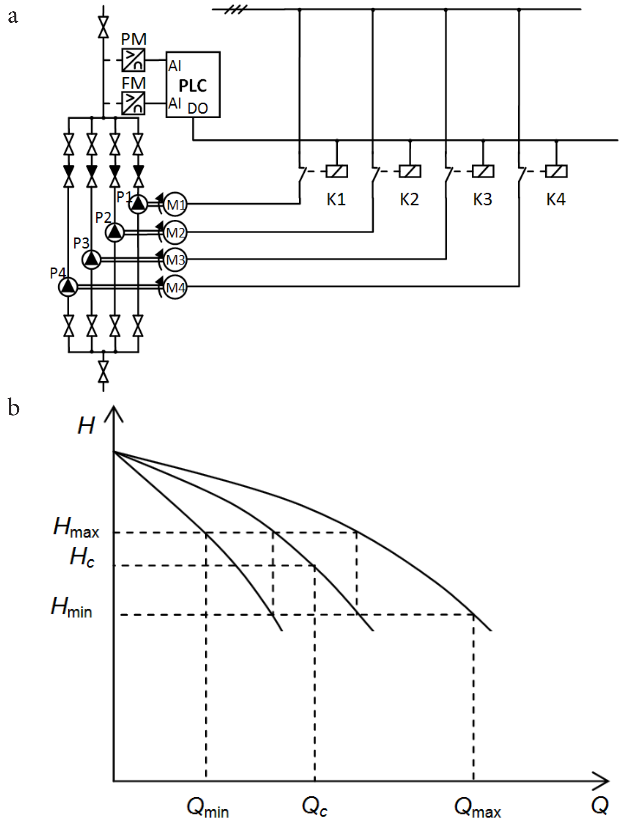

Fig. 1. Cascade control system: a) plumbing and wiring diagram, b) curve of a pump set flow
Source: [own work]

Energy-saving control systems for water pumping processes should select rotational speeds nzi of pump units so as to maximise total efficiency ηc of a pump unit while providing for minimum requirements of users. Efficiency ηc of a pump unit is expressed as [13]:

$$\eta_c = \frac{Q_c}{\sum_{i=1}^{m} \frac{Q_{zi}}{\eta_{zi}}} \tag{1}$$

where: Q_c – total efficiency of a pump set; Q_{zi} – capacity of ith pump unit; η_{zi} – total efficiency of a pump set; m – number of working pump units.

To assess the energy consumption for water pumping when selected control systems are applied to pumping operations, a general dependency is defined for the unit energy consumption e of pumping:

$$e = \frac{1}{367} \frac{H_c}{Q_c} \sum_{i=1}^{m} \frac{Q_{zi}}{\eta_{zi}} \tag{2}$$

Based on equation (2), which defines unit energy consumption e of water pumping, dependencies can be developed to define unit energy consumptions for pumping for selected control systems of pump sets.

2.1. Energy consumption for pumping, where cascade control is applied

Cascade control (Fig.1b) involves turning pumps in a pump set on and off depending on momentary water distributions Q_c and set values of head – maximum H_{max} and minimum H_{min}. Pump motors are powered directly from electricity mains of constant voltage frequency f=50Hz. As frequency converters are not part of this control system, the efficiency η_{fi} is assumed to equal one. The characteristic curve of a pump set flow changes depending on the number of pumps in operation (Fig. 1a). Declared head values of H_{max} and H_{min} determine a variation range of a pump station's flow rate from Q_{max} to Q_{min}. Energy consumption unit e_k for cascade controlling is [13]:

$$e_k = \frac{1}{367} \frac{H_c}{\eta_{zi}(Q_{zi}, H_c)} \tag{3}$$

2.2. Energy consumption for pumping, where a single-drive control is applied

Converter control involves selection of a lead pump in a pump set, with its motor supplied from a frequency converter (Fig. 2a). Such a pump operates at variable rotational speed, which stabilises pressure around a set head H_{zad} (Fig. 2b). At a nominal rotational speed n_N, the lead pump operates at

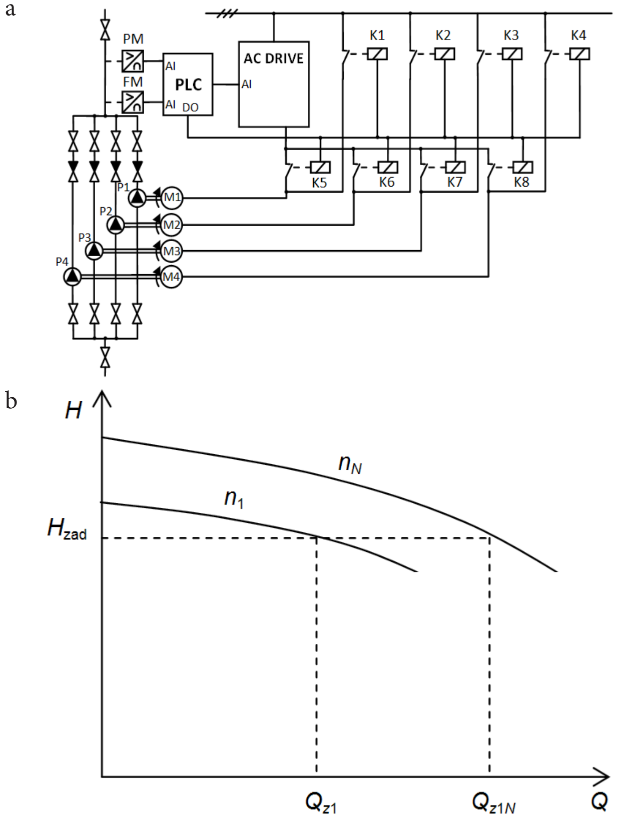

Fig. 2. Single-drive control system: a) plumbing and wiring diagram, b) curve of a pump unit flow
Source: [own work]

flow rate Q_{z1N} with head H_{zad}. If water flow rate diminishes from Q_{z1N} to Q_{z1} in order to maintain head H_{zad}, the rotational speed is reduced to n_1, so that the pump's working point (Q_{z1}, H_{zad}) is part of the flow characteristic curve determined for n_1. If water flow rate rises above Q_{z1N}, additional pumps in the set are turned on and working at a rotational speed n_N. The pump unit energy consumption e_p is defined [13]:

$$e_p = \frac{1}{Q_m}\left(\frac{H_{zad}}{367}\frac{Q_{z1}}{\eta_{z1}(Q_{z1},H_{zad})}+\frac{H_{zad}}{367}\sum_{i=2}^{m}\frac{Q_{zi}}{\eta_{zi}(Q_{zi},H_{zad})}\right) \quad (4)$$

where: η_{z1} - efficiency of the leading pump unit Q_{z1}

2.3. Energy consumption for pumping, where a multi-drive control is applied

A multi-drive control system involves varying rotational speeds of all pumps in operation in order to maintain H_{zad} of the pump unit, when pump station's distribution Q_c changes [3], [13]. Each pump motor is supplied from a frequency converter (Fig. 3).

Rotational speed n_{zi} of operating pumps is selected in order to maintain the total efficiency η_c of a pump set at a maximum. Unit energy consumption e_M of a pump station under a multi-drive control is:

$$e_M = \frac{1}{367}\frac{H_{zad}}{Q_m}\sum_{i=1}^{m}\frac{Q_{zi}}{\eta_{zi}(Q_{zi},H_{zad})} \quad (5)$$

3. Efficiency of a pumping unit

Efficiency η_{zi} of ith pump unit is defined as efficiency η_{fi} of a frequency converter multiplied by efficiency η_{si} of a pump drive and efficiency η_{pi} of a pump [7], [13]:

$$\eta_{zi} = \eta_{fi}\eta_{si}\eta_{pi} \quad (6)$$

It is assumed here that efficiency η_{fi} of a frequency converter is constant regardless of the voltage frequency f at the converter input and of the output active power P_1.

3.1. Pump's efficiency

Depending on a control system, pump units may operate at constant nominal rotational speed n_N or variable rotational speed n_{zi}. Determination of the pump's η_{pi} with regard to both types of pump operation requires the application of different calculation algorithms.

Efficiency η_{pi} of ith pump, where a pump set operates at constant rotational speed n_N, is calculated on the basis of characteristic curves supplied by a pump manufacturer. The dependence efficiency $\eta_{pi}=f(Q_{zi})$ can be expressed as a quadratic function [5], [7], [13]:

$$\eta_{pi} = aQ_{zi}^2 + bQ_{zi} + c \quad (7)$$

where: a, b, c – quadratic equation factors.

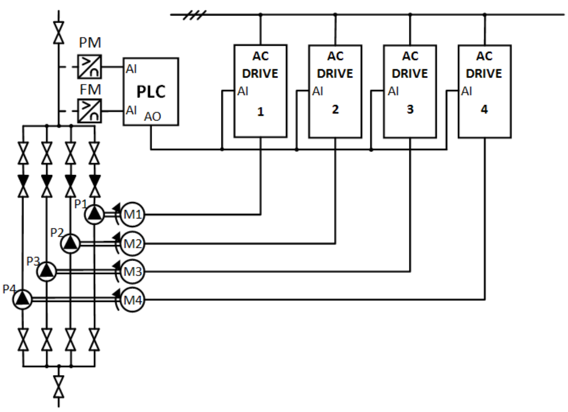

Fig. 3. Plumbing and wiring diagram for a multi-drive control
Source: [own work]

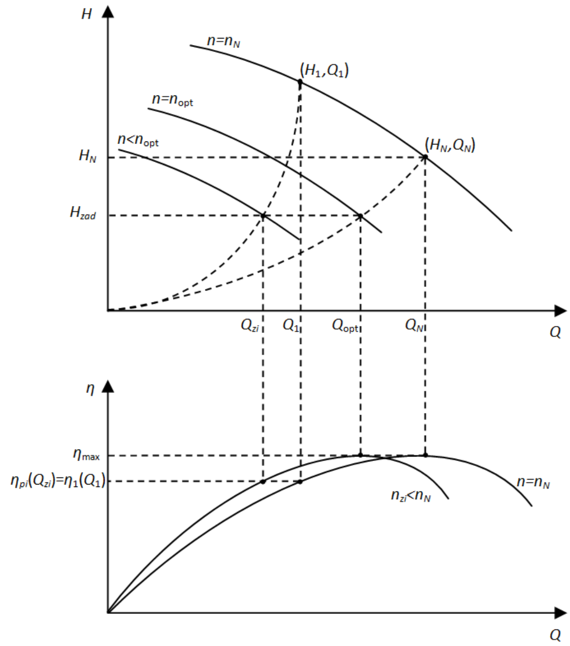

Fig. 4. Graphic algorithm to determine the efficiency of a pump at variable rotational speed
Source: [own work]

The head H_{pi} of a pump is based on a flow characteristic curve expressed by [7]:

$$H_{pi} = H_0 - AQ_{zi} - BQ_{zi}^2 \tag{8}$$

where: H_0 – static pump head; A, B – quadratic equation factors.

In order to determine efficiency η_{pi} of ith pump operating at a variable rotational speed n_{zi}, the method described in [13] is employed (Fig. 4). The pump's operation at a variable rotational speed causes its flow Q_{zi} and head H_{pi} to vary. According to the theory of probability, the flow Q_{zi} is assumed to vary following [7]:

$$\frac{Q_{zi}}{Q_1} = \frac{n_{zi}}{n_N} \tag{9}$$

where: Q_1 – pump unit flow rate at a nominal speed n_N and pump head H_1 (Fig. 4).

The pump's head H_{zad} varies in proportion to a square of rotational speed n_{zi} [13]:

$$\frac{H_{zad}}{H_1} = \left(\frac{n_{zi}}{n_N}\right)^2 \tag{10}$$

Equations (9) and (10) produce a relation between the pump's head and flow rate at variable rotational speed:

$$\frac{H_{zad}}{H_1} = \left(\frac{Q_{zi}}{Q_1}\right)^2 \tag{11}$$

To determine the pump's efficiency η_{pi} for a working point (Q_{zi}, H_{zad}) at efficiency n_{zi}, it is necessary to establish flow rate Q_1 for the pump's rotational speed n_N corresponding to flow rate Q_{zi} (Fig. 4) [13]

A characteristic curve of a pump's flow at nominal efficiency n_N is defined:

$$H_1 = H_0 - AQ_1 - BQ_1^2 \tag{12}$$

On the basis of equations (11) and (12), a dependency defining flow rate Q_1 is derived [7], [13]:

$$Q_1 = \frac{\sqrt{A_2 + 4H_0\left(B + \frac{H_{zad}}{Q_{zi}^2}\right)} - A}{2\left(B + \frac{H_{zad}}{Q_{zi}^2}\right)} \tag{13}$$

Efficiency $\eta_1(Q_1)$ is defined by means of equation (7). Employing the resultant efficiency η_1 and the original power function of the pump [7], the pump efficiency η_{pi} is computed:

$$\eta_{pi} = \eta_1\left(\frac{n_{zi}}{n_N}\right)^{0,09} = \eta_1\left(\frac{Q_{zi}}{Q_1}\right)^{0,09} \tag{14}$$

Rotational speed n_{zi} of a pump unit is derived from equation (10) and defined:

$$n_{zi} = n_N\sqrt{\frac{H_{zad}}{H_1}} \tag{15}$$

3.2. Efficiency of an induction motor

Based on the pump's head H_{pi}, flow rate Q_{zi} and efficiency η_{pi}, the power P_{2i} across the motor of ith pump unit is defined according to [7], [13]:

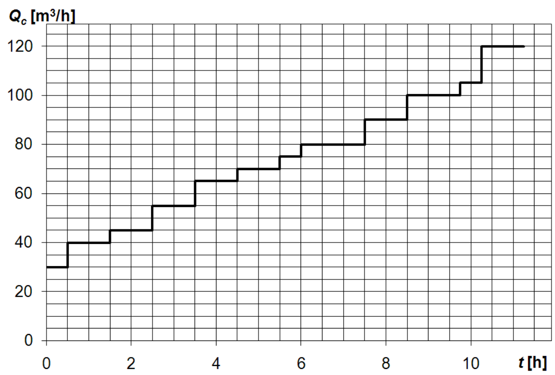

Fig. 5. Sample arranged characteristic curve of distribution in an irrigation system
Source: [own work]

$$P_{2i} = \frac{\rho g}{3600} \frac{H_{pi} Q_{zi}}{\eta_{pi}} \qquad (16)$$

where: ρ – water density; g – acceleration of gravity.

Torque T_i across an induction motor shaft is defined as the relation of P_{2i} across the shaft to the motor's rotational speed n_{zi} [8], [9], [12]:

$$T_i = 9{,}55 \frac{P_{2i}}{n_{zi}} \qquad (17)$$

Assuming a linear dependence of the motor's slide s on shaft torque T_i ranging from $0.5T_N$ to T_N, relative frequency f^* of the motor supply voltage can be determined by means of:

$$f^* = \frac{f_{zi}}{f_N} = \frac{n_{zi}}{n_N} \frac{1 - s_N}{1 - s_N \frac{T_i}{T_N}} \qquad (18)$$

Papers [1] and [4] define power losses ΔP_i across a squirrel-cage induction motor as a function of f^* and relative shaft torque T_i^*:

$$\Delta P_i = 0{,}2\Delta P_{2N} + 0{,}15\left(f^*\right)^2 \Delta P_{2N} + 0{,}65\left(T_i^*\right)^2 \Delta P_{2N} \qquad (19)$$

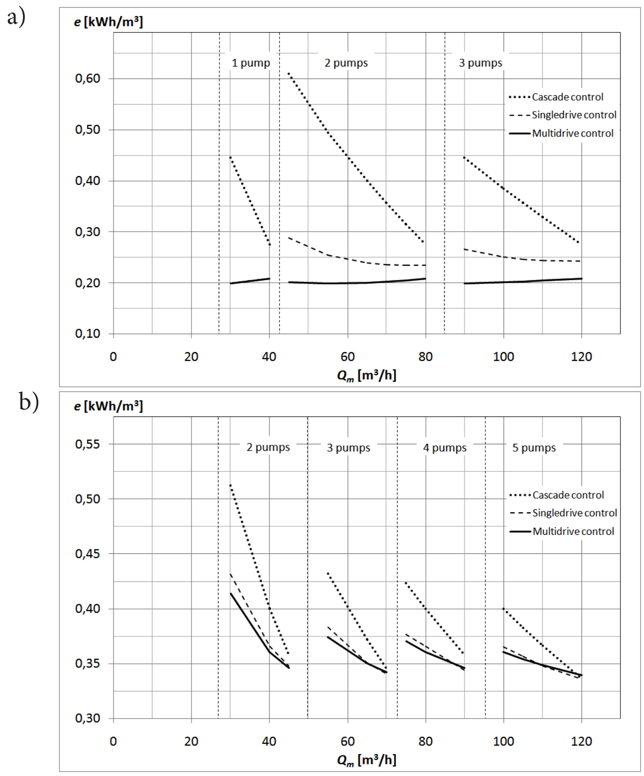

Fig. 6. Variation of the unit energy consumption e as a function of the total flow rate Qc: a) Hzad=50m, b) Hzad=85m. Source: [own work]

Table 1. Unit energy consumption e.

