COMPARISON OF ENERGY CONSUMPTION OF VARIOUS ELECTRICAL MOTORS OPERATING IN A PUMPING UNIT

Purpose. Comparative analysis of energy consumption of various types electric motors in fixed speed centrifugal industrial pump applications is carried out. The purpose of the analysis is to choose the most efficient motor in the considered application. It is assumed that hydraulic flow of the pump is adjusted by throttling. The rated power of the pump unit is 2.2 kW. Direct on line motors of various energy efficiency classes from various manufacturers are considered; induction motors with permanent magnets on the rotor of IE3 class and squirrel cage induction motors of IE3 and IE4 classes. Methodology. Assessment of energy consumption of the motors is carried out based on the catalogue data from manufacturers of the pump and the motors. Pump hydraulic equations, interpolation of motor catalogue data and statistical data are also used. Results. The following values have been obtained: annual and daily energy consumption of the motors and electricity cost savings comparing with the least effective motor considered. Practical value. The following practical consideration are presented based on the theoretical results: choosing the motor based only on its IE efficiency class according to IEC 60034-30-1 is not enough to ensure the minimum energy consumption of pump units with variable load during the flow cycle. In addition, the energy consumption may be higher in the case of permanent magnet motors of IE4 class in comparison with induction motors of IE4 or even IE3 class. Therefore, it is necessary to take into account efficiency of the motors at underload and it is needed to calculate the energy consumption during the actual load cycle. It should be noted, that the existing approach based on the Energy Efficiency Index (EEI) calculation does not provide information about absolute values of energy savings and cost savings, in contrast to the described approach. While choosing motors to run in the considered application it is also important to take into account that the motors with permanent magnets on the rotor have significantly higher price and very restricted starting capabilities comparing with induction motors. In addition, the production of rare earth magnets causes a significant environmental damage. References 40, tables 5, figures 6.

Key words: centrifugal pump, induction motor, line-start permanent magnet synchronous motor (LSPMSM), efficiency class, energy efficiency, throttle control.

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Introduction. The widely known advantages of variable frequency drives (VFDs) are high efficiency and high dynamic and static characteristics, such as stiffness, control range, and the accuracy of maintaining adjustable values.

However, the proportion of variable frequency drives according to the European Commission [1] for Germany was about 30%, and for Switzerland according to the study described in [2] was about 20%.

Thus, in many applications, electric motors powered directly from the electrical network are widely used.

In particular, such common mechanisms as centrifugal pumps, compressors and fans do not require a wide range of regulation, high starting torque and speed. Therefore, asynchronous electric motors (IMs), operating directly from the network, are widely used in the drives of the mentioned turbo-mechanisms. A number of manufacturers also propose the use of line-start permanent magnet synchronous motor (LSPMSMs) of high energy efficiency class, powered directly from the network. In this case, the pump performance is regulated by means of valves (throttle control), by means of a controlled change in the characteristics of the hydraulic network.

According to the International Energy Agency [3], electric motors consume 46% of the electricity generated in the world. They account for about 70% of total industrial electricity consumption. According to the report of the European Commission [3], pumping systems account for almost 22% of the energy supplied by electric motors in the world, as shown in Fig. 1. Therefore, the study of the possibilities of increasing the energy efficiency of pumping units is an urgent task.

Improving the energy efficiency of the pumping unit is possible due to changes in the hydraulic network for which the unit is operating, the use of control systems, including VFD, load optimization and distribution (in the case of parallel-running units), as well as due to the proper selection of the unit's components, in particular the use of electric motors more high class energy efficiency [4]. The last mentioned method is studied in this paper, as the most relevant for pumps with throttle control.

The minimum level of energy efficiency of electric motors is defined in Appendix I to [5]. Energy efficiency classes are based on the values specified in [6]. In accordance with the EU regulation [5] since January 1, 2017, all electric motors with power from 0.75 to 375 kW must have an energy efficiency class of at least IE3 or IE2, if they are used as part of the VFD. Until 2030, according to Policy Option 4 [7], one should expect the introduction of the minimum acceptable energy efficiency class not lower than IE4.

The classification of electric motors in [5, 6] is based only on efficiency in the nominal operating mode, that is, at rated power on the shaft, but does not take into account the efficiency of electric motors at partial load, which is typical for electric motors in pumping units [8].

In practice, most of the time centrifugal pumping units are operated at low or medium loads which occurs due to changes in the number of people in buildings and/or atmospheric conditions, while the pumps are designed to satisfy maximum loads [9]. In [10], it was estimated that 75% of centrifugal pumping units have an overestimated power, many of them more than 20%. In [11] it was estimated that only 20% of electric motors in pumps operate at rated power.

The publications [12, 13] compare the energy consumption of the pumping unit with electric motors of different types and classes IE with VFD, since frequency regulation achieves significant energy savings, especially under low loads. Nevertheless, in view of the mass application of unregulated electric drives that has been...
preserved in many industries, a number of works compare the characteristics of electric motors that operate directly from the network. For example, in the paper [14], a comparative analysis of the energy efficiency class IE3 IM and LSPMSM as a part of the fan in start-up and in steady-state modes was carried out. This analysis showed that the efficiency and power factor of LSPMSM are significantly higher than that of IM. However, the analysis was carried out for nominal load conditions. The paper [15] discusses the operation of LSPMSM as part of the pumping unit. The characteristics of the proposed design of the electric motor are compared with the simulation results in the nominal mode of the pumping unit under start-up conditions with high moment of inertia. In paper [16], the design and the characteristics of the steady-state and transient modes of operation of the IM and LSPMSM with power of 2.2 kW in the nominal mode and at idle are considered. For the operating mode with rated power, an indicator of annual cost savings is determined in the case of using LSPMSM.

One of the main conclusions of publications [13-16] is the advantage of LSPMSM over IM in such parameters as efficiency and power factor. Note, however, that in these publications, the comparison of IM and LSPMSM was carried out mainly for operating modes with a nominal load. This paper discusses the modes of operation of IM and LSPMSM as part of a pumping unit with variable load, depending on water consumption, for example, in a large building. The work calculates the energy consumption of electric drives at loads different from the rated load of the electric motor, and the obtained data are compared to assess the energy saving potential of electric motors of energy efficiency classes IE3 and IE4.

Due to the fact that the energy efficiency class IE of the electric motor is assigned according to efficiency in nominal mode in accordance with IEC 60034-30-1 [6], but in HVAC (Heating, Ventilation, & Air Conditioning) applications an electric motor in this mode works only a small fraction of the time, the main goal of this paper is to determine the criterion for choosing electric motors under the condition of minimum energy consumption, taking into account the actual operating conditions of centrifugal pumping units.

Characteristics of the pumping unit and electric motors. The drive of the pumping unit with one electric motor, powered directly from the electric network, is shown in Fig. 2 [8]. It consists of a centrifugal pump, which is connected to an electric motor without intermediate mechanical gears.

The active power $P_1$ consumed by the drive is converted by the electric motor into the mechanical power $P_{mech}$. Power $P_{mech}$ is less than $P_1$ by the value of losses in the electric motor [8]:

$$P_{mech} = P_1 - \Sigma P_{loss,mech}$$

where $\Sigma P_{loss,mech}$ are the total losses of the electric motor.

The mechanical power of the electric motor $P_{mech}$ is transmitted to the pump and, therefore, in the absence of intermediate mechanical gears, is equal to the input mechanical power of the pump. In the pump, the mechanical power $P_{mech}$ is converted to the hydraulic power $P_{hydr}$. The difference between $P_{mech}$ and $P_{hydr}$ is the value of the total losses $\Sigma P_{loss,pump}$ in the pump [8]:

$$P_{hydr} = P_{mech} - \Sigma P_{loss,pump}$$

The hydraulic power is determined by the flow rate $Q$ and the pump head $H_{pump}$. The pump head depends on the flow rate in accordance with the $Q-H$ characteristic of the pump at a given pump rotation speed $n$. Therefore, the required electric power $P_1$ depends on the flow rate $Q$ [8]:

$$P_1 = \rho g Q H_{pump} + \Sigma P_{loss,pump} + \Sigma P_{loss,ns}$$

where $\rho$ is the fluid density, $g$ is the acceleration of gravity.

