UDC 621.313 **doi: 10.20998/2074-272X.2020.1.03**

V.V. Goman, S.Kh. Oshurbekov, V.M. Kazakbaev, V.A. Prakht, V.A. Dmitrievskii

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 IE4 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 flow during the load 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.**

Мета. Порівняльний аналіз енергоспоживання електродвигунів різних типів і класів енергоефективності в електроприводі відцентрового насоса потужністю 2,2 кВт системи водопостачання з дросельним регулюванням. Порівнювалися синхронні електродвигуни з прямим пуском і постійними магнітами на роторі класу енергоефективності IE4 і асинхронні електродвигуни класів енергоефективності IE4 і IE3 різних виробників. Методика. Розрахунок енергоспоживання проводився на основі даних насоса і електродвигунів, що надаються виробниками, і включав в себе розрахунок енергоспоживання відцентровим насосом в типовому робочому циклі, який передбачає роботу зі зниженими навантаженнями протягом тривалого часу. Результат. Отримано розрахункові дані по добовому і річному енергоспоживанню розглянутих електродвигунів в типовому робочому циклі насоса, річна вартість електроенергії виходячи з середньоєвропейського тарифу, економія в грошовому вираженні щодо найгіршого електродвигуна з розглянутих. Практичне значення. Показано, що вибір електродвигуна за КПД при найменшому навантаженні, тобто фактично на основі присвоєного відповідно до стандарту IEC 60034-30-1 класу енергоефективності IE, не призводить до мінімального енергоспоживання відцентрового насосного агрегату зі змінною подачею протягом типового робочого циклу. Також показано, що застосування в насосних агрегатах зі змінною витратою синхронних електродвигунів з прямим пуском і постійними магнітами класу IE4 в ряді випадків призводить до більшого енергоспоживання, ніж застосування асинхронних електродвигунів класу IE4, а іноді і класу IE3. Таким чином, при виборі класу енергоефективності електродвигуна як для насосного агрегату, так і для будь-якого іншого механізму, що працює значний час при знижених навантаженнях, слід проводити розрахунок енергоспоживання на підставі даних про типовий робочий цикл або з експериментальних даних. При цьому існуючий підхід, заснований на визначенні індексу енергетичної ефективності EEI, не дає інформації про економію електроенергії в натуральному і вартісному виразах, на відміну від описаного в роботі підходу. При виборі електродвигуна за принципом дії слід враховувати, крім енергоспоживання, те, що синхронні електродвигуни з постійними магнітами мають велику вартість, ніж асинхронні електродвигуни, є труднощі їх запуску при значному моменті інерції, а отримання магнітів з рідкоземельних металів пов'язане зі значним екологічним збитком. Бібл. 40, табл. 5, рис. 6.

Ключові слова: **відцентрові насоси, асинхронні електродвигуни, синхронні електродвигуни з прямим пуском і постійними магнітами, клас енергоефективності, коефіцієнт корисної дії, дросельне регулювання.**

Цель. Сравнительный анализ энергопотребления электродвигателей разных типов и классов энергоэффективности в электроприводе центробежного насоса мощностью 2,2 кВт системы водоснабжения с дроссельным регулированием. Сравнивались синхронные электродвигатели с прямым пуском и постоянными магнитами на роторе класса энергоэффективности IE4 и асинхронные электродвигатели классов энергоэффективности IE4 и IE3 различных производителей. Методика. Расчет энергопотребления проводился на основе данных насоса и электродвигателей, предоставляемых производителями, и включал в себя расчет энергопотребления центробежным насосом в типовом рабочем цикле, предполагающем работу с пониженными нагрузками в течение продолжительного времени. Результат. Получены расчетные данные по суточному и годовому энергопотреблению рассмотренных электродвигателей в типовом рабочем цикле насоса, годовая стоимость электроэнергии исходя из среднеевропейского тарифа, экономия в денежном выражении относительно наихудшего электродвигателя из рассмотренных. Практическое значение. Показано, что выбор электродвигателя по КПД при номинальной нагрузке, то есть