Cascade control	Converter control	Multi-drive control
e_k	e_p	e_M
[kWh/m³]	[kWh/m³]	[kWh/m³]
0.396	0.283	0.253

Knowing power losses ΔP_i and power P_{2i} across the motor shaft, the motor's efficiency η_{si} can be defined [8], [9], [12]:

$$\eta_{si} = \frac{P_{2i}}{P_{1i}} = \frac{P_{2i}}{P_{2i} + \Delta P_i} \qquad (20)$$

where: P_{1i} – active power consumer by the motor of ith pump unit.

4. Modelling of a pump set's operations for a selected characteristic distribution curve

With the aid of the foregoing dependencies, a comparative analysis is undertaken of unit energy consumption for pumping e for selected control systems. Minimum value of unit energy consumption e serves as the criterion of analysis.

The comparative analysis is based on the following assumptions:

- the pump station consists of five Grundfos CR32-5 pumps [2], [10],
- flow rate Q_c of the pump station varies according to the flow curve (Fig. 5),
- head H_{zad} of the pump station ranges from 40 to 85 m,
- working time of the pump station is t=11.5 h,
- efficiency of frequency converters is constant $\eta_f = 0.95$,
- flow characteristic curves and pump's efficiency η at nominal rotational speed are derived from pump manufacturer's technical specifications [2],
- at the time of cascade operation, a set head equals minimum head $H_{zad}=H_{min}$.

Unit energy consumption coefficients for selected control (Tab. 1) were derived from simulations. The lowest coefficients were obtained for the multi-drive control system. For a set characteristic curve of distribution, the multi-drive reduced the unit energy consumption by 11% compared to the converter control system and by as much as over 50% in comparison with the cascade controlling.

Numbers of pumps operating in pump sets are indicated in figures 8 and 9. At a head of 50 m (Fig. 6a) and maximum flow rate Q_{max} of a pump set, only three pump units operate. At a head of 85 m, the number of operating pumps rises to five in order to reach the maximum flow rate Q_{max} (Fig. 6b). This results from the characteristic curve of the pump's flow (8), where an increased set head reduces the pump's capacity. Reduction of the set head H_{zad} increases the energy consumption for pumping under the cascade pumping system (Fig. 6). The principal reason for the increased energy consumption is the impossibility to reduce the pump's H, closely connected with the flow rate Q_{zi} at a constant nominal rotational speed n_N of a pump unit.

The operating principle of the cascade control system causes head H in the pump station collector to be greater than the minimum head H_{min} sufficient for the operation of irrigation equipment. The difference in heads $\Delta H=H-H_{min}$ causes head losses that generate additional losses of electric power. The application of converter control reduces this effect and, when only a single pump is in operation, the unit energy consumption for pumping is the same as in the case of multi-drive control (Fig. 6a).

However, the addition of more pumps operating at the nominal rotational speed n_N increases unit energy consumption e_p for pumping, when compared to the multi-drive system. When a pump set operates close to its nominal capacity Q_{mN} and its nominal head H_N, the differences among the control systems are negligible (Fig. 6b). Adverse effects of applying a frequency converter on the unit energy consumption for pumping can be noted in Fig. 6b. Where a pump unit works at its nominal capacity Q_N and nominal head H_N, the frequency converter generates additional losses associated with electricity conversion [11] and, in these cases, causes the unit energy consumption for pumping for multi-drive and converter control systems to be greater than for the cascade controlling. Given the selected characteristic curve of distribution, however, this does not lead to increasing the total unit energy consumption for multi-drive and converter control systems. Our calculations indicate that, where a multi-drive control system is employed, the maximum power and torque across the pump motor's shaft are approximately 20% lower than in the case of cascade control.

6. Conclusions

The comparative analysis of a pump station's energy consumption in irrigation systems suggests that the multi-drive provides for the most energy-saving water pumping, given a sample characteristic curve of distribution. Calculation results lead us to believe that the application of this control system to irrigation should bring expected reductions of electricity costs. The converter and the multi-drive systems exhibit lower unit energy consumption at the flow rate ranging from $0.25Q_{mN}$ of a pump set's flow rate Q_{mN}. In addition, the multi-drive system reduces the unit energy consumption for pumping when it becomes necessary to lower the head in the pump station. The application of frequency converters to drive all motors additionally reduces water hammers associated with a direct start-up. This prevents faults of irrigation systems by extending the lifecycle of hydraulic equipment and reducing the fatigue of pipeline and fitting materials.

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