To compare the energy consumption of the electric motors of the pumping unit when regulating the flow rate using a valve, the centrifugal pump NM4 40/25B (manufactured by Calpeda) with power of 2.2 kW and rated rotation speed $n = 1450$ rpm was considered [17]. Pump data are given in Table 1, where $Q_{BEP}$ is the flow rate at the best efficient point (BEP), $H_{BEP}$ is the pressure at BEP.

| Parameter       | Value          |
|-----------------|----------------|
| Type            | NM4 40/25B     |
| $P_1$, W        | 2200           |
| $n$, rpm        | 1450           |
| $Q_{BEP}$, m³/h | 19             |
| $H_{BEP}$, m    | 17.8           |
| Efficiency, %   | 60             |

The calculation was carried out for 8 different 4-pole electric motors with power of 2.2 kW, namely: three IE4 class LSPMSMs powered from the network (Bharat Bijlee SynchroVERT [18], WEG [19], SEW-Eurodrive [20]), two class IE4 IMs (Siemens [21] and WEG [22]) and three class IE3 IMs (Siemens [21], WEG [23] and ABB [24]). Data on the value of the efficiency of electric motors are given in Table 2.

| $m$ | Type               | Class | Efficiency, % at load, % |
|-----|--------------------|-------|--------------------------|
|     | LSPEMSM            | IE4   | 88.0 90.5 91.2           |
|     | SEW DRU J          | IE4   | 88.6 89.4 89.5           |
|     | LSPEMSM            | IE4   | 86.0 89.0 90.2           |
|     | SynchroVERT        | IE4   | 88.3 89.6 89.5           |
|     | WEG WQuattro       | IE4   | 88.5 89.5 89.5           |
|     | SEW-SEW-Eurodrive  | IE4   | 86.4 87.3 86.7           |
|     | Siemens 1LE1004    | IE3   | 86.5 87.0 87.0           |
|     | Siemens 1LE1003    | IE3   | 85.1 86.9 86.7           |
|     | WEG W21            | IE3   | 86.5 87.0 87.0           |
|     | ABB M3BP           | IE3   | 85.1 86.9 86.7           |
Assessment of energy consumption of the pumping unit. The operation of the pumping unit is considered in modes where the water flow rate during the cycle of the pumping unit varies, in accordance with the hydraulic load characteristic of HVAC applications. A typical pump operation cycle (Fig. 3), defined by EU regulation [25], is divided into 4 modes. A feature of the cycle is that most of the time the pump operates at a flow rate much less than the nominal. For example, with a flow rate of 25 % of the nominal, the pump operates during the relative time \( t_1/t_S = 44 \% \), where \( t_S \) is the total operating time, taken equal to 24 hours, \( t_1 \) is the pump operation time in this mode. Here, the relative operating time in the nominal mode does not exceed 6 %. This load profile is typical for pumping systems with the need to vary the flow rate over a wide range (systems with variable flow rate) [6].

The electric motor is directly connected to the network, that is, the motor speed is not controlled by the frequency converter during the cycle, and the pump flow rate \( Q \) is controlled by the valve. The water pressure in this case changes in accordance with the \( Q-H \) curve of the pump, and the operating point is the intersection point of the pump characteristic and the hydraulic system characteristic. Figure 4 shows the results of the \( Q-H \) characteristic interpolation for the selected pump and the starting points according to the manufacturer [17], as well as the pump power in the operating range of flow rates.

The pump power curve as a function of flow rate is given by the pump manufacturer (Fig. 4). According to this curve, the pump power was determined in 4 standard operating modes (25 %, 50 %, 75 %, 100 % of the flow rate). A flow rate corresponding to 100 % was determined as the maximum efficiency. Based on the known passport values of the efficiency of electric motors (Table 2), by means of polynomial interpolation of the loss curve \( \Sigma P_{\text{loss,m}} \) of each electric motor, the efficiency values for four operating modes of the pumping unit were determined. As shown in [27], the dependence of the electric motor losses on the load is well described by a second-order polynomial, whose coefficients can be easily obtained from 3 points of the initial data on the efficiency of electric motors.

![Fig. 3. Time dependence of water flow rate per cycle](image3)

![Fig. 4. Q-H – pump characteristic and power versus flow rate dependence](image4)

The obtained values of the efficiency for each electric motor \( \eta_{m,i,m} \) are given in Table 3 which also indicates for each operating mode: flow rate, pump pressure, pump power, electric motor output power as a percentage of the nominal.

Active electric power consumed from the network in each mode was calculated according to expression (4)

\[
P_{1,i,m} = P_{\text{mech,i,m}} / \eta_{m,i,m}. \tag{4}
\]

where \( \eta_{m,i,m} \) is the efficiency of the \( m \)-th electric motor in the \( i \)-th mode of operation.

The calculation results are given in Table 4.

The daily energy consumption of each electric motor (kW·h) for the full cycle of the pumping unit in accordance with the considered load profile is determined by the expression

\[
E_{d,m} = \frac{t_S}{1000} \sum_{i=1}^{4} (P_{1,i,m} \cdot t_i / t_S). \tag{5}
\]

At year-round operation of the pump unit, the annual energy consumption can be calculated as:

\[
E_{y,m} = E_{d,m} \cdot 365. \tag{6}
\]
### Table 3

| \(i\) | 1  | 2  | 3  | 4 |
|-----|----|----|----|---|
| \(Q_i, \%\) | 25 | 50 | 75 | 100 |
| \(Q_i, m^3/h\) | 4.75 | 9.50 | 14.25 | 19.00 |
| \(H_{pump,i}, m\) | 21.4 | 21.0 | 20.2 | 17.8 |
| \(P_{mech,i}, W\) | 851 | 1116 | 1361 | 1573 |
| \(P_{mech,i}, \%\) | 38.7 | 50.7 | 61.9 | 71.5 |

### Table 4

| Type | \(P_{1,i,m}, W\) |
|-----|------------------|
| LSPMSM SEW DRU J | 996.2 |
| LSPMSM SynchroVERT | 971.3 |
| LSPMSM WEG WQuattro | 1022.6 |
| IM Siemens 1LE1004 | 982.2 |
| IM WEG W22 | 992.9 |
| IM Siemens 1LE1003 | 1003.1 |
| IM WEG W21 | 1004.4 |
| IM ABB M3BP | 1029.4 |

### Table 5

| Type | \(E_{d,m}, kW\cdot h\) | \(E_{y,m}, kW\cdot h\) | \(C_{y,m}, €\) | \(S_{y,m}, €\) |
|-----|------------------------|------------------------|----------------|----------------|
| LSPMSM SEW DRU J | 29.1 | 10635 | 2113.1 | 73.8 |
| LSPMSM SynchroVERT | 28.9 | 10535 | 2093.3 | 93.6 |
| LSPMSM WEG WQuattro | 29.8 | 10882 | 2162.3 | 24.6 |
| IM Siemens 1LE1004 | 29 | 10585 | 2103.1 | 83.8 |
| IM WEG W22 | 29.1 | 10630 | 2112.1 | 74.8 |
| IM Siemens 1LE1003 | 29.6 | 10822 | 2150.3 | 36.6 |
| IM WEG W21 | 29.7 | 10843 | 2154.4 | 32.5 |
| IM ABB M3BP | 30.2 | 11006 | 2186.9 | 0 |

The cost of electricity consumed (Euro) taking into account the adopted average European electricity tariff \(GT = 0.1149 \text{€/kW} \cdot \text{h}\) for non-household consumers in the second half of 2018 [28], is calculated as

\[
C_{y,m} = E_{y,m} \cdot GT. \tag{7}
\]

To compare the energy consumption and the cost of electricity consumed by pumping units with various electric motors, the expression (8) were used to calculate the differences in the cost of electricity relative to the pumping unit with the electric motor with the highest energy consumption at the considered load profile (motor No. 8 of IE3 class manufactured by ABB)

\[
S_{y,m} = C_{y,m} - C_{y(1…7)} \tag{8}
\]

The results of calculations by formulas (4)-(8) are summarized in Table 4, 5, and are also shown in Fig. 5, 6.

The graph in Fig. 5 shows that the electric motor No. 3 – LSPMSM of class IE4 in the cycle under consideration, which is typical for pumps with variable flow rate, consumes more electricity than IMs of class IE3 No. 6 and No. 7, but less than the class IE3 IM No. 8. So, according to Fig. 6, this IE4 class electric motor provides lower cost savings than IE3 class electric motors No. 6 and No. 7. LSPMSMs No. 1 and No. 2 have energy consumption indicators that approximately coincide with class IE4 IMs No. 4 and No. 5. The smallest energy consumption has electric motor No. 2 – LSPMSM SynchroVERT, and the largest – electric motor No. 8, the IM AB.
motors are classified according to energy consumption in the fact that according to the adopted standard [6], electric than IMs (especially IE3 class), due to the presence of the pumping unit (see below).

Thus, the selection of an electric motor based on its energy efficiency class IE, in a number of applications, such as variable flow rate pumps, will not lead to minimum energy consumption. Note that for frequency-controlled electric motors, the IEC 60034-30-2 Standard with existing standards.

The results shown in Fig. 5, 6 are the consequence of the fact that according to the adopted standard [6], electric motors are classified according to energy consumption in accordance with the value of efficiency in the nominal mode of operation, at a load equal to 100 %. However, in pumping units, electric motors operate for a significant part of the time at a load 2...4 times less than the nominal and as a result have a reduced efficiency. Here, the existing standards do not establish the minimum values of the efficiency of electric motors powered directly from the network at loads below nominal.

Thus, when choosing an electric motor for a pumping unit operating with a variable flow rate, you can not be guided only by the energy efficiency class IE and the nominal value of the efficiency, but it is worthwhile to calculate the energy consumption depending on the operating modes or focus on the energy efficiency index of the pumping unit (see below).

It is worth noting that LSPMSMs have a higher cost than IMs (especially IE3 class), due to the presence of expensive rare-earth magnets in the design. Production of magnets from rare-earth metals is associated with significant environmental damage, for example in [31] it is indicated that the production of each ton of material for rare-earth magnets is associated with the generation of 1-1.4 tons of radioactive waste. Only a small part of these wastes contains rare-earth elements and is further processed to extract them [31]. There is also technological dependence on rare-earth suppliers from China, since more than 95 % of the global production of rare earth elements is controlled by China [32]. Due to the monopoly of China, the prices of rare-earth elements are unstable and can change several times over several years [33].

We also note the difficulties of starting LSPMSMs at significant moment of inertia of the load, which significantly limits their scope. A review of modern papers on LSPMSMs [34-37] shows that the maximum load inertia moment for such electric motors is relatively small and insufficient to start and reach rated speed, for example, for a turbo-mechanism with a steel impeller. These electric motors are not able to start with many typical mechanisms, such as: reciprocating compressors, screw compressors, plunger pumps, conveyors, escalators, etc. [34-37].

According to the results of comparing LSPMSMs and IMs classes IE3 and IE4, described in [38] LSPMSMs show a higher peak value of the starting current, which can cause the operation of typical circuit breakers. Inrush currents can cause unwanted switches off and can damage contactors, fuses and protective devices, such as circuit breakers or switchgears [38]. In this case, starting with star-delta switching or using electronic soft starters is not recommended or not possible for LSPMSMs [38]. Also, LSPMSMs are much more sensitive to voltage drop [38] and more sensitive to phase asymmetry [38].

Taking into account the above-mentioned drawbacks of LSPMSMs, it is more justified at the present time to use in applications with a variable load, which is very different from the nominal mode, of IMs class of IE4, and not LSPMSMs.

Calculation and assessment of the energy efficiency index of the pumping unit in accordance with existing standards. The energy efficiency of circulation pumps operating primarily with variable flow rate is evaluated in accordance with EU regulations [25]. In this document, the profile indicated in Fig. 3, according to which the above calculations were carried out is accepted as a typical pump load profile. According to [8], the energy efficiency index (EEI) is well established for evaluating the energy efficiency of circulation pumps and is now proposed for other pump applications.

That is, EEI is the most suitable indicator for assessing the energy efficiency of variable-flow pump systems for various purposes, in contrast to the minimum efficiency index (MEI), which is defined in [39] and is based on efficiency values in a relatively limited range of operating points (75...110 % flow rates) [8].

According to the approach of the Europump association [26, p. 12] and [40] EEI is defined by:

$$EEI = \frac{P_{1,avg}}{P_{1,ref}},$$

where $P_{1,avg}$ is the weighted average value of the electric power consumed by the pump, which is determined by the following expression [25]:

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Fig. 6. Saving energy costs relative to electric motor No. 8:
1 – LSPMSM IE4 SEW DRU J; 2 – LSPMSM IE4 Synchrovert; 3 – LSPMSM IE4 Weg WQuattro; 4 – IM IE4 Siemens 1LE1004; 5 – IM IE4 Weg W22; 6 – IM IE3 Siemens 1LE1003; 7 – IM IE3 Weg W21; 8 – IM IE3 ABB M3BP
\[
P_{\text{avg}} = \frac{1}{4} \sum_{i=1}^{4} [\ell_i/t_i] \cdot P_{i,1}.
\] (10)

The denominator in the expression (9) \( P_{1,\text{ref}} \) is the electric power of the «reference» system, which according to [26, 40] is determined by the expression

\[
P_{1,\text{ref}} = P_{\text{hyd.ref}} / (\eta_{\text{motor.ref}} \cdot \eta_{\text{pump.min.req}}).
\] (11)

In both expressions, \( P_{\text{hyd.ref}} \) is the hydraulic power of the reference system, which is defined as the product of the flow rate \( Q_{\text{BEP}} \) (m³/s) and pressure \( H_{\text{BEP}} \) (Pa): in this case, \( P_{\text{hyd.ref}} = 921.6 \) W.

In expression (11) \( \eta_{\text{motor.ref}} \) is the efficiency of the reference electric motor, which was taken equal to the efficiency of a 4-pole electric motor with power of 2.2 kW energy efficiency class IE3 according to [6] \( \eta_{\text{motor.ref}} = 86.7 \% \); \( \eta_{\text{pump.min.req}} \) is the minimum required efficiency of the reference pump at the best efficient point [39], depending on the tabular coefficient \( C \), determined by the type of pump, the rated rotation speed of the pump \( n \) and its energy efficiency, flow rate \( Q_{\text{BEP}} \) and specific rotation speed \( n_s \), in turn dependent on \( H_{\text{BEP}} \) and \( n \). A detailed calculation of \( \eta_{\text{pump.min.req}} \) is not given in this paper, the calculation result: \( \eta_{\text{pump.min.req}} = 50.66 \% \).

According to formula (11), the value of \( P_{1,\text{ref}} = 2098.23 \) W in this case.

The calculation results for expressions (9)-(11) are given in Table 6.

Table 6 shows that the EEI values for the pumping unit with various electric motors correspond to the patterns shown in Fig. 5, 6. Thus, EEI characterizes the energy consumption of the pumping unit more objectively than the energy efficiency class of the electric motor (IE), which depends only on the efficiency in the nominal mode.

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