фактически на основе присвоенного в соответствии со стандартом IEC 60034-30-1 класса энергоэффективности IE, не приводит к минимальному энергопотреблению центробежного насосного агрегата с переменной подачей в течение типового рабочего цикла. Также показано, что применение в насосных агрегатах с переменным расходом синхронных электродвигателей с прямым пуском и постоянными магнитами класса IE4 в ряде случаев приводит к большему энергопотреблению, чем применение асинхронных электродвигателей класса IE4, а иногда и класса IE3. Таким образом, при выборе класса энергоэффективности электродвигателя как для насосного агрегата, так и для любого другого механизма, работающего значительное время при пониженных нагрузках, следует проводить расчет энергопотребления на основании данных о типовом рабочем цикле либо экспериментальных данных. При этом существующий подход, основанный на определении индекса энергетической эффективности EEI, не дает информации об экономии электроэнергии в натуральном и стоимостном выражениях, в отличие от описанного в работе подхода. При выборе электродвигателя по принципу действия следует учитывать помимо энергопотребления, то, что синхронные электродвигатели с постоянными магнитами имеют большую стоимость, чем асинхронные электродвигатели, имеются трудности их запуска при значительном моменте инерции, а получение магнитов из редкоземельных металлов сопряжено со значительным экологическим ущербом. Библ. 40, табл. 5, рис. 6.

Ключевые слова: **центробежные насосы, асинхронные электродвигатели, синхронные электродвигатели с прямым пуском и постоянными магнитами, класс энергоэффективности, коэффициент полезного действия, дроссельное регулирование.**

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.

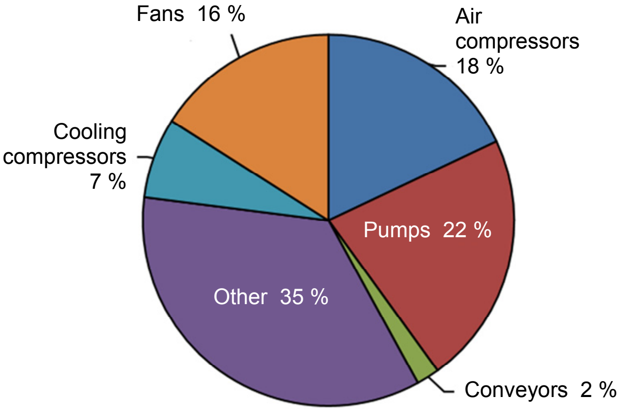

Fig. 1. Power consumption for various applications

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.

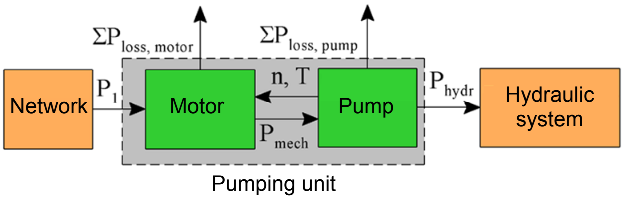

Fig. 2. Diagram of an unregulated pumping unit

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]:

$$P_{\text{mech}} = P_1 - \Sigma P_{\text{loss.m}}, \qquad (1)$$

where $\Sigma P_{\text{loss.m}}$ 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 $\Sigma P_{\text{loss.pump}}$ in the pump [8]:

$$P_{\text{hydr}} = P_{\text{mech}} - \Sigma P_{\text{loss.pump}}. \qquad (2)$$

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 P1 depends on the flow rate Q [8]:

$$P_1 = \rho g Q H_{\text{pump}} + \Sigma P_{\text{loss.pump}} + \Sigma P_{\text{loss.m}}, \qquad (3)$$

where ρ 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*.

Table 1

Passport characteristics of the pump [17]

Parameter	Value
Type	NM4 40/25B
P, 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.

Table 2

Efficiency of 4-pole electric motors of power of 2.2 kW [18-24]

m	Type	Class	Efficiency, % at load, %		
			50 %	75 %	100 %
1	LSPMSM SEW DRU J	IE4	88.0	90.5	91.2
2	LSPMSM SynchroVERT	IE4	88.6	89.4	89.5
3	LSPMSM WEG WQuattro	IE4	86.0	89.0	90.2
4	IM Siemens 1LE1004	IE4	88.3	89.6	89.5
5	IM WEG W22	IE4	88.5	89.5	89.5
6	IM Siemens 1LE1003	IE3	86.4	87.3	86.7
7	IM WEG W21	IE3	86.5	87.0	87.0
8	IM 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 $t_i/t_\Sigma = 44$ %, where t_Σ is the total operating time, taken equal to 24 hours, t_i 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].

