Article

Comparative Study of Energy Consumption and CO₂ Emissions of Variable-Speed Electric Drives with Induction and Synchronous Reluctance Motors in Pump Units

Victor Goman ¹ , Vladimir Prakht ² , Vadim Kazakbaev ^{2,*} and Vladimir Dmitrievskii ²

¹ Nizhniy Tagil Technological Institute, Ural Federal University, 622000 Nizhniy Tagil, Russia; v.v.goman@urfu.ru

² Department of Electrical Engineering, Ural Federal University, 620002 Yekaterinburg, Russia; va.prakht@urfu.ru (V.P.); vladimir.dmitrievsky@urfu.ru (V.D.)

* Correspondence: vadim.kazakbaev@urfu.ru

Abstract: This study carried out a comparative analysis of indicators of electricity consumption and CO₂ emissions for four-pole induction motors (IMs) of efficiency classes IE3 and IE4 with a rated power of 2.2–200 kW in a variable speed pump unit. In addition, innovative IE4 converter-fed synchronous reluctance motors (SynRMs) were evaluated. The comparison was derived from the manufacturer's specifications for the power drive systems (PDSs) at various rotational speeds and loads. The results showed that the emission indicators for IE3 class motors were significantly worse compared with IE4 class motors for low power ratings, which make up the vast majority of electric motors in service. This justifies expanding the mandatory power range for IE4 motors to at least 7.5–200 kW or even 0.75–200 kW, as it will dramatically contribute to the achievement of the new ambitious goals for reducing greenhouse gas emissions. In addition, the operational advantages of IE4 SynRMs over IE4 IMs were demonstrated, such as their simpler design and manufacturing technology at a price comparable to that of IE3 IMs.

Keywords: carbon dioxide emissions; climate change mitigation; electric motors; energy conversion; energy efficiency; energy efficiency class; energy policy and regulation; energy saving; sustainable utilization of resources

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1. Introduction

Recently, the European Union has set new ambitious targets to achieve a climate-neutral economy by 2050 according to the European Green Deal plan [1]. In addition, the Council of Europe has raised the target for reducing greenhouse gas emissions by 2030 from the 1990 level of 40% to 55% [2]. The main greenhouse gas is carbon dioxide (CO₂). The most modern methods of electricity generation result in CO₂ emissions. Therefore, the CO₂ emissions can be limited by reducing the electricity consumption of the most significant consumers [3,4]. Electric motors are the largest consumers of electricity. Reducing their consumption will have a significant positive impact on climate change mitigation. According to [5], electric motors consume about half of all electricity in the European Union, which is about 2000 TWh per year; the number of electric motors is about 8 billion; and the volume of associated annual greenhouse gas emissions is 800 MtCO₂-eq. It is also known that electric motors account for approximately 53% of all electric power generated worldwide, or 10,700 TWh per year [6]. As a result, ever more stringent legal requirements for the energy efficiency of mains [7] and frequency-converter-powered motors [8] are being adopted.

In accordance with the European Commission Regulations 2009 and 2014 [9] of 1 January 2017, in the European Union, every direct-on-line motor with a power rating of 0.75–375 kW must be at least as efficient as the IE3 energy efficiency class, and the converter-fed motors must not be less efficient than the IE2 class. In 2019, these requirements were

updated: in accordance with European Commission Regulation 2019 [10] of 1 July 2021; both motors with the mains supply and converter-fed motors from 0.75 to 1000 kW with the number of poles from 2 to 8 must correspond to at least IE3 class. In many other countries, the IE3 efficiency class has already been adopted as mandatory for newly installed motors, as Table 1 suggests [11,12]. Moreover, in accordance with [10], the European Union plans to adopt the IE4 class as mandatory for motors with a power rating from 75 to 200 kW with the number of poles from 2 to 6.

Table 1. Adopting national regulations for the mandatory IE3 class.

Country	Power Range	First Year of Implementation	Country	Power Range	First Year of Implementation
Switzerland,	0.75–375 kW	2017	Japan	0.75–375 kW	2014
Turkey	0.75–200 kW	2007	Saudi Arabia	0.75–375 kW	2018
USA	0.18–2.2 kW	2015	Brazil	0.75–185 kW	2017
USA	0.75–150 kW	2017	Taiwan	0.75–200 kW	2016
Canada	0.75–375 kW	2010	Singapore	0.75–375 kW	2013
Mexico	0.75–200 kW	2017	-	-	-
South Korea					

It is known that electrically driven fluid-processing mechanisms such as pumps, fans, and compressors use about 70% of electric power consumed by all electric motors [6]. In this regard, reducing the energy consumption of pumping units becomes critical. There are many ways to reduce the energy consumption of a pump unit. For instance, it is well known that the reduction of their energy consumption is possible with the help of variable-speed drives (VSDs) [13]. A further improvement in the energy efficiency of a pump unit equipped with a VSD can be achieved through the use of a more energy-efficient electric motor.

2. Literature Review and Novelty of the Study

The energy efficiency of three-phase AC electric motors such as induction motors (IMs, Figure 1a), permanent magnet synchronous motors (PMSMs), and synchronous reluctance motors (SynRMs, Figure 1b) has been extensively compared in previous studies.

Figure 1. Machine general design representations: (a) IM; (b) SynRM.

Some studies were not devoted to the analysis of pumps driven by VSDs, but to the analysis of pumps with motors powered directly from the mains. For instance, in [14], a comparison of the efficiency and power factor of the IE1–IE3 induction motors and a direct-on-line permanent magnet motor of the IE4 class was provided. It was concluded that direct-on-line PMSMs could be competitively capable with IMs in the power range of ≤ 15 kW due to significantly higher efficiency, despite their significantly higher cost. The article claimed that PMSMs cost 2.2–38 times more than IE2 IMs. However, it should be noted that the paper was published more than 7 years ago, motor manufacturers have further mastered PMSM production, and the market price of PMSMs has dropped significantly. In any case, it is shown that PMSMs can have a payback period of fewer than 3 years, even if their cost is 2.3 times higher than IE2 IMs.

In [15], the energy consumption of induction and direct-on-line permanent magnet motors of the IE3 and IE4 energy-efficiency classes and with a power rating of 2.2 kW was assessed for a pump application. A number of energy-efficiency metrics were compared for these motors, such as annual energy costs and lifetime energy costs, as well as cost savings. The study demonstrated that for maximum energy savings, it was necessary to ensure high motor efficiency not only under maximum flow conditions, but also under reduced flow conditions, which have the longest duration in the typical duty cycle of pumping systems with VSDs. In [16], the energy consumption and payback period of IE1 and IE2 induction motors with a rated power of 15 kW were compared. However, CO₂ emissions were not evaluated in [12–16].

A number of papers were devoted to accessing the energy consumption of pump units controlled by VSDs. In [17], the dependencies of efficiency on speed and torque were determined for a pump drive based on 15 kW IMs of IE3 class, 15 and 18.5 kW SynRMs of IE4 class, and 15 kW PMSM of IE5 class. A typical pump load profile with a variable flow rate was considered. Annual energy indicators such as electricity consumption and cost, as well as electricity savings, were assessed. Paper [18] compared experimental data on the energy consumption of IE1 and IE2 IMs and an IE3 SynRM with a power rating of 45 kW in a pumping application. In [19], an IE2 IM and an IE5 SynRM with a power rating of 0.75 kW were compared in the case of a VSD pump application. In [20], an IM and SynRM with a power rating of 1.1 kW were considered in a pump unit with an approximately constant flow rate. The annual energy consumption, annual electricity costs, and annual cost savings were determined. In [21], efficiency maps for an 11 kW IM and SynRM were experimentally obtained and compared.

Paper [22] was devoted to the comparison of the service life of induction motors of various IE classes in various conditions; for example, with an asymmetric and distorted power supply. Paper [23] showed the effect of an overvoltage and undervoltage imbalance on the temperature and performance of IMs of the classes IE2, IE3, and IE4. Paper [24] presented issues related to motor protection, and compared a 7.5 kW IM and PMSM under various operating conditions: thermal steady state at full and partial load, starting, locked rotor, voltage unbalance, and undervoltage. Paper [25] developed and validated simple energy models for pump systems with a VSD drive. In [26], an estimate of energy savings for single pump systems for a storage fill application was developed using various control strategies.

All the previous studies mentioned above [15–26] did not assess CO₂ emissions. In addition, in [15–24], the analyses were carried out only for one specific power rating of the pump and PDS, which did not allow the authors to draw conclusions about the energy savings, cost savings, and CO₂ emissions for the wide range of power ratings commonly used in the industry.

Based on the literature overview presented above, it can be concluded that the energy efficiency metrics and CO₂ emissions for IMs and SynRMs of the IE3 and IE4 classes over a wide range of power outputs in the application of variable speed pumps have not yet been investigated in previous studies.

This paper presents a comparative analysis of the main metrics of energy efficiency, cost savings, and CO₂ emissions of PDSs with four-pole IMs of the IE3 and IE4 classes and SynRMs of the IE4 class with rated outputs of 2.2, 15, 75, 200 kW in a variable-speed pump unit. An analysis of PMSM metrics was not included in this study, as they are rarely used in variable speed pumps due to their higher cost compared to IMs and SynRMs. The main advantage of PMSMs is their reduced weight and dimensions, but this is not in demand in the considered application [20]. The authors believe that the converter-powered PMSMs are more suitable for use in applications such as traction and servo drives. The power ratings of 75 and 200 kW were selected for the analysis, as they are the upper and lower limits of the mandatory range of IE4 motors according to the directive [10].

For the comparative analysis, data from catalogues of pump manufacturers [27–30] and a typical flow-time diagram for the application under consideration were used.

The pump characteristics from the catalogues were interpolated by the second-order polynomial, which was most often used in previous works [31–33]. The semianalytical pump model based on interpolation of catalogue data at the rated rotational speed is commonly used for pumping system analysis [15,33]. When analyzing pumping systems, methods of multicriteria optimization [34,35], statistical methods of reliability analysis [36], and neural networks [37] are also often used.

Typical pump operating conditions and flow-time diagrams are well described in the literature [38,39]. The flow-time diagram with the approximately constant flow rate given in [38,39] was selected for analysis as the most suitable for considered power range. As shown in Figure 2, it was considered: 75% flow for a quarter of the total duty cycle (below this case marked as $i = 1$, where i is the index of the duty cycle load point); 100% flow for half of the total duty cycle ($i = 2$); and 110% flow for another quarter of the total duty cycle ($i = 3$).

Figure 2. Flow versus time for the constant flow pump units [38,39].

The PDS efficiency depends on the torque and rotational speed. We considered the PDS as a power drive system in terms of the standard IEC 61800-9-2: 2017 [40]. It consisted of a complete drive module (CDM) and an electric motor. The CDM included a frequency converter and protection devices. Nowadays, sensorless field-oriented control is commonly used as a method for controlling AC motors in applications that do not require high-precision control, such as pumps and fans [41]. According to [40], the PDS power loss measurement must be provided at eight loading points (Figure 3a). Values of the motor efficiency under variable speed operations and partial load conditions can be calculated, for example, according to [42], but this does not provide values for the entire PDS efficiency. Some manufacturers already provide such information; therefore, their experimental data were used for analysis as the most reliable source. Information on PDS loss at these eight points is available in the online application Sinasave [43]. Since the range of the power rating of the Siemens SynRM was limited to 45 kW, a PDS based on ABB's SynRMs were considered for 75 and 200 kW ratings. Efficiency data for the ABB PDSs at 16 loading points (shown in Figure 3b) were provided in the manufacturer's statements [44,45].

Figure 3. Data formats for PDS efficiency interpolation: (a) Siemens (losses according to IEC 61800-9-2:2017 [40]; source: Sinasave software [43]); (b) ABB (efficiency; source: manufacturer's statements [44,45]).

3. Evaluation of Pump and PDS Performances

Data from the Grundfos NB 50-200/210 [27], NB 80-315/305 [28], NB 150-400/375 [29], and NB 250-500/445 [30] pumps with the rated powers $P_{RATE,pump}$ consequently of 2.2, 15, 75, and 200 kW were considered in the analysis. All considered pumps had a rated rotational speed of 1450 rpm. The key parameters of these pumps at the best efficiency point (BEP) are specified in Table 2, where H is the pump head, Q is the pump flow rate, and η is the pump efficiency. Let us evaluate the power consumption of the PDS in combination with a pump of a certain power rating. First, a polynomial interpolation of the head-flow curve for the rated rotational speed was carried out according to Equation (1):

$$H(Q) = a_2 \cdot Q^2 + a_1 \cdot Q + a_0. \quad (1)$$

Table 2. Nameplate data of pumps.

No. of Pump	Type	$P_{RATE,pump}$, kW	$n_{RATE,pump}$, rpm	Q_{BEP} , m ³ /h	H_{BEP} , m	η_{BEP} , %
1	NB 50-200/210	2.2	1450	35.2	13.7	69.8
2	NB 80-315/305	15	1450	125.0	29.0	76.8
3	NB 150-400/375	75	1450	441.3	45.0	84.4
4	NB 250-500/445	200	1450	852.5	60.1	81.5

At nonrated rotational speed n_{pump} , according to the hydraulic affinity laws [33], which were applicable for the considered flow variation range (75...110%), the H - Q curve is described as:

$$H(Q) = a_2 \cdot Q^2 + a_1 \cdot \frac{n_{pump}}{n_{RATE,pump}} \cdot Q + a_0 \cdot \left(\frac{n_{pump}}{n_{RATE,pump}} \right)^2 \quad (2)$$

The rotational speeds required to provide 75% and 110% of the rated flow were determined according to the reference control curve $C(Q)$ [38], which was a straight line (3) passing through points $(0, H_{BEP}/2)$ and (Q_{BEP}, H_{BEP}) , where Q_{BEP} and H_{BEP} are the flow and head of the pump in the BEP:

$$C(Q) = k \cdot Q + b. \quad (3)$$

The rotational speed $n_{pump,i}$ (in rpm) for each required value of a flow was determined by jointly solving Equations (2) and (3). Using the results of the pump operating performances (n_i , Q_i , H_i) and the manufacturer's ISO efficiency curves [27–30], the pump efficiency $\eta_{pump,i}$ was evaluated at each operating point considered (75, 100, and 110% of the rated flow). According to Equations (4) and (5), the motor mechanical power and torque were evaluated at i -th loading point:

$$P_{mech,i} = \rho \cdot g \cdot Q_i \cdot H_i / \eta_{pump,i} \quad (4)$$

$$T_{pump,i} = 9.55 P_{mech,i} / n_{pump,i} \quad (5)$$

where $g = 9.81 \text{ m/s}^2$; $\rho = 1000$ is the water density, kg/m^3 ; and $i = 1, 2, 3$ (see Figure 1).

The rated rotational speed $n_{RATED,motor}$ and rated torque $T_{RATED,motor}$ of the motors employed in the considered PDSs are shown in Table 3.

Table 3. Catalogue data of motors.

<i>m</i>	Type of Motor, IE Class	$n_{RATED,motor}$, rpm				$T_{RATED,motor}$, N·m			
		2.2	15	75	200	2.2	15	75	200
1	SynRM, IE4	1500	1500	1500	1500	14.0	95.0	478	1272
2	IM, IE4	1465	1480	1490	1490	14.3	97.0	480	1280
3	IM, IE3	1465	1475	1485	1488	14.3	97.0	480	1280

In the case of the data format shown in Figure 3a, the loss of the m -th PDS at the i -th load point $P_{loss,i,m}$ was calculated using two-dimensional interpolation of the initial loss points according to the methodology given in [40]. In the case of the data format shown in Figure 3b, the traditional bilinear interpolation was used. The PDS efficiency $\eta_{PDS,i,m}$ was determined using Equation (6):

$$\eta_{PDS,i,m} = P_{mech,i} / (P_{mech,i} + P_{loss,i,m}) \quad (6)$$

4. PDS Energy Consumption

The mechanical power obtained according to Equation (4) and the interpolated PDS efficiency were used to calculate the electrical power consumed from the grid (7):

$$P_{1,i,m} = P_{mech,i} / \eta_{PDS,i,m} \quad (7)$$

The annual electricity consumption of each PDS with the adopted flow-time diagram (Figure 2) of the pump unit was determined according to Equation (8):

$$E_{y,m} = 365 \cdot t_{\Sigma} \cdot \sum_{i=1}^3 \left(P_{1,i,m} \cdot \frac{t_i}{t_{\Sigma}} \right) \quad (8)$$

where t_i is the time of running the pump at each point of the flow-time diagram; and t_{Σ} is the total duration of the daily operation of the pump (24 h).

The electricity cost was calculated using Equation (9):

$$C_{y,m} = E_{y,m} \cdot GT \quad (9)$$

where $GT = \text{EUR } 0.1781/\text{kWh}$ is the electricity tariff for nonhousehold consumers in Germany in the first half of 2020, excluding VAT [46].

To compare the cost of energy consumed by different electric motors in a certain pump unit, the difference in the electricity cost relative to case $m = 3$ (PDS with the IE3 motor) was calculated as Equation (10):

$$S_{y,3m} = C_{y,3} - C_{y,m} \quad (10)$$

It is known that the service life of a pump unit is about 15–20 years, and the most significant contribution to the lifetime expenses of a pump is made by the cost of consumed electricity, which can exceed 50–60% of the total cost [47,48]. In this study, we assumed that the design life of the pump unit was $n = 20$ years.

The net present value (NPV) for the lifetime energy cost was calculated according to Equation (11):

$$C_{LCCen.m} = C_{y.m} / (1 + (y - p))^n, \quad (11)$$

where $p = 0.02$ is the assumed annual inflation rate; and $y = 0.04$ is the interest rate [47,48].

The lifetime cost savings of PDSs with different IE4 motors ($m = 1, 2$) compared to a PDS with IE3 motors ($m = 3$) was evaluated as:

$$\Delta C_{LCCen.3m} = C_{LCCen.3} - C_{LCCen.m}. \quad (12)$$

5. Evaluation of CO₂ Emission Intensity

The yearly CO₂ emission intensity was evaluated according to Equation (13):

$$CDE_{y,m} = E_{y,m} \cdot EFE. \quad (13)$$

where $EFE = 418.8$ g/kW·h is the CO₂ emission factor for electricity consumption for Germany [49].

The yearly avoided CO₂ emissions were estimated as:

$$\Delta CDE_{y,3m} = CDE_{y,3} - CDE_{y,m}. \quad (14)$$

The emission intensity estimation using Equations (13) and (14) did not take into account the total volume of emissions. CO₂ emissions arise from the consumption of primary energy sources in power plants. Therefore, to assess the CO₂ emissions associated with the electricity calculated by Equation (8), it was necessary to use the primary energy factor (PEF) characterizing the average efficiency of conversion of primary energy into the final one [50,51]. Therefore, the annual emission including $PEF CDE_{y,m}^*$ and the corresponding avoided CO₂ emissions $\Delta CDE_{y,3m}^*$ were evaluated as the follows:

$$CDE_{y,m}^* = CDE_{y,m} PEF. \quad (15)$$

$$\Delta CDE_{y,3m}^* = CDE_{y,3}^* - CDE_{y,m}^*. \quad (16)$$

where $PEF = 2.2$ is the primary energy factor evaluated.

A default PEF value of 2.5 should be applied in accordance with directive 2012/27/EU [50]. However, recent studies indicated the need to revise this factor to 1.8–2.2 [52,53]. Based on this, $PEF = 2.2$ was adopted in this study.

6. Results and Discussions

Figure 4 shows the catalogue points of the pump head-flow characteristic calculated according to Equation (2) head-flow curves and reference control curve for the 2.2 kW pump as an example. Table 4 shows the calculation results for the pump performances during the operating cycle. Table 5 shows the interpolated PDS efficiency at the pump operating points indicated in Figure 2 for the four power ratings considered.

Figure 4. Calculated head-flow curves of the pump at 75, 100, and 110% flow and initial points of the 2.2 kW pump, and reference control curve.

Table 4. Performances of the pumps of different power ratings during the operating cycle.

No. of Pump	1 (NB 50-200/210, 2.2 kW)			2 (NB 80-315/305, 15 kW)			3 (NB 150-400/375, 75 kW)			4 (NB 250-500/445, 200 kW)		
	1	2	3	1	2	3	1	2	3	1	2	3
Q_i , %	75	100	110	75	100	110	75	100	110	75	100	110
Q_i , m ³ /h	23.4	35.2	38.7	93.8	125.0	137.5	331.0	441.3	485.4	639.4	852.5	937.8
H_i , m	12.0	13.7	14.4	25.4	29.0	30.5	39.4	45.0	47.2	52.6	60.1	63.1
a_2		−0.0038			−5.5371 × 10 ^{−4}			−8.8848 × 10 ^{−5}			−3.7879 × 10 ^{−5}	
a_1		0.066			0.0398			0.0318			0.286	
a_0		16.27			33.18			48.83			63.00	
k		0.195			0.116			0.051			0.0352	
b		6.855			14.5			22.49			30.05	
$n_{pump,i}$, rpm	1310	1450	1508	1310	1450	1508	1310	1450	1508	1310	1450	1508
$n_{pump,i}$, %	90.3	100.0	104.0	90.3	100.0	104.0	90.3	100.0	104.0	90.3	100.0	104.0
$\eta_{pump,i}$, %	68.9	69.8	69.5	75.9	76.8	76.3	82.9	84.4	84.1	79.6	81.5	81.2
$P_{mech,i}$, kW	1.25	1.88	2.18	8.54	12.86	14.95	42.82	64.09	74.29	115.1	171.3	198.6
$P_{mech,i}$, %	56.9	85.5	99.2	56.9	85.7	99.7	57.1	85.5	99.1	57.6	85.7	99.3
$T_{pump,i}$, N·m	9.18	12.44	13.87	62.50	85.32	95.52	313.2	424.4	473.3	838.1	1126	1255

Table 5. Interpolated efficiencies of selected power drive systems.

m	Type of Motor, IE Class	Interpolated Motor Efficiency $\eta_{M,i,m}$, % in the Load Points											
		2.2 kW			15 kW			75 kW			200 kW		
		1	2	3	1	2	3	1	2	3	1	2	3
1	SynRM, IE4	86.8	88.5	89.1	91.6	92.2	92.4	93.1	93.5	93.6	94.2	94.5	94.4
2	IM, IE4	84.1	85.4	85.7	89.9	90.4	90.6	92.4	92.7	92.8	93.7	93.8	93.8
3	IM, IE3	82.1	82.4	82.6	88.5	89.1	89.3	91.8	91.9	92.0	93.1	93.2	93.2

Table 6 summarizes the results of calculations using Equations (8)–(12). The annual energy consumption is shown in Figure 5. According to these results, the PDS based on SynRM demonstrated the lowest annual electricity consumption and the highest cost savings. Based on the annual $S_{y,3m}$ and lifetime savings $\Delta C_{LCCen,3m}$, replacing the IE3 IM with the IE4 SynRM provided approximately 2 times more savings than replacing it with the IE4 IM for all power ratings considered. Table 7 summarizes the results for the CO₂ emissions according to Equations (13)–(16). The results for CO₂ emissions in Table 7 showed similar patterns; i.e., the PDS with IE4 SynRM allowed the highest avoided annual emissions: $\Delta CDE_{y,3m}$ and $\Delta CDE^*_{y,3m}$.

Figure 5. Annual energy consumption (MW·h).

Table 6. Results for the PDS electricity costs and cost savings.

<i>m</i>	Type of Motor, IE Class	$E_{y,m}$, MW·h	$C_{y,m}$, k€	$S_{y,3m}$, k€	$C_{LCCen,m}$, k€	$\Delta C_{LCCen,3m}$, k€
2.2 kW						
1	SynRM, IE4	17.84	3.18	0.23	51.94	3.743
2	IM, IE4	18.47	3.29	0.12	53.80	1.884
3	IM, IE3	19.12	3.41	-	55.68	-
15 kW						
1	SynRM, IE4	117.0	20.83	0.73	340.6	11.90
2	IM, IE4	119.2	21.24	0.32	347.3	5.216
3	IM, IE3	121.0	21.56	-	352.5	-
75 kW						
1	SynRM, IE4	574.8	102.38	1.66	1674	27.22
2	IM, IE4	579.4	103.20	0.846	1688	13.83
3	IM, IE3	584.2	104.04	-	1702	-
200 kW						
1	SynRM, IE4	1522	271.14	3.62	4437	59.12
2	IM, IE4	1533	272.97	1.79	4464	29.21
3	IM, IE3	1543	274.76	-	4493	-

Table 7. Results of calculating the annual CO₂ emissions.

<i>m</i>	Type of Motor, IE Class	Emissions Considering the Final Energy		Emissions Considering the Primary Energy	
		<i>CDE</i> _{<i>y,m</i>} , Tons	$\Delta CDE_{y,3m}$, Tons	<i>CDE</i> [*] _{<i>y,m</i>} , Tons	$\Delta CDE^*_{y,3m}$, Tons
2.2 kW					
1	SynRM, IE4	7.465	0.538	16.43	1.184
2	IM, IE4	7.737	0.271	17.02	0.596
3	IM, IE3	8.008	-	17.62	-
15 kW					
1	SynRM, IE4	48.98	1.711	107.75	3.764
2	IM, IE4	49.94	0.750	109.87	1.650
3	IM, IE3	50.69	-	111.52	-
75 kW					
1	SynRM, IE4	240.7	3.914	529.64	8.611
2	IM, IE4	242.7	1.989	533.87	4.376
3	IM, IE3	244.7	-	538.24	-
200 kW					
1	SynRM, IE4	637.6	8.502	1402.7	18.70
2	IM, IE4	641.9	4.201	1412.2	9.242
3	IM, IE3	646.1	-	1426.6	-

The percentages shown in Table 8 and Figure 6 were the same for the cost savings and avoided CO₂ emissions.

Table 8. Cost savings (avoided CO₂ emissions, in%) relative to the PDS with an IE3 motor.

<i>m</i>	Type of Motor, IE Class	2.2 kW	15 kW	75 kW	200 kW
1	SynRM, IE4	6.72	3.38	1.60	1.32
2	IM, IE4	3.38	1.48	0.81	0.65

Figure 6. Cost savings/avoided CO₂ emissions (in %) for an output power range of 2.2–200 kW relative to the PDS with an IE3 motor.

As seen in Figure 6, the relative savings were about 5 times greater for low-power motors compared to high-power motors. Nevertheless, according to [54], for Europe, in the power range of 0.75–200 kW, the share of motors with rated power from 0.75 (1 hp) to 7.5 kW (10 hp) is 79.1%, and the share of motors with rated power from 7.5 (10 hp) to 75 kW (100 hp) is only 19.8%. Therefore, to fulfill the tasks of the European Green Deal, it is recommended to legislatively expand the mandatory power range for electric motors

of the IE4 class to at least 7.5–200 kW, or even to 0.75–200 kW. However, the authors are aware that in the range of 0.75–7.5 kW, it is more difficult to achieve the IE4 class for induction motors [55].

Using the results shown in Table 8, the interpolation polynomials (17) for the PDS with SynRM and (18) for the PDS with IE4 IM were obtained, which can be used to calculate the cost savings, CS , % (avoided CO_2 emissions taking into account the final energy, ΔCDE , %; avoided CO_2 emissions taking into account the primary energy, ΔCDE^* , %) for intermediate power ratings not specified in Table 8, without carrying out a detailed calculation using Equations (1)–(16).

$$CS_{SynRM} = -0.02 \cdot P^3 + 0.91 \cdot P^2 - 5.93 \cdot P + 11.76, \quad (17)$$

$$CS_{IE4 IM} = -0.125 \cdot P^3 + 1.37 \cdot P^2 - 5.135 \cdot P + 7.27. \quad (18)$$

7. Payback Period Assessment

Studies [56,57] described SynRMs of the IE4 class designed using the same stator as an IE3 IM. Based on this, the cost of the IE4 SynRM was taken to be equal to the cost of the IE3 IM. At the same time, the SynRM has a simpler rotor design (Figure 1), is more reliable, and requires fewer active materials for their production [58,59]. The SynRM was characterized by higher efficiencies at lower loads than IMs [55,59]. The IE4 energy efficiency class (and even IE5) for SynRM can be achieved relatively easily, without the use of expensive solutions typical for the class IE4 of IMs [55]: the use of copper conductors in the rotor, the use of higher-quality electrical steel, and an increase in the mass and volume of active materials, which, in turn, leads to an increase in the dimensions of the motor and, in some cases, the transition to the next frame size for the same rated power. Thus, the SynRM can be expected to cost no more than the IE3 class IM in mass production.

The disadvantages of SynRMs are that they have a slightly lower power factor than IMs [59], and therefore a slightly higher rated current. The current values of the considered electric motors, taken from the manufacturers' catalogues, are shown in Table 9. The rated currents of the IE3 IM and the IE4 IM of the same power rating were approximately the same. The rated current of the IE4 SynRM was 15–33% higher than the IE3 IM, which was higher than the overcurrent limit usually provided by frequency converter manufacturers. Due to this, it is required to use a more expensive converter with a higher power rating when using a SynRM, in comparison with an IM. The cost of the converter turned out to be 10–40% higher, which led to an increase in the cost of the PDS.

Let us calculate the payback period of using a PDS based on a SynRM and IE4 IM instead of PDS based on IE3 IM, for two cases, according to Formulas (19) and (20), where $C_{iic,m}$ is the turnkey costs of the m -th PDS, which are presented in Table 9. Formula (19) describes the calculation of the payback period for the case of a newly commissioned pump unit. Replacing the motor in a pump unit already put into operation is implied when calculating according to Formula (20):

$$T_{m1} = (C_{iic,m} - C_{iic,3}) / S_{y,3m}, \quad (19)$$

$$T_{m2} = C_{iic,m} / S_{y,3m}. \quad (20)$$

To evaluate the cost of frequency converters and IE3 class IMs, their market prices were taken from manufacturers' websites [58,60]. It was assumed that the cost of the SynRM was the same as the cost of the IE3 IM. An analysis of recent studies [5,61–63] and available market prices showed that the difference in the turnkey price of motors of related energy efficiency classes was usually 15–30%. In this paper, it was assumed that the cost of the IE4 class IMs was 22.5% higher than the cost of the IE3 class IMs. Table 9 shows the assumed costs. For the considered power range, the cost of the frequency converter, as shown in Table 9, was 60–140% of the motor cost, and the difference in the price of the PDS based on SynRM and IM was in the range of −8–+5%. Based on the results in

Table 9, it can be concluded that the PDSs with SynRM and IE4 IM had similar initial costs. However, despite this, the payback period of the SynRM turned out to be significantly shorter (Figure 7) due to the greater energy savings, $S_{y.3m}$.

Table 9. Motor payback period.

<i>m</i>	Motor Type	Motor Current, A	Motor Price, €	Converter Price, €	PDS Price, $C_{iic,m}$, €	Payback Time 1, T_{m1} , Years	Payback Time 2, T_{m2} , Years
2.2 kW							
1	SynRM, IE4	5.7	286	242	528	0.09	2.32
2	IM, IE4	4.5	351	222	573	0.56	4.95
3	IM, IE3	4.4	286	222	508	-	-
15 kW							
1	SynRM, IE4	32.9	763	818	1581	0.34	2.22
2	IM, IE4	29	935	575	1510	0.54	4.71
3	IM, IE3	28.5	763	575	1338	-	-
75 kW							
1	SynRM, IE4	173	2954	3085	6039	0.27	3.61
2	IM, IE4	133	3618	2637	6255	0.78	7.32
3	IM, IE3	130	2954	2637	5590	-	-
200 kW							
1	SynRM, IE4	427	6883	9468	16,351	0.38	4.51
2	IM, IE4	345	8431	8092	16,524	0.87	9.28
3	IM, IE3	345	6883	8092	14,975	-	-

Figure 7. Payback time versus motor power rating.

8. Conclusions

This study provided a comparative assessment of metrics of energy consumption and CO₂ emission for various PDSs with a rated power in the range of 2.2–200 kW. The converter-fed PDSs with the IE3 IM, IE4 IM, and SynRM are considered. The analysis was based on extensive data from the technical specifications of the PDS [43–45] and pump manufacturers [27–30]. These data were processed using mathematical methods of polynomial and bilinear interpolation, regression, and a semianalytical model of a variable-speed pump unit. As a result of the analysis, the interpolating polynomials were constructed to evaluate the metrics of interest for any PDS from the entire considered power range.

This study showed that to achieve the goals of reducing greenhouse gas emissions, it is extremely important to use electric motors of higher energy-efficiency classes. The state of the art (IMs and SynRMs of the IE4 class) already allows effectively implementing the requirements of the European Commission [10], prescribing the mandatory use of IE4 class motors in the rated power range of 75–200 kW from 1 July 2023. The results showed that when replacing IE3 motors with IE4 motors, the largest reduction in CO₂ emissions was

shown by the low-power motors, which make up the vast majority of electric motors in service [54]. This justifies the mandatory use of IE4 motors for lower power ratings.

In addition, it was shown that the SynRMs of the IE4 class demonstrated significantly better indicators of reduction of CO₂ emissions and energy savings than the IMs of the same energy-efficiency class. Moreover, SynRMs have several operational advantages, such as their simpler design and manufacturing technology, at a price comparable to the price of the IE3 IMs. As a result, when replacing an IE IM, the energy savings of an IE4 SynRM will be approximately 2 times higher, and the payback period will be approximately half that of the IE4 IM for the entire considered power range. At the same time, the influence of the SynRM's lower power factor compared to IMs and the associated need for frequency converters with a higher power rating does not significantly affect the payback period.

According to the results of this study, in order to achieve the goals of the European Green Deal [1,2], it is recommended to legislatively expand the mandatory power range of electric motors of IE4 class from 75–200 kW to at least 7.5–200 kW.

In future work, the potential for significant reductions in greenhouse gas emissions in other mass applications of electric machines will be investigated. For example, fans and compressors are in principle similar to pumps, but have different typical operating conditions. The subject of future work may be an assessment of the energy-saving potential, payback periods, and CO₂ emissions for various typical operating profiles of such equipment. Moreover, a fast-growing quantity of electric vehicles also consumes an increasing share of electricity, which makes analysis in this area relevant.

In addition, on the basis of the developed model, it is possible to optimize the operating points of multipump units, which include pumps operating in parallel on the same pipeline.

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