ENERGY EFFICIENCY IMPROVEMENTS IN ELECTRIC DRIVES WITH CENTRIFUGAL LOAD

36th International Conference on Information Technologies (InfoTech-2022)
IEEE Conference, Rec. # 55606, 15-16 September 2022, Bulgaria

15-16 September 2022

Assoc. Prof. D-r Mihail Digalovski
Prof. D-r Goran Rafajlovski
Prof. D-r Krste Najdenkoski

* Pumps are the most numerous working machines, therefore the electric drives with pump will be considered in this paper. First, as opportunity to increase energy efficiency will be presented the replacement of existing electric motors in these drives with high efficient motors - HEM. Will be made an analysis how much is savings due to reduced losses in high efficient electric motors.

* The next, will be given a brief introduction to pump systems and then will be presented the ways in which the operating point of the pump can be regulated. In addition, is presented a calculation for energy savings was made a comparison between conventional ways of regulating the operating point of the pump and regulation of the operating point through variable electric drive speed. It analyzes 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

INTRODUCTION

* In this paper highlights the importance of energy efficiency in electric drives and what it represents. At electric drives, there are two possible ways to increase energy efficiency. One of them is the application of high efficient induction motors [1]. It shows the energy efficiency classes according to a standard published by the International Commission for Electrical Engineering and presents the electricity consumption for all standard powers up to 1MW in induction motors (IM) operating at nominal load 2000, 4000 and 6000 hours per year, respectively according to the energy class to which they belong. In addition, a comparison is made when replacing a standard efficiency motor with a motor with the highest efficiency class to see what the impact of high efficient motors is on improving energy efficiency and energy savings. The second way that is considered and contributes to the improvement of energy efficiency at electric drives involves the application of energy 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

2.1. Use of high efficient motors (HEM)

In March 2014, the standard IEC 60034-30-1: 2014 was published by the International Commission for Electrical Engineering (IEC), which includes single-phase and three-phase induction cage motors [2]. This standard replaces and extends IEC 60034-30: 2008 which defined three energy efficiency classes for induction cage motors. The new standard from 2014 includes four classes of energy efficiency, includes induction cage motors up to 8 poles, nominal voltage of 50 - 1000 V and output power of 0.12 - 1000 kW.

The following energy efficiency classes are included in IEC 60034-30-1:

- IE1 (Standard Efficiency)
- IE2 (High Efficiency)
- IE3 (Premium Efficiency)
- IE4 (Super Premium Efficiency)

Application field of the standard:

- Power range: 0.12 - 1000 kW
- Voltage range: up to 1 kV
- Frequency: 50Hz / 60Hz
- Number of poles: 2,4,6,8
- Degree of protection: all
- Temperature range: -20°C to + 40°C
- Altitude: up to 4000 m
- Load character: S1

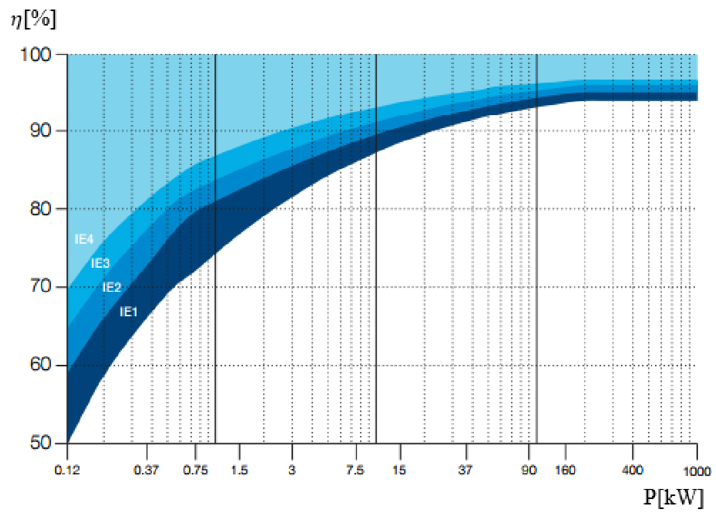

Fig. 1. Energy efficiency classes for four-pole IM, 50 Hz according to IEC 60034-30-1: 2014 [2]

Fig. 2. Analysis of the required costs during 15 years work life for 11kW IM [3]

Table 1 presents the energy efficiencies η [%] for energy classes IE1, IE2, IE3 and IE4 for induction motors with 2 and 4 poles, and Table 2 for 6 and 8 poles.

Depending on the purpose and the drive, the motors can have different number of working hours per year. Table 3 shows the price in euros for electricity consumed in one year if a 2-pole motor operates with a nominal load of 2000, 4000 and 6000 hours per year. The price of electricity is assumed to be 0.12 euros per kWh. The calculations are made for motors with nominal power from 11kW to 1000kW.

$$E = \frac{P[kW] \cdot t[h] \cdot \text{electricity price } [€ \text{ per kWh}]}{\eta} \qquad (1)$$

t - number of working hours per year

η - motor energy efficiency

* It can be concluded that with the increase of the energy efficiency, i.e. with the increase of the energy efficiency class of IM, the consumed electricity decreases. In addition, it will be presented how much is the improvement of motor efficiency in percent, and what are the savings in money for the saved electricity depending on the power and the number of working hours per year if a motor with 2 poles of energy class IE1 is replaced with the same such as energy class IE4, and the price for electricity is 0.12 € per kWh.

* As can be seen from Table 4, replacing an induction motor of a lower energy class with an induction motor of a higher energy class may increase the efficiency k of the system from 2.5% to 5%. The savings are most pronounced in motors that have more working hours per year and more power. It is clear that more efficient engines with a higher energy efficiency class are more expensive compared to those with lower energy efficiency, but at the same time bring greater energy savings and have a shorter time to return on capital investment.

Table 3. Costs for electricity consumed in euros per year depending on the energy class and the number of working hours per year for induction motors with 2 poles

P	2000 h				4000 h				6000 h			
kW	**IE1**	**IE2**	**IE3**	**IE4**	**IE1**	**IE2**	**IE3**	**IE4**	**IE1**	**IE2**	**IE3**	**IE4**
11	3013.7	2953	2894.7	2851	6027.4	5906	5789.5	5701.9	9041.1	8859.1	8684.2	8552.9
15	4058.6	3986.7	3917.3	3858.5	8117.2	7973.4	7834.6	7717	12175.9	11960.1	11751.9	11575.6
18.50	4972	4884.5	4810.4	4738.5	9944	9769	9620.8	9477.1	14916	14553.5	14431.2	14215.6
22	5873.2	5783.1	5695.8	5617	11746.4	11566.3	11391.6	11234	17619.6	17349.4	17087.4	16851.1
30	7938.3	7826.1	7717	7619	15876.5	15652.2	15434.1	15238.1	23814.8	23478.3	23151.1	22857.1
37	9736.8	9600	9477.1	9367.1	19473.7	19200	18954.1	18734.2	29210.5	28800	28431.2	28101.3
45	11777.5	11625.4	11489.4	11368.4	23555.1	23250.8	22978.7	22736.8	35332.6	34876.2	34468.1	34105.3
55	14332.2	14163.1	13997.9	13851	28664.5	28326.2	27995.8	27702	42996.7	42489.3	41993.6	41553
75	19417.5	19189.8	19007.4	18828.5	38835	38379.5	38014.8	37656.9	58252.4	57569.3	57022.2	56485.4
90	23225.8	22954.3	22736.8	22547	46451.6	45908.6	45473.7	45093.9	69677.4	68862.9	68210.5	67640.9
110	28295.8	27995.8	27731.1	27500	56591.6	55991.5	55462.2	55000	84887.5	83987.3	83193.3	82500
132	33882.4	33488.4	33207.5	32931.4	67764.7	66976.7	66415.1	65862.8	101647	100465	99622.6	98794.2
160	40938.2	40506.3	40167.4	39875.4	81876.3	81012.2	80334.7	79750.8	122815	121519	120502	119626
200	51063.8	50526.3	50104.4	49740.9	102123	101053	100209	99481.9	153192	151579	150313	149223
250	63829.8	63157.9	62630.5	62176.2	127660	126316	125261	124352	191489	189474	187891	186529
315	80425.5	79578.9	78914.4	78342	160851	159158	157829	156684	241277	238737	236743	235026
355	90638.3	89684.2	88935.3	88290.2	181277	179368	177871	176580	271915	269053	266806	264871
400	102128	101053	100209	99481.9	204255	202105	200418	198964	306383	303158	300626	298446
450	114894	113684	112735	111917	229787	227368	225470	223834	344681	341053	338205	335751
1000	255319	252632	250522	248705	510633	505263	501044	497409	765957	757895	751566	746114

Table 4. Money savings in Euros when replacing IM of energy class IE1 with IM of energy class IE4 depending on the number of working hours per year

P [kW]	k [%]	2000 h	4000 h	6000 h
11	5	162.7	325.5	488.2
15	4.6	200.1	400.2	600.3
18.50	4.4	233.5	466.9	700.4
22	4.1	256.2	512.4	768.5
30	3.8	319.3	638.4	957.7
37	3.6	369.7	739.5	1109.2
45	3.3	409.1	818.3	1227.3
55	3.2	481.2	962.5	1443.7
75	2.9	589	1178.1	1767
90	2.8	678.8	1357.7	2036.5
110	2.7	795.8	1591.6	2387.5
132	2.7	951	1901.9	2852.9
160	2.5	1062.8	2125.5	3188.3
200	2.5	1322.9	2645.8	3968.7
250	2.5	1653.6	3307.3	4960.9
315	2.5	2083.5	4167.2	6250.7
355	2.5	2348.1	4696.3	7044.4
400	2.5	2645.8	5291.6	7937.4
450	2.5	2976.5	5953	8929.6
1000	2.5	6614.4	13229	19843.4

2.2. Use of U/f electric motor regulation v.s. valve regulation in a pump system

- **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. 1 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}.

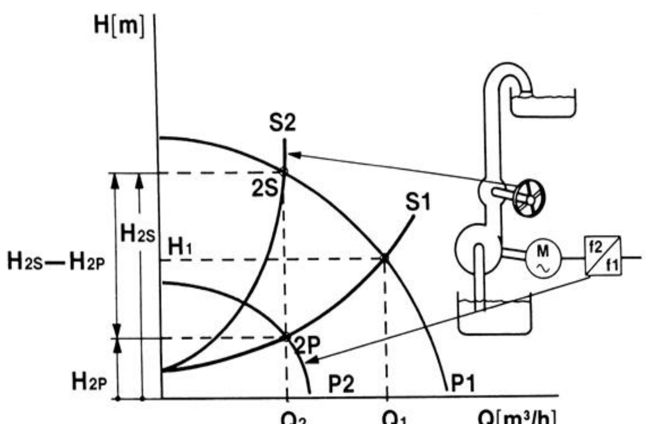

Fig. 3. Centrifugal pump flow regulation [4]

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

2.2. Use of U/f electric motor regulation v.s. valve regulation in a pump system

- **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 engine 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}.

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.

2.2.1 Result analysis

The purpose of the analysis is to compare the two ways of regulation of flow in an arbitrarily selected pump and to show the saved electricity if the flow is regulated by changing the speed of rotation compared to the conventional way of regulation by using regulating valves. The equations used for the analysis are given below:

Required mechanical power of the pump shaft in both regimes of regulation is:

Required pump power for valve control, P_v:

$$P_V = \frac{Q_m[m^3/h] \cdot H_{2S}[m] \cdot \rho[kg/dm^3] \cdot g[m/s^2]}{3600 \cdot \eta_1} \ [kW] \qquad (1)$$

Required pump power for motor speed control, P_e:

$$P_e = \frac{Q_m[m^3/h] \cdot H_{2P}[m] \cdot \rho[kg/dm^3] \cdot g[m/s^2]}{3600 \cdot \eta_2} \ [kW] \qquad (2)$$

Required electrical power in both regimes of regulation is:

Required electrical power for valve control, P_{1m}:

$$P_{1m} = \frac{P_V}{\eta_m} \ [kW] \qquad (3)$$

Required electrical power for motor speed control, P_{2m}:

$$P_{2m} = \frac{P_e}{\eta_m \cdot \eta_{vfd}} \ [kW] \qquad (4)$$

Energy saving, E_s:

$$E_s = (P_{1m} - P_{2m}) \cdot t_a \ [kWh/year] \qquad (5)$$

Saving money per year, K_s:

$$K_s \ [savig\ many\ per\ year] = E_S \ [kWh/year] \cdot k \ [price/kWh] \qquad (6)$$

Where is:

ρ [kg/dm^3] – liquid density

g [m/s^2] - ground acceleration

η_1 - pump efficiency at operating point 2S, Fig. 3

η_2 - pump efficiency at operating point 2P, Fig. 3

η_m - motor efficiency

η_{vfd} - efficiency of the inverter

t_a - number of working hours per year

Pumps data

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 [5]. 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.

Table 5. Pumps data [5]

Pump serial number	P_n [kW]	P_2 [HP]	Q_n [m^3/h]	H_n [m]	η_{pn} [%]	η_{mn} [%]	IE	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

Operating mode

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

When **regulating the valve opening**, to reduce the flow by 20% from $Q_1=Q_n$ to $Q_2 = Q_m$ (Fig. 3), 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 **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 can't 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 Table 6.

Table 6. Pumps 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} [m]
1.5	15.8	17.37	8.702	60.4	62.8	88.9	3000	0.12	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 data required to perform the calculations, and an explanation of the variables 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.

Table 7 shows the results of the calculation for each of the pumps defined in Table 5 and Table 6:

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:

$P_s = (Pe/P_v) \times 100$

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

Table 7. Result 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

CONCLUSION

The biggest part in the improvement of the energy efficiency of an electric drives has the improvement of the efficiency of the working mechanism. In second place are the application of energy converters and then the use of high efficient motors - HEM. The application of energy converters and high efficient motors - HEM are profitable investments, whose return depending on the number of working hours and power, and is from several months to 5 years.

Replacing an standard energy efficiency induction motor (energy class IE1) with a high efficient motor (energy class IE4) can improve the system energy efficiency from 20% for low power motors to a few percent for high power motors. However, the improvement of energy efficiency even by 2% in high power IM contributes to large electricity savings.

To reduce the pump flow by only 20% at a reduced motor speed of 25% of the nominal, the power required by the pump is 50% lower than the power required for valve control. This is a significant reduction in power and a confirmation of the general law which states that the power of a pump depends on the cube of the speed at which it rotates. Reducing the flow of a pump with a valve control is just as inefficient as regulating the car speed only with brakes. Mechanical control consumes electricity unnecessarily. How much is higher the number of working hours and the higher the power of the pump, the energy savings is greater. Knowing that pumps make up 33% of all working mechanisms, it is concluded that by increasing the energy efficiency of pump systems there is a great potential for saving energy and improving their work.