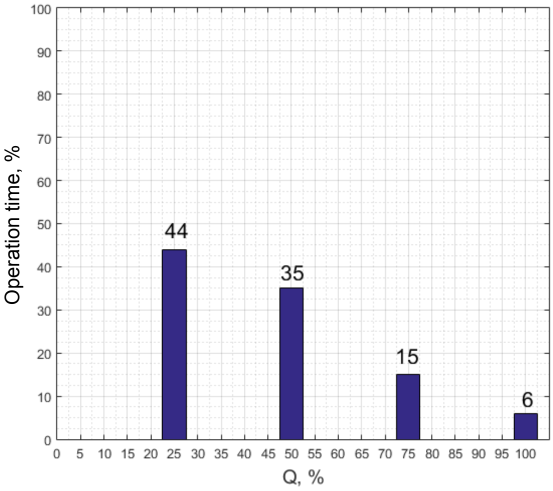

Fig. 3. Time dependence of water flow rate per cycle

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 from the pump efficiency curve [17] as corresponding to 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 $\Sigma P_{\mathrm{loss.m}}$ 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.

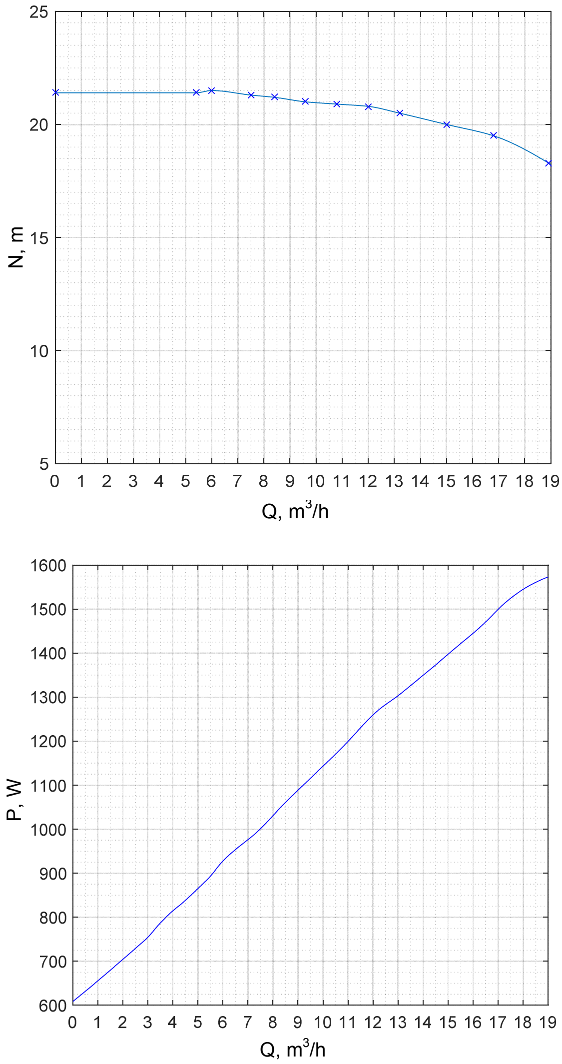

Fig. 4. Q-H – pump characteristic and power versus flow rate dependence

The obtained values of the efficiency for each electric motor $\eta_{\mathrm{m}.i.m}$ 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)

$$P_{1.i.m} = P_{\mathrm{mech}.i.m} \;/\; \eta_{\mathrm{m}.i.m}, \tag{4}$$

где $\eta_{\mathrm{m}.i.m}$ 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

$$E_{d.m} = \frac{t_\Sigma}{1000} \cdot \sum_{i=1}^{4} \left(P_{1.i.m} \cdot t_i / t_\Sigma\right). \tag{5}$$

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

$$E_{\mathrm{y.m}} = E_{\mathrm{d.m}} \cdot 365. \tag{6}$$

Table 3

Interpolated motor efficiency values

i	1	2	3	4
Q_i, %	25	50	75	100
Q_i, m^3/h	4.75	9.50	14.25	19.00
$H_{\text{pump}.i}$, m	21.4	21.0	20.2	17.8
$P_{\text{mech}.i}$, W	851	1116	1361	1573
$P_{\text{mech}.i}$, %	38.7	50.7	61.9	71.5
Efficiency $\eta_{\text{m}.i.m}$, %				
i	1	2	3	4
LSPMSM SEW DRU J	85.5	88.1	89.5	90.3
LSPMSM SynchroVERT	87.7	88.6	89.1	89.3
LSPMSM WEG WQuattro	83.3	86.1	87.8	88.7
IM Siemens 1LE1004	86.7	88.4	89.2	89.5
IM WEG W22	85.8	88.2	89.3	89.7
IM Siemens 1LE1003	84.9	86.5	87.1	87.3
IM WEG W21	84.8	86.3	86.9	87.2
IM ABB M3BP	82.7	85.2	86.3	86.8

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

$$C_{\text{y.m}} = E_{\text{y.m}} \cdot GT. \tag{7}$$

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)

$$S_{\text{y.m}} = C_{\text{y.8}} - C_{\text{y}(1\ldots7)}, \tag{8}$$

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

Table 4

Power consumption $P_{1.i,m}$, W

i	1	2	3	4
LSPMSM SEW DRU J	996.2	1266.1	1520.3	1742.3
LSPMSM Synchro-VERT	971.3	1258.6	1527.4	1760.8
LSPMSM WEG WQuattro	1022.6	1295.2	1550.9	1773.1
IM Siemens 1LE1004	982.2	1262	1526.3	1757.5
IM WEG W22	992.9	1264.8	1524.4	1753.8
IM Siemens 1LE1003	1003.1	1289.9	1562.5	1802.5
IM WEG W21	1004.4	1293.1	1566	1805
IM ABB M3BP	1029.4	1309.4	1576.4	1812.2

Table 5

Cost characteristics of power consumption

Type	$E_{\text{d.m}}$, kW·h	$E_{\text{y.m}}$, kW·h	$C_{\text{y.m}}$, €	$S_{\text{y.m}}$, €
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 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.

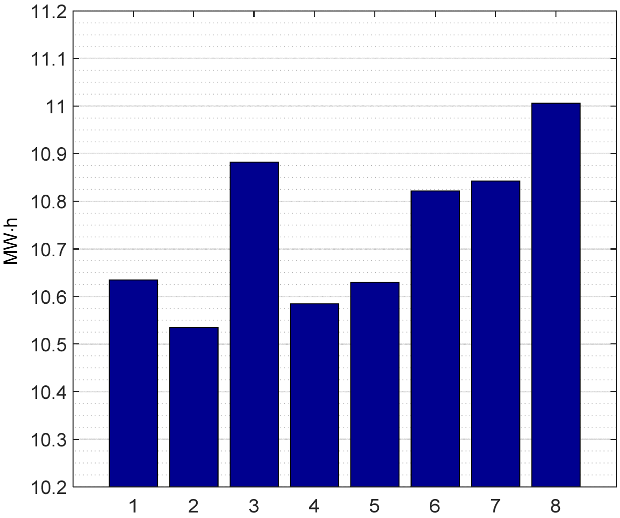

Fig. 5. Annual energy consumption:
1 – LSPMSM IE4 SEW DRU J; 2 – LSPMSM IE4 Synchrovert; 3 – LSPMSM IE4 Weg WQuattro; 4 – IM IE4 Siemens 1LE1004; 5 – IM IE4 Weg W22; 6 – IM IE3 Siemens 1LE1003; 7 – IM IE3 Weg W21; 8 – IM IE3 ABB M3BP

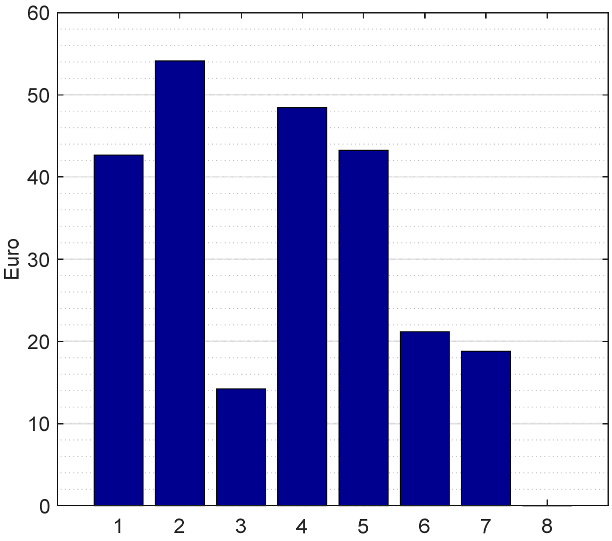

Fig. 6. Saving energy costs relative to electric motor No. 8:
1 – LSPMSM IE4 SEW DRU J; 2 – LSPMSM IE4 Synchrovert; 3 – LSPMSM IE4 Weg WQuattro; 4 – IM IE4 Siemens 1LE1004; 5 – IM IE4 Weg W22; 6 – IM IE3 Siemens 1LE1003; 7 – IM IE3 Weg W21; 8 – IM IE3 ABB M3BP

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, 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 [29] defines the efficiency values in seven load modes different from the nominal one. In the draft version of IEC 60034-30-2 [30], it was proposed for frequency-controlled electric motors of pumps and fans (drives with a quadratic dependence of the load on speed) to calculate the total efficiency as an average weighted average indicator of efficiency at reduced speeds and loads.

Therefore, 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:

$$EEI = P_{1.\mathrm{avg}} / P_{1.\mathrm{ref}}, \qquad (9)$$

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

$$P_{1.\mathrm{avg}} = \sum_{i=1}^{4} \left[\left(t_i / t_\Sigma \right) \cdot P_{1.i} \right]. \qquad (10)$$

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

$$P_{1.\mathrm{ref}} = P_{\mathrm{hydr.ref}} / (\eta_{\mathrm{motor.ref}} \cdot \eta_{\mathrm{pump.min.req}}). \quad (11)$$

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

In expression (11) $\eta_{\mathrm{motor.ref}}$ 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] ($\eta_{\mathrm{motor.ref}}$ = 86.7 %); $\eta_{\mathrm{pump.min.req}}$ 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_{BEP} and specific rotation speed n_s, in turn dependent on H_{BEP} and *n*. A detailed calculation of $\eta_{\mathrm{pump.min.req}}$ is not given in this paper, the calculation result: $\eta_{\mathrm{pump.min.req}}$ = 50.66 %.

According to formula (11), the value of $P_{1.\mathrm{ref}}$ = = 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.

Table 6

Energy efficiency index determination for pumping system

m	Type	$P_{1.\mathrm{avg}}$, W	*EEI*
1	LSPMSM SEW DRU J	1214.0	0.5786
2	LSPMSM SynchroVERT	1202.6	0.5732
3	LSPMSM WEG WQuattro	1242.3	0.5921
4	IM Siemens 1LE1004	1208.3	0.5759
5	IM WEG W22	1213.4	0.5784
6	IM Siemens 1LE1003	1235.4	0.5888
7	IM WEG W21	1237.7	0.5899
8	IM ABB M3BP	1256.4	0.5988

Note that for circulation pumps, which are the subject of EU regulations [25], since 2005 there is a voluntary labeling of products by members of the Europump association using the letters *A*...*G* of the energy efficiency class. It seems relevant to introduce such labeling for industrial pumping units operating at variable flow rates.

Conclusions.

A comparative analysis of the energy consumption of electric motors of various types (LSPMSMs and IMs) and energy efficiency class (IE3 and IE4) as a part of a 2.2 kW variable-flow pumping unit with throttle regulation is carried out in the work. The approach used to compare the energy characteristics of electric motors is described, including the calculation of the energy consumption of the pumping unit in a typical operation cycle with various process loads. Electric power, energy consumption and cost savings for 8 electric motors have been calculated.

Using the results of the calculation according to the described method, based on the passport data of electric motors and pumps, it has been shown that the use of an electric motor with high efficiency at rated load (high energy efficiency class according to [6]) does not always provide the minimum power consumption in a variable speed pump unit's operation cycle.

It is noted in the paper that it is possible to select the best electric motor according to a technique based on the determination of the energy efficiency index *EEI* [26], since the mode of operation of the pumping unit is also taken into account in its calculation. However, the calculated value of *EEI* does not provide information on energy savings in physical and cost terms, in contrast to the approach described in the work.

It is also shown in the paper that the considered LSPMSMs of IE4 class do not have significant advantages over IMs of IE4 class, and sometimes also of IE3 class, if used in pumping units with variable flow rate.

Acknowledgment.

The results of the work have been obtained with the support of the Ministry of Education and Science of the Russian Federation, task No. 8.9549.2017/8.9.

REFERENCES

1. De Almeida A.T. et al. *EuP Lot 11 Motors, Final report to the European Commission*, 2008.

2. Phillips R., Tieben R. Improvement of Electric Motor Systems in Industry (IEMSI). *Proceedings of the 10th international conference on energy efficiency in motor driven systems (EEMODS' 2017)*, Rome, Italy, September 6-8, 2017. pp. 53-67. **doi: 10.2760/345473**.

3. *European Commission. Study on improving the energy efficiency of pumps*, 2001.

4. Arun Shankar V.K., Umashankar S., Paramasivam S., Hanigovszki N. A comprehensive review on energy efficiency enhancement initiatives in centrifugal pumping system. *Applied Energy*, 2016, vol. 181, pp. 495-513. **doi: 10.1016/j.apenergy.2016.08.070**.

5. *European Commission Regulation (EC) No. 640/2009 implementing Directive 2005/32/ EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Electric Motors*, (2009), amended by Commission Regulation (EU) No 4/2014 of January 6, 2014.

6. *Rotating electrical machines – Part 30-1: Efficiency classes of line operated AC motors (IE code)*. IEC 60034-30-1/ Ed. 1; IEC: 2014-03.

7. De Almeida A., Fong J., Falkner H. New European ecodesign regulation proposal for electric motors and drives. *Proceedings of the 9th International Conference on Energy Efficiency in Motor Driven Systems (EEMODS' 15)*, Helsinki, Finland, September 15-17, 2015. **doi: 10.2790/903731**.

8. Stoffel B. *Assessing the Energy Efficiency of Pumps and Pump Units. Background and Methodology*. Elsevier: Amsterdam, The Netherlands, 2015. **doi: 10.1016/B978-0-08-100597-2.00009-4**.

9. Gevorkov L. *Simulation and Experimental Study on Energy Management of Circulating Centrifugal Pumping Plants with Variable Speed Drives*. PhD Thesys, Tallinn University of Technology, 2017.

10. Shuvalova J. *Optimal Approximation of Input-Output Characteristics of Power Units and Plants*. PhD Thesys, Tallinn University of Technology, 2004.

11. Glover A., Lukaszczyk M. Oversizing pump motors – the problems. *World Pumps*, 2005, vol. 2005, no. 466, pp. 36-38. **doi: 10.1016/s0262-1762(05)70638-6**.

12. Safin N., Kazakbaev V., Prakht V., Dmitrievskii V. Calculation of the efficiency and power consumption of induction IE2 and synchronous reluctance IE5 electric drives in the pump application based on the passport specification according to the IEC 60034-30-2. *2018 25th International Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED)*, Jan. 2018. **doi: 10.1109/IWED.2018.8321381**.

13. Kazakbaev V., Prakht V., Dmitrievskii V., Ibrahim M., Oshurbekov S., Sarapulov S. Efficiency Analysis of Low Electric Power Drives Employing Induction and Synchronous Reluctance Motors in Pump Applications. *Energies*, 2019, vol. 12, no. 6, p. 1144. **doi: 10.3390/en12061144**.

14. Mutize C., Wang R-J. Performance comparison of an induction machine and line-start PM motor for cooling fan applications». *Proceedings of SAUPEC*, 2013. **doi: 10.13140/RG.2.1.2542.1922.**

15. Jian Li, Jungtae Song, Yunhyun Cho. High Performance Line Start Permanent Magnet Synchronous Motor for Pumping System. *IEEE International Symposium on Industrial Electronics*, 2010. **doi: 10.1109/ISIE.2010.5637082**.

16. Kahrisangi M.G., Isfahani A.H., Vaez-Zadeh S., Sebdani M.R. Line-start permanent magnet synchronous motors versus induction motors: A comparative study. *Frontiers of Electrical and Electronic Engineering*, 2012, pp. 2095-2732. **doi: 10.1007/s11460-012-0217-8.**

17. *NM, NMS, Close Coupled Centrifugal Pumps with Flanged Connections; Catalogue*; Calpeda, 2018. Available at: https://www.calpeda.com/system/products/catalogue_50hzs/53/en/NM_NMS_EN2018.pdf?1549893188 (accessed 23 March 2019).

18. *Catalogue of super premium efficiency SynchroVERT LSPM motors*. Available at: https://www.bharatbijlee.com/media/14228/synchrovert_catalogue.pdf (accessed 15 May 2019).

19. Available at: https://www.weg.net/catalog/weg/RU/en/Electric-Motors/Special-Application-Motors/Permanent-Magnet-Motors/Line-Start-PM-Motors/Wquattro-2-2-kW-4P-100L-3Ph-230-400-V-50-Hz-IC411---TEFC---B3T/p/13009386 (accessed 28 August 2019).

20. *Addendum to the operating instructions: AC Motors DR.71.J-DR.100.J with LSPM technology, 21281793/EN, 09/2014, SEW Eurodrive*. Available at: https://download.sew-eurodrive.com/download/pdf/21343799.pdf (accessed 20 August 2019).

21. *Catalog Siemens D81.1 Simotics GP, SD, XP, DP low-voltage motors, 05/2018*. Available at: www.siemens.com/drives/catalogs (accessed 27 August 2019).

22. Available at: https://www.weg.net/catalog/weg/MV/en/Electric-Motors/Low-Voltage-NEMA-Motors/General-Purpose-ODP-TEFC/Cast-Iron-TEFC-General-Purpose/W22-Super-Premium-Efficiency/W22-Super-Premium-Efficiency-3-HP-4P-182-4T-3Ph-208-230-460-380-V-60-Hz-IC411---TEFC---Foot-mounted/p/12792146 (accessed 28 August 2019).

23. Available at: https://www.weg.net/catalog/weg/RU/en/Electric-Motors/Low-Voltage-IEC-Motors/General-Purpose-ODP-TEFC/Aluminum-TEFC-General-Purpose/Aluminium-TEFC-General-Purpose/Multimounting-IE3/Multimounting-IE3-2-2-kW-4P-100L-3Ph-220-240-380-415-460-V-50-Hz-IC411---TEFC---B3T/p/12397774 (accessed 24 August 2019).

24. *Catalog ABB - Low Voltage General Performance motors, June 2018*. Available at: https://library.e.abb.com/public/00389a1977844886b7e3e7560a6c22bf/9AKK105789%20EN%2006-2018%20General%20Perf.pdf (accessed 14 May 2019).

25. *Commission Regulation (EC) No 641/2009* of July 22, 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for glandless standalone circulators and glandless circulators integrated in products, amended by Commission Regulation (EU) No 622/2012 of July 11, 2012.

26. *Extended product approach for pumps*, Copyright © 2014 by Europump. Published by Europump.

27. Ferreira F.J.T.E., De Almeida A.T. Energy savings potential associated with stator winding connection mode change in induction motors. *2016 XXII International Conference on Electrical Machines (ICEM)*, pp. 2775-2783. **doi: 10.1109/ICELMACH.2016.7732915.**

28. *Eurostat Data for the Industrial Consumers in Germany*. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_industrial_consumers (accessed 10 September 2019).

29. *Rotating electrical machines – Part 30-2: Efficiency classes of variable speed AC motors* (IE-code) IEC 60034-30-2/ IEC: 2016-12.

30. *Rotating electrical machines – Part 30-2: Efficiency classes of variable speed AC motors* (IE-code) IEC 60034-30-2 (draft). Available at: https://www.iec.ch/dyn/www/f?p=103:52:0::::FSP_ORG_ID,FSP_DOC_ID,FSP_DOC_PIECE_ID:1221,151336,279593 (accessed on 17 September 2019).

31. W. Ismar Borges de Lima, editor. *Rare Earth Industry*. Elsevier, 2015. **doi: 10.1016/C2014-0-01863-1**.

32. Dent P.C. Rare earth elements and permanent magnets (invited). *Journal of Applied Physics*, 2012, vol. 111, no. 7, p. 07A721. **doi: 10.1063/1.3676616**.

33. Goss J., Popescu M., Staton D. A comparison of an interior permanent magnet and copper rotor induction motor in a hybrid electric vehicle application. *Proceedings of IEEE International Electric Machines & Drives Conference, EMDC 2013*, Chicago, IL, USA. **doi: 10.1109/IEMDC.2013.6556256**.

34. Ismagilov F.R., Vavilov V.E., Gusakov D.V. Line-Start Permanent Magnet Synchronous Motor for Aerospace Application. *2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC)*, Nov. 2018. **doi: 10.1109/ESARS-ITEC.2018.8607689**.

35. Sorgdrager A.J., Wang R.-J., Grobler A.J. Multiobjective Design of a Line-Start PM Motor Using the Taguchi Method. *IEEE Transactions on Industry Applications*, 2081, vol. 54, no. 5, pp. 4167-4176. **doi: 10.1109/TIA.2018.2834306**.

36. Kurihara K., Rahman M.A. High-Efficiency Line-Start Interior Permanent-Magnet Synchronous Motors. *IEEE Transactions on Industry Applications*, 2004, vol. 40, no. 3, pp. 789-796. **doi: 10.1109/TIA.2004.827476**.

37. Niaz Azari M., Mirsalim M. Line-start permanent-magnet motor synchronisation capability improvement using slotted solid rotor. *IET Electric Power Applications*, 2013, vol. 7, no. 6, pp. 462-469. **doi: 10.1049/iet-epa.2013.0042**.

38. Ferreira F.J.T.E., Leprettre B., de Almeida A.T. Comparison of protection requirements in IE2- IE3- and IE4-class motors. *IEEE Transactions on Industry Applications*, 2016, vol. 52, no. 4, pp. 3603-3610. **doi: 10.1109/TIA.2016.2545647**.

39. *Commission regulation (EU) No 547/2012* of June 25, 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for water pumps.

40. Lang S., Ludwig G., Pelz P.F., Stoffel B. *General methodologies of determining the Energy Efficiency Index of pump units in the frame of the Extended Product Approach*. Rio de Janeiro, EEMODS, 2013. **doi: 10.2790/28891**.

Received 29.10.2019

V.V. Goman[1], *Candidate of Technical Science,*
S.Kh. Oshurbekov[2],
V.M. Kazakbaev[2], *Candidate of Technical Science,*
V.A. Prakht[2], *Candidate of Technical Science,*
V.A. Dmitrievskii[2], *Candidate of Technical Science,*
[1] Nizhny Tagil Technological Institute (branch)
of Ural Federal University,
59, Krasnogvardeiskaia Str., Nizhny Tagil,
Sverdlovsk Region, 622013, Russia,
e-mail: v.v.goman@urfu.ru
[2] Ural Federal University,
19, Mira Str., Ekaterinburg, 620002, Russia,
e-mail: s.oshurbekov@mail.ru, vadim.kazakbaev@urfu.ru,
va.prakht@urfu.ru, vladimir.dmitrievsky@urfu.ru

How to cite this article:
Goman V.V., Oshurbekov S.Kh., Kazakbaev V.M., Prakht V.A., Dmitrievskii V.A. Comparison of energy consumption of various electrical motors operating in a pumping unit. *Electrical engineering & electromechanics*, 2020, no.1, pp. 16-24. **doi: 10.20998/2074-272X.2020.1.03.**