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Increase of Energy Efficiency in Pump Electric Drive

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Abstract*–Typical low efficiency drives are pumps, fans and blowers that have a centrifugal torque characteristic $T=f(n^2)$. In these electric drives there is great technical and economic potential for significant energy savings. Pumps are the most numerous working machines, therefore the electric drives with pump will be considered in this paper. First a brief introduction to pump systems will be given and then the ways in which the operating point of the pump can be regulated will be also presented. For the purpose of this investigation, a program was developed in the MATLAB software package for the calculation of energy savings and with its helpa comparison between conventional ways of regulating the operating point of the pump and regulation of the operating point through variable electric drive speed was realized. Using this program, the electricity consumption of low, medium and high power pumps driven by induction motors that have the ability to regulate the rotation speed through an inverter with U/f regulation will be analyzed.

1 Introduction

The industry is a large consumer of electricity which in 2014 participated with approximately 42.5% in the total electricity consumption in the world.As much as 65% -70% of the total electricity consumption in industry is accounted for by electric drives [1].Due to their wide application, electric drives as a major consumer of electricity are becoming quite attractive for finding ways to improve their energy efficiency and its implementation.

This paper highlights the importance of energy efficiency in electric drives and what it represents in general. In electric drives, there are two possible ways to increase energy efficiency.One of them is the application of high efficient induction motors [2]. The second way that is considered and contributes to the improvement of energy efficiency at electric drives involves the application of power converters. For this purpose, scalar U/f regulation is explained as one of the ways to regulate it. Then an example is presented for improving the energy efficiency of the electric drives with pumps in which the regulation of the operating point is needed. In addition a brief introduction to pumping systems and their characteristics is given. Furthermore, a program has been developed in the MATLAB software package that calculates energy savings in operating point regulation by applying inverters with U/f regulation compared to operating point regulation with mechanical control. With the help of the program, an analysis was made of seventeen types of centrifugal pumps with low, medium and high power driven by induction motors. At the end, the results are presented, conclusions are drawn and the benefits of the implementation of energy converters are listed.

2 Pump system

At the beginning of this work a brief presentation of a pump system is going be presented. A pump is an energy machine or device in which energy is exchanged between the working fluid flowing through the pump and the moving parts of the pump, thereby increasing the mechanical energy of the fluid flowing from the inlet to the outlet of the pump.Pump height or pump effortH_T(m), is a measure of the pressure required to transport liquid from one tank (sucked) to another tank (suppressed) at a given flow.There is a difference between static effort and dynamic effort.Static effort H_S(m) is a measure of the pressure required to transport fluid from one tank to another in order to perform useful work.

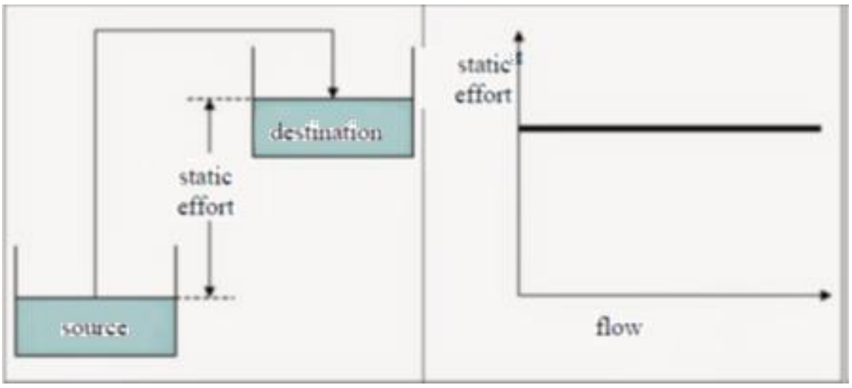


Fig.1 Static effort and its dependence on flow

Friction effort or dynamic effortH_d(m), is a measure of the components resistance that make up the system, of the energy losses that occur and is a result of the size and diameter of the pipes, the materials from which they are madeetc. and in the first approximation is proportional to the square of the flow.

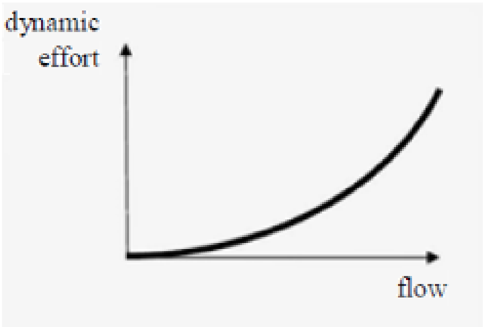
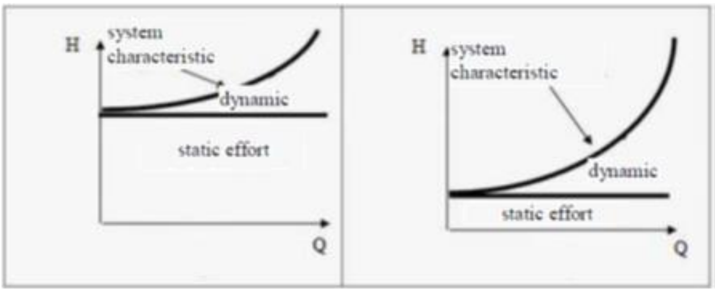


Fig.2 Dynamic effort and its dependence on flow

The sum of the static and the dynamic effort is the total effort that the pump must achieve to transfer the fluid to the required level (total head of the pump).

$$H_T=H_s+H_d \quad (1)$$

When the static effort and the dynamic effort are taken into account, is obtained the plant characteristic or the system characteristic.Two of these are shown in Fig. 3. a) and 3. b).



a) b)

Fig. 3 System characteristic at a) high static and low dynamic effort b) low static and high dynamic effort

The system characteristic is the one that is significant for the possibility of saving electricity and improving the efficiency of the system.If the static effort is relatively large compared to the dynamic one as in the case of Fig. 3a then there are smaller possibilities for energy savings.If this is not the case as shown in Fig. 3b then there is a greater potential for energy savings.

There are two types of pump systems: open and closed. Closed pump systems are circulating systems such as heating and cooling systems such as condensate cooling systems in an industry where the pump has to overcome only losses in the elements that make up the system such as friction through pipes, valves and other equipment. In other words, the pump spends all its effort on overcoming the hydraulic resistances in the piping system. Fig.4 gives an example of a closed pump system, followed by Fig.5 for the corresponding system characteristic.

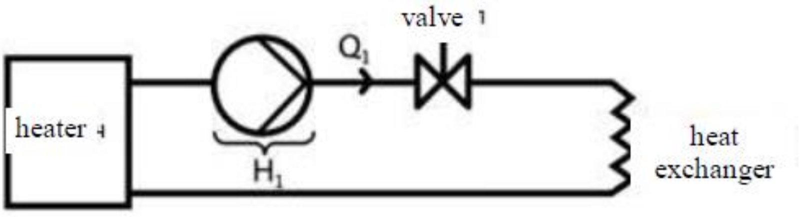


Fig. 4 Schematic representation of a closed pump system [3]

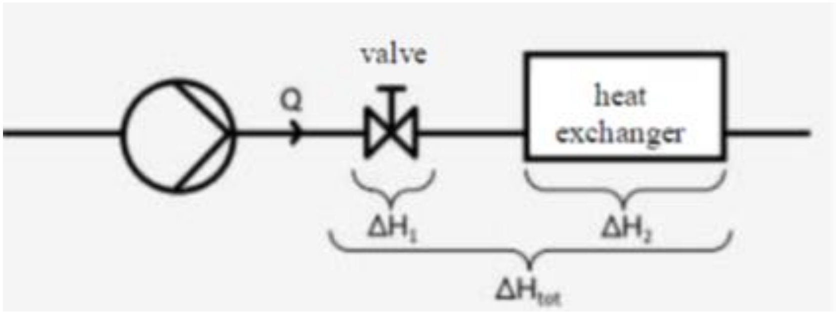


Fig. 5 Resistance of system components and losses [3]

The total hydraulic losses in the system are represented by $\Delta H_{tot} = \Delta H_1 + \Delta H_2$.By adding resistance in series increases the hydraulic losses and thus increases the effort that the pump ΔH_{tot} has to overcome (m).

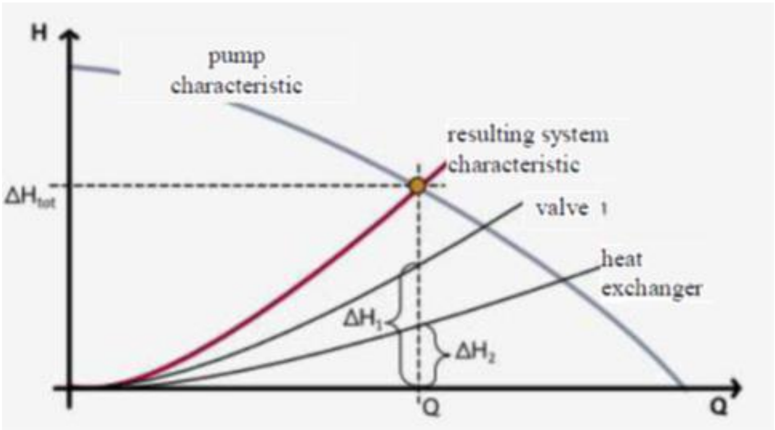


Fig. 6 Reduction of flow-Q by increasing resistance in a closed pump system [3]

As shown in Fig. 6 the effort to be overcome by the pump increases, the resulting system characteristic becomes steeper and at the intersection of the system characteristic and the pump characteristic is the new operating point of the pump with higher H and lower Q.

In open systems, the role of the pump is to generate sufficient pressure or sufficient effort H (m) to overcome the static and dynamic effort of the system (losses in pipelines and other components) to transfer the fluid to the appropriate level.

An example of an open system can be the water supply system, when the water is drained from a river and it is stored in one tank and then transferred to the required locations to be distributed. Open systems also include irrigation systems, etc. Fig.7 shows a schematic representation of an open system and Fig. 8 shows the corresponding system characteristic.

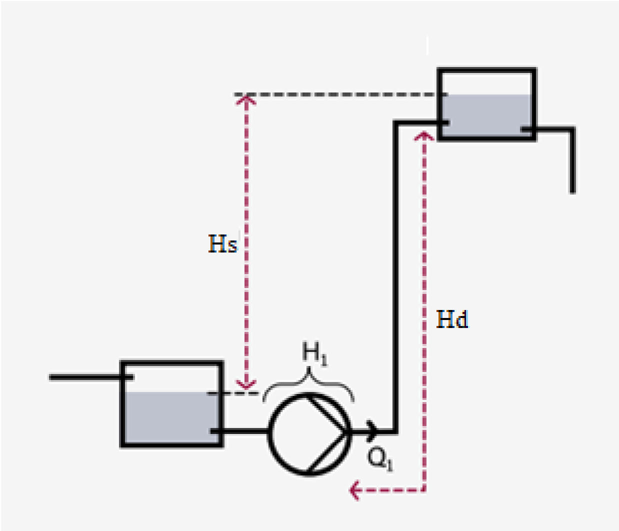


Fig. 7 Schematic representation of an open pump system [3]

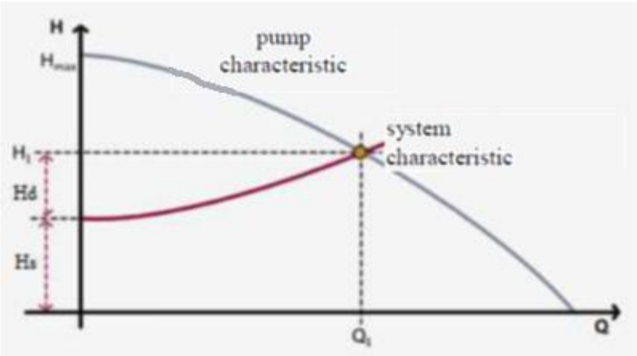


Fig. 8 System characteristic of an open pump system [3]

If the system characteristics of open and closed systems are compared, a difference will be noticed in the starting point of the parabola. In closed systems it starts from the coordinate origin, and in open systems from the value of static effort. This is because as it was previously stated in closed systems it is necessary to overcome only the hydraulic losses in the system and in open systems to those losses is added the static effort that needs to be overcome.

The characteristic of the pump is the interdependence of H and Q also known as the effort characteristic $H = f(Q)$, it is different for each pump and is given in a catalog by each manufacturer. The intersection of the system characteristic and the characteristic of the pump determines the operating point of the pump, Fig. 8.

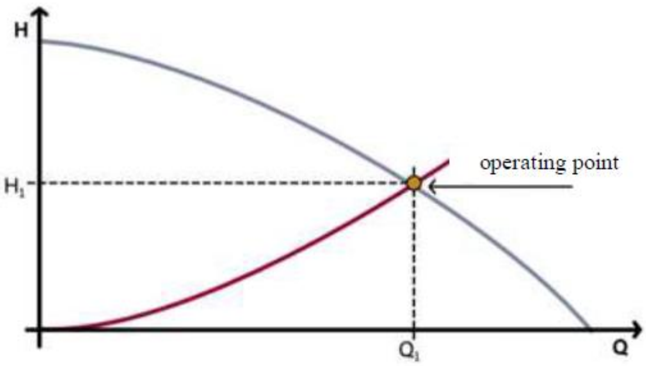


Fig. 9 Pump operating point (Q_1, H_1), intersection of system characteristic with pump characteristic

Regardless of the type of pump, the plant and the pump are two coupled parts of one system, and each of them has its own characteristic as stated above in the text. The operating point defines such operating regime of the pump in which the required effort is equal to the effort generated by the pump. The partial operating characteristics of the pump, given in the catalog by each manufacturer, provide information on the pump operating properties under variable operating conditions. The effort characteristic of the pump, as well as the characteristic of the plant can't separately provide information in which operating regime the pump will operate. In order to obtain information in which operating regime the pump will operate, it is necessary to make a joint analysis of the pumping plant characteristic with the effort characteristic of the pump.

Pump manufacturers also include several other important characteristics of the pump: the dependence of the pump efficiency on the flow, the dependence of the power on the flow and others.These characteristicsare shown in Fig.10 and 11.

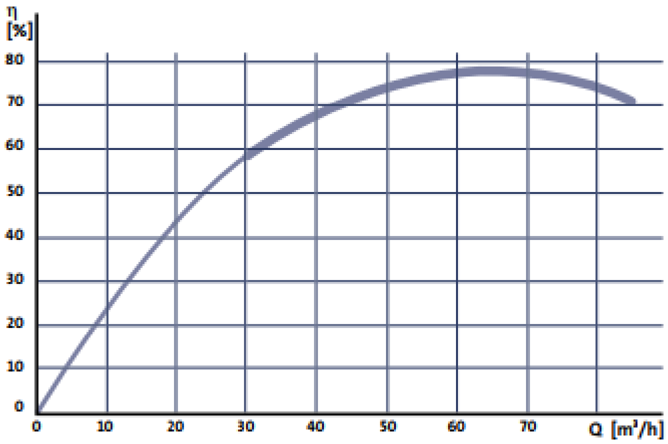


Fig. 10 Efficiency characteristic of a typical centrifugal pump [3]

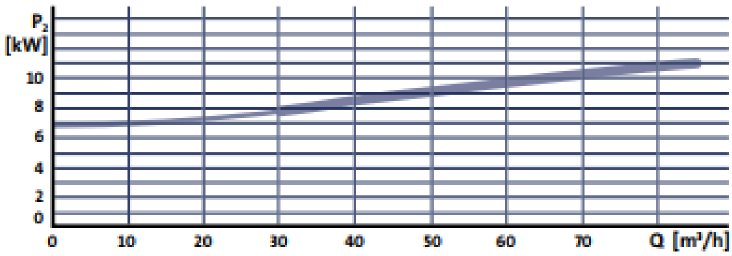


Fig. 11 Power characteristic of a typical centrifugal pump [3]

3 Changing of pump operating point

Pump regulation means intentional change of pump parameters such as flow and pressure.This can be done in two ways: by changing the pump characteristics or by changing the plant characteristics.

The operating point of the pump, flow and pressure, as needed, can be changed in one of the following ways: mechanically by applying regulating valves, by changing the blades angle of the impeller, bypass control or regulation with bypass line, useof multiple pumping system, speed regulation etc.

By installing regulating valves, usually just behind the pump, it is possible to change the hydraulic losses in the piping to be overcome by controlling its openness. Namely, by opening the regulating valve, the losses are reduced, and by closing the valve, i.e. by closing it, they increase, thus changing the resistance coefficient of the pipeline and thus changing the position of the operating point of the pump along the curve $H = f(Q)$. This method of regulation is the cheapest and simplest to apply. Fig. 12 shows how the system characteristic changes at different valve openings. Characteristic R4 shows the largest valve opening and characteristic R1 the smallest opening.

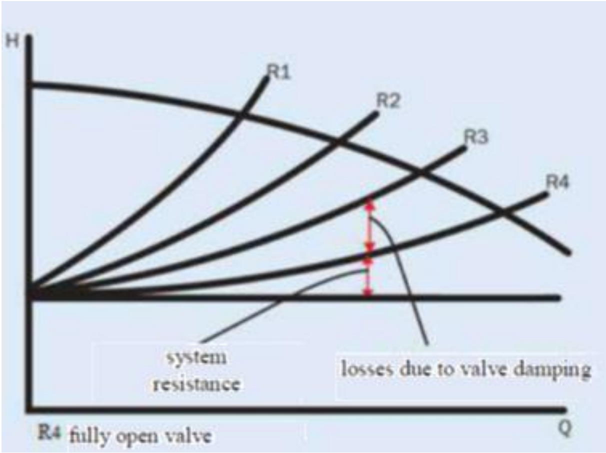


Fig. 12 Change the operating point by closing the valve in a several position

The pump is usually driven by an electric motor, more recently by an induction motor, and since one of the ways to regulate the flow of the pump is by changing the rotation speed it follows that the regulation of the flow of the pump can be donebymotor speed control.For pump systems, it is sufficient for the motor speed regulation to be scalar by applying a voltage and frequency – *U/f* converter.

For variable speed pumps, instead of the standard $H = f(Q)$ characteristic, the operating range corresponds to a set of characteristics corresponding to different rotational speeds of the electric motor.One such characteristic is shown in Fig.13.

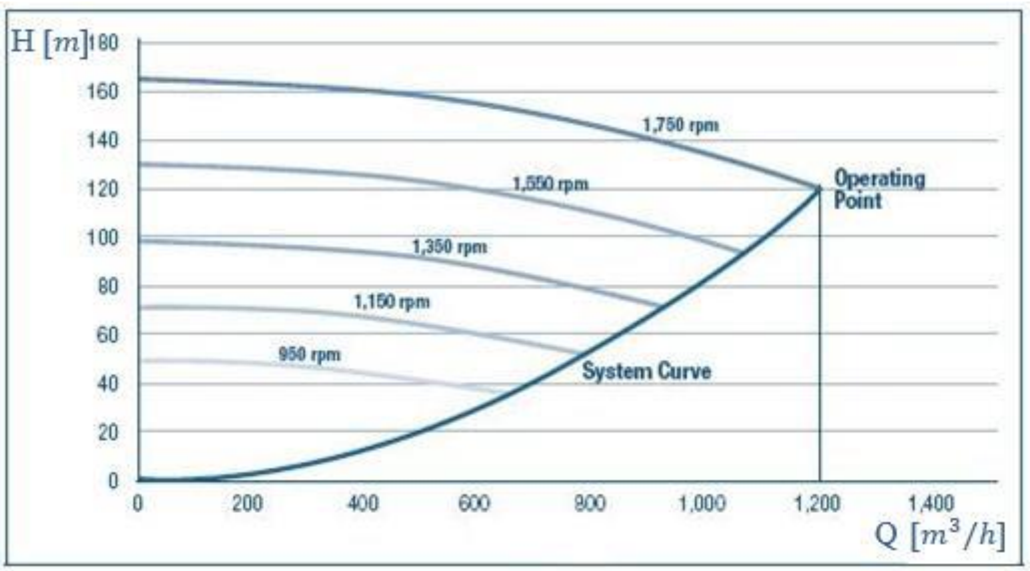


Fig. 13 Q-H characteristics at different speeds

4 Regulation of water flow in the pump system

Fig. 14 shows a diagram for the regulation of water flow through a pump in two ways.The aim is to change the water flow from Q_1 to Q_2.The first is the conventional way, with mechanical control, i.e. with the use of a control valve where the motor speed does not change.The second way is by regulating the motor speed by using an inverter.

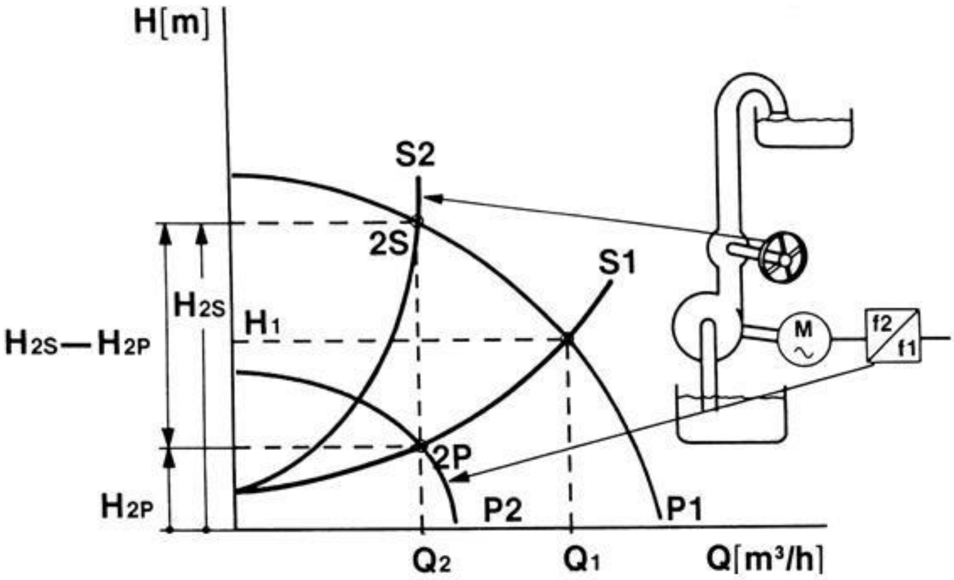


Fig. 14Centrifugal pump diagram with flow regulation

P_1– pump characteristic at rated speed n_1(min^{-1})
P_2– pump characteristic at reduced speed n_2(min^{-1})
S_1– system characteristic
S_2– system characteristic
Q_1, Q_2– pump flow (m^3/h)
H_{2S}– pump effort expressed in (m) at flow Q_2 during valve control
H_{2P} – pump effort expressed in (m)at flow Q_2 during motor speed control

In the text that follows a brief presentation of the two types of flow regulations is presented.

- **Valve control**

To reduce the flow from Q_1 to Q_2 it is necessary to close properly the regulating valve. The operating point of the pump is moved along the characteristic $H=f(Q)$ marked in Fig.14 as P_1, and passes from the system characteristic S_1 to the system characteristic S_2. The system characteristic changes from S_1 to S_2 because resistance is added to the system (damping) i.e. the hydraulic losses increase. Increasing the hydraulic losses by closing the valve, increases the effort that the pump has to make to overcome those losses during flow Q_2. In fact, damping changes the coefficient of resistance of the pipeline and thus changes the position of the operating point of the pump along the curve $P_1=H=f(Q)$. The pump effort increases from H_1 to H_{2S}.

- **Motor speed control**

To reduce the flow from Q_1 to Q_2, the operating point of the pump is shifted from characteristic P_1 with a rotational speed n_1 of the P_2 curve with a reduced motor speed n_2.By reducing the motor speed at flow Q_2, the effort required for the pump to overcome system losses and the required pressure is reduced from H_1 to H_{2P}.

The equations for the calculation of the required mechanical power of the pump generated on the shaft in both regimes of regulation is presented in the text below.

The required pump power for valve control(P_v) can be calculated using the following equation:

$$P_v = \frac{\mathrm{Q_m}[m^3/h] \times \mathrm{H_{2S}}[m] \times \rho[kg/dm^3] \times g[m/s^2]}{3600 \times \eta_1} \quad [kW] \tag{2}$$

Where the required pump power for motor speed control(P_e) can be determined using equation (3).

$$P_e = \frac{Q_m[m^3/h] \times H_{2P}[m] \times \rho[kg/dm^3] \times g[m/s^2]}{3600 \times \eta_2} \quad [kW] \tag{3}$$

The equations for the required input electrical power for both regimes of regulation is presented with the following equations.

The required input electrical power for valve control (P_{1m}), can be determined with equation (4), where the required input electrical power for motor speed control (P_{2m})can be determined with equation (5).

$$P_{1m} = \frac{P_v}{\eta_m} \quad [kW] \tag{4}$$

$$P_{2m} = \frac{P_e}{\eta_m \times \eta_{vfd}} \quad [kW] \tag{5}$$

The energy saving (E_s) if the valve control system is replaced with a power converter control can be determined using equation (5):

$$E_s=(P_{1m}-P_{2m}) \text{ x } t_a\text{(kWh/year)} \tag{6}$$

This energy converted into saved money per year (K_s) can be determined using equation (7):

$$K_s\text{(saving many per year)} =E_s \text{ (kWh/year) x k (price/kWh)} \tag{7}$$

where:

ρ(kg/dm^3)– liquid density
g(m/s^2)–ground acceleration
η_1– pump efficiency at operating point 2S, Fig.1
η_2– pump efficiency at operating point 2P, Fig.1
η_m–motor efficiency
η_{vfd}– efficiency of the inverter
t_a– number of working hours per year

5 Computer Program for calculation of energy efficiency and electricity savings

Significant energy savings can only be achieved if a wider range of control is required. If the process does not require any regulation and is constant and not dynamic, then there can be no question of saving energy by changing the working point. However, a small percentage of processes do not need regulation. In many activities related to human life such as water supply systems, heating, air conditioning, condensate cooling in industrial processes, etc. due to different activities and needs during different parts of the day, different seasons, different processes, etc. regulated processes are necessary.

To calculate the energy savings if the pump flow is regulated by changing the motor speed by means of a *U/f* converter compared to the use of regulating valves, a short computer program has been developed in MATLAB software package.

- **Program description**

The aim of the program is to enable a comparison of the two regimes of flow regulation at an arbitrarily selected pump and to give an overview of the saved electricity if the flow is regulated by changing the rotation speed compared to the conventional mode of regulation using regulating valves.The program works for any pumpentry data.

At the beginning, a function has been defined in order the user to be able to select whether the input data needed for the program should be entered from the keyboard, read from an Excel document or the user wants to close the program. In addition, a function for entering data from the keyboard is made and it is called if the user selects that option. Input variables are the flow with which the pump should operate, the pump effort corresponding to the inlet flow during valve control and the effort at the appropriate speed change, the efficiency of the pump in both regimes of regulation, motor efficiency, number of working hours per year and electricity price per kWh. It works with global variables which are then called and written to. The function for reading the above mentioned input parameters from an Excel file is made in a similar way.

The energy saving function is then activated and it invokes the previously entered variables as input data from the keyboard and reading from an Excel file. The energy saving calculation function calculates: the required power of the pump when regulating the flow with a regulating valve and when regulating the flow by changing the rotation speed, the required electric power in both modes of regulation, the consumed electricity annually the same for both regimes.It then compares them and gives how much power has been reduced in percentages if the flow is regulated by changing the rotational speed, not mechanically.Finally, it shows the annual energy savings in kWh and money saving for the predefined price.The equations used in the program are given in the text earlier.

6 Results

In order to evaluate the efficiency of the two solutions that can regulate the water flow through the pump, it is necessary to make an analysis for a specific pump.For this purpose, a comparison and analysis of the two regulation modes on 17 types of centrifugal single-stage pumps was made, selected from the catalogue of the pump manufacturer Grundfos [4].The pumps are from the same family and are powered by high efficient induction motors with low, medium and high power.The power range of the motors that will be considered is from 1.5kW to 426kW.

The parameters used in the calculations are taken from the characteristics of each of the pumps from the appropriate catalogues.Table1 provides data on the pumps used in the analysis, such as the type and serial number of the pump, the rated power of the pump and the induction motor in the drive, nominal flow and effort, efficiency, efficiency class and number of poles.

Table2 shows the data for the operating point of each of the pumps and the corresponding efficiencies depending on it in both regulation modes, then shows the efficiency of the motor that drives each of the pumps, the number of working hours per year andthe price per consumed kWh electric energy.

The analysis goes in the direction of changing the operating point of the pump.A flow reduction of 20% of the nominal was made.

Table 1Pumps data [4]

Serial number of the pump	P_n (kW)	P_2 (HP)	Q_n (m^3/h)	H_n (m)	η_{pn} (%)	η_{mn} (%)	IE	Number of poles
NKE 32-125.1/121 A1-F-A-E-BAQE	1.5	2	19.7	15.7	63.0	88.9	IE4	2
NKE 32-125.1/140 A1-F-A-E-BAQE	2.2	3	23.4	22.6	67.4	90.1	IE4	2
NKE 32-160/151 A2-F-L-E-BQQE	3	4	24.8	24.9	61.1	87.1	IE3	2
NKE 32-160/177 A2-F-K-E-BQQE	5.5	7.5	32.5	36.1	65.4	89.2	IE3	2
NKE 40-160/172 A1-F-A-E-BAQE	7.5	10	43.7	38.6	75.3	90.1	IE3	2
NKE 40-160/177 A2-F-A-E-BAQE	11	15	46.0	41.5	75.3	89.4	IE2	2
NKE 40-200/219 A2-F-L-E-BQQE	15	20	60.2	51.9	69.3	90.3	IE2	2
NKGE 150-125-250/249 A1-F-A-E-BAQE	18.5	25	254	17.4	79.8	91.2	IE2	4
NB 65-250/238 AS-F2-B-E-BAQE	37	50	134	68.1	72.7	92.6	IE2	2
NB 65-250/251 A-F2-A-E-BAQE	45	60	145	77.0	73.6	93.7	IE3	2
NB 65-250/270 AS-F-B-E-BAQE	75	100	161	89.5	75.0	94.6	IE3	2
NK 80-315/295 A1-F-A-E-BAQE	110	150	244	113.8	75.5	94.3	IE2	2
NKG 125-80-315/310 A1-F-L-E-BQQE	132	180	263	126.8	75.5	94.6	IE2	2
NK 80-315/328 A1-F-I-E-BQQE	160	210	289	143.7	76.8	95.6	IE3	2
NKG 125-80-400/398 A1-F-R-E-DAQF	250	340	289	196.9	70.2	95.4	IE2	2
NKG 200-150-315.1/335 G1-F-A-E-BAQE	355	480	965	148.9	83.0	95.5	IE2	2
TP 400-540/4 A-F-A-DBUE	450	540	2890	35.0	83.1	94.0	IE2	4

When the flow is realized by **regulating the valve opening**, to reduce the flow by 20% from Q_1=Q_n to Q_2 = Q_m (Fig. 14), it is necessary to close it properly.The operating point of the pump moves along the characteristic P_1=H=$f(Q)$ and passes from the system characteristic S_1 to the system characteristic S_2.The speed at which the motor runs is 100% of the nominal.The pump effort increases from H_1 to H_{2S}.

When the flow is realized by **regulating the motor speed** to reduce the flow by 20% from Q_1 to Q_2=Q_m, the operating point of the pump is shifted from characteristic P_1 with a rotational speed n_1 of the P_2 curve with a reduced engine speed n_2. By reducing the rotational speed of the motor at flow Q_2, the effort required for the pump to overcome system losses and the required pressure is reduced from H_1 to H_{2P}. The percentage for which the rotation speed should be reduced in order to achieve the required flow depends on the characteristics of the system, i.e. the system characteristic. In other words, the percentage of speed reduction cannot be arbitrary but depends on how much effort the pump has to withstand at reduced flow. For the purposes of this analysis the speed of all analyzed pumps is reduced by 25% of the nominal, which means the motor is running at 75% of the nominal speed and it is assumed that the total effort that the pump has to overcome is not greater than the value H_{min} of Table2.

Table 2Pumps working point data

P (kW)	Q_m (m^3/h)	H_{2s} (m)	H_{2p} (m)	η_1 (%)	η_2 (%)	η_m (%)	t_a(h)	(€/kWh)	H_{min}
1.5	15.8	17.37	8.702	60.4	62.8	88.9	3000	0.15	8
2.2	18.7	24.67	12.77	65.6	67.0	90.1	3000	0.12	12
3	18.4	27.6	14.43	57.8	61.1	87.1	3000	0.12	14
5.5	26	39.6	19.57	64.0	64.8	89.2	3000	0.12	19
7.5	35	41.46	21.83	71.0	75.0	90.1	3000	0.12	21
11	36.8	44.42	23.56	71.0	76.1	89.4	3000	0.12	23
15	48.2	58.4	29.24	68.4	69.1	90.3	3000	0.12	29
18.5	203	19.58	9.938	77.0	80.1	91.2	3000	0.12	9
37	107	75.1	38.22	71.0	72.6	92.6	3000	0.12	38
45	116	85	42.34	72.6	73.3	93.7	3000	0.12	42
75	130	98.66	48.78	74.2	74.4	94.6	3000	0.12	48
110	195	121.5	51.5	73.8	75.0	94.3	5000	0.12	61
132	210	134.8	71.03	73.3	75.4	94.6	5000	0.12	71
160	231	152.7	79.37	74.8	76.5	95.6	5000	0.12	79
250	231	213.7	107	69.1	70.1	95.4	5000	0.12	107
355	773	131.2	69.53	81.6	85.0	95.5	5000	0.12	69
450	2310	41.27	18.69	79.5	82.6	94.0	5000	0.12	18

The pump data shown in Table2, as previously stated, is the data required to perform the calculations. The definition of the variables presented in Table 2 is given below:

Q_m– flow through the pump (m^3/h)
H_{2S}– pump effort expressed in (m) at Q_m flow with valve regulation and rated motor speed
H_{2P}– pump effort expressed in (m) at Q_m flow with motor speed regulation with inverter at 75% of nominal speed
η_1– pump efficiency at operating point (Q_m, H_{2S})
η_2 - pump efficiency at operating point (Q_m, H_{2P})
η_m– motor efficiency
t_a– number of working hours per year.

In Table3a presentation of the calculated data for each of the pumps defined in Table1 and Table2 is presented. The definition of the variables presented in Table 3 is stated as:

P_v (kW) – required pump power for valve regulation
P_e (kW) – required pump power for motor speed regulation at 75% of rated speed
P_s (%) – percentage of power required less when the flow is regulated by motor speed to 75% of the nominal compared to the valve regulation, where:

$$P_s = (P_e/P_v) \times 100 \quad (8)$$

E_s (kWh) – saving electricity by applying an energy converter with *U/f* regulation at a reduced speed of 25%
K_s (€) – saving money from the saved electricity.

As can be seen from the results of the table, the regulation of the motor speed by using energy converters as a way to change the operating point of the pump is a much more efficient solution compared to the valve control and brings great savings in electricity if it is the same implements. This is especially true for drives that have variable operating regimes.

Table 3Result analysis

P (kW)	P_v (kW)	P_e (kW)	P_s (%)	E_s(kWh)	K_s(€)
1.5	1.238	0.597	48.183	2165.100	259.810
2.2	1.916	0.971	50.682	3146.900	377.620
3	2.394	1.184	49.459	4167.900	500.140
5.5	4.384	2.140	48.809	7547.500	905.700
7.5	5.569	2.776	49.845	9300.700	1116.100
11	6.274	3.105	49.845	10635.000	1276.200
15	11.214	5.558	49.561	18792.000	2255.000
18.5	14.066	6.863	48.792	23695.000	2843.400
37	30.841	15.350	49.771	50188.000	6022.600
45	37.009	18.259	49.336	60033.000	7203.900
75	47.103	23.226	49.310	75719.000	9086.200
110	87.482	43.573	49.807	232819.297	27983.315
132	105.237	53.908	51.225	271297.099	32555.651
160	128.503	65.309	50.822	330516.350	39661.962
250	194.672	96.082	49.355	516719.967	62006.396
355	338.680	172.305	50.875	871070.850	104528.502
450	326.773	142.432	43.588	980535.586	117664.270

As can be seen from the results of the table, the regulation of the motor speed by using energy converters as a way to change the operating point of the pump is a much more efficient solution compared to the valve control and brings great savings in electricity if it is the same implements. This is especially true for drives that have variable operating regimes.

7 Conclusion

The world industry and economy are facing a major energy challenge. Global electricity demand is growing, and pressures to reduce electricity consumption and reduce the impact on the environment and climate change are growing. If we take into account, the fact that as much as 65% -70% of the total electricity consumption in industry is accounted for by electric motors then it is clear that the potential for saving electricity is huge and their role in reducing environmental pollution is crucial.

The control strategy of the working mechanisms depends on its mechanical characteristic. With mechanical control of the working mechanisms is consumes unnecessarily much electricity. Reducing the flow of a pump with a valve control is as inefficient as regulating the car speed only with brake. At a reduced motor speed of 25% of the rated power of converter, the power required by the pump is 50% lower than the power required for valve control. This means a reduction of the required electricity by 50%. Given the fact that pumps make up 33% of all working mechanisms, it is again concluded that by increasing the energy efficiency of pump systems there is a great potential for energy savings and improvement of their work.

The concept of energy efficiency is a very effective way to reduce the emission of carbon dioxide and other harmful substances into the air that contribute to global warming, air pollution and climate change. Global programs aimed at helping industrial companies improve the energy efficiency of their electric drives are needed and are of great importance for raising awareness and assisting in the implementation of energy efficiency.

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