Comparison of Power Consumption of Synchronous Reluctance and Induction Motor Drives in a 0.75 kW Pump Unit

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Abstract—This paper is devoted to the comparative study of performance data of a 0.75 kW variable speed electric drive with synchronous reluctance motor (SynRM) and induction motor (IM) in a pump application. The experimental data on the IM and SynRM drives efficiency within a wide range of working modes are used to assess the power consumption. The working modes of motors are calculated with the help of nameplate data and the mathematical model of a pump. It is shown that the use of SynRM significantly reduces the power consumption of a pump unit.

Keywords—Induction motors; industrial power system economics; reluctance motors, pumps; variable speed drives

I. INTRODUCTION

Electric motors consume up to 46% of the worldwide generated power. At the same time, the majority of units using electric motors can be classified into 4 types of applications: compressors (32%), handling equipment and processing machines (30%), pumps (19%) and fans (19%) [1]. This means that about 32% of the world's power is consumed by fluid-handling applications of various types. In particular, about 9% of power is consumed by pumps. In industrial applications, the pump units account for about 20% of the total power consumption [1].

An essential part of operated pump units is equipped with a variable frequency drive (VFD). Thus, according to the report of the European Commission in 2008, up to 30% of all newly introduced electric motors in Germany are supplied together with frequency converters [1]. There is a reason to believe that such an approximate ratio is fair for the drive of industrial pumps as well.

Apart from achieving high quality of a served process, the VFD application allows obtaining a significant energy saving effect.

Due to the fact that pump units comprise a significant part of power consumption, much attention has been paid to the issues of their efficient energy use over the last years. A controlled pump unit consists of a pump, a motor and a frequency converter [1]. An approach to the efficient energy use control of a pump unit is widely used at present and involves the efficiency normalization of each of the above nodes taken separately [1].

In the countries, in which the IEC standards are valid or adapted in the form of national standards (including the countries of the European Union (EU)), the motor efficiency is normalized by the standard IEC 60034-30-1 "Efficiency Classes of Line Operated AC Motors (IE Code)" that introduces the IE classes for the line operated motors. Since 2017, the motors of 0.75-375 kW in the EU must conform to at least the IE2 class as part of a variable speed drive or the IE3 class as part of an uncontrolled drive [2]. It should be noted that the second part of the standard IEC 60034-30-2 "Efficiency Classes of Variable Speed AC Motors (IE-Code)", which will introduce the norms for variable speed motors, has not been yet officially published. Therefore [2], the IEC 60034-30-1 norms are applied for both line and FC operated motors. In the future, the IEC 60034-30-2 norms should be applied to the motors configured for FC operation only [16]. The IES classes can be used as a criterion of the frequency converter efficiency according to [4].

The Minimum Efficiency Index (MEI) is currently an efficiency criterion for the hydraulic part of a pump unit legislatively adopted in the EU [1], [3]. The MEI is a dimensionless quantity, the value range of which for modern pumps is 0.1 (least efficient) to 1 (most efficient). Since 2014, all the pumps repeatedly put into operation in the EU must satisfy the MEI ≥ 0.4 requirement [3]. A defined MEI value corresponds to a certain value of pump efficiency in nominal rating. The required efficiency depends on the rated flow Q, specific speed nₑ and design type of a pump. Apart from the mode Q = 100%, H = 100%, the efficiency is also regulated at the rated speed at partial load (Q = 75%) and overload (Q = 110%). To meet the MEI specific value in these modes, the pump efficiency should be at least 94.7 and 98.5% of the rated value, respectively [1].

A reason to normalize the nodes efficiency of a pump unit taken separately is that all these nodes are generally supplied by different manufacturers independently of each other. A manufacturer of pump units selects the components independently and it requires energy indicators for each node.
It is also evident that testing of an entire complex is generally more difficult and expensive than of its separate nodes.

At the same time, the efficiency of a pump unit in real conditions depends not only on the rated efficiency of its nodes. The loading cycle, the efficiency of separate nodes in modes with fractional load, and the applied method for pump control are of significant importance as well. When comparing the efficient energy use of pump units, an approach, in which the values of efficiency nodes only are standardized in nominal rating [2], [3], results in that these factors are not taken into account. Therefore, in estimating the power consumption of a pump unit, it becomes appropriate to use a more flexible criterion.

Previously, the authors presented a methodology for assessing the energy consumption of a pump unit based on the above factors through comparing 37 kW pump units with an induction motor (IM) and a synchronous reluctance motor. The calculation was based on the experimental data available in the literature [15].

This paper compares the efficient energy use of pump units by comparing their energy consumption in a typical operational cycle. For this purpose, the experimental data obtained by the authors on the efficiency of motors and FC in a wide range of modes is used. The cases of using a serially produced IE3 IM and energy-efficient synchronous reluctance motor (SynRM) are observed [13]. The experimental data published by the pump manufacturer [12] and a mathematical model are used for the hydraulic part. As compared to [15], the mathematical model of the hydraulic part was revised for the purpose of a more accurate calculation of the operation modes for the lightly loaded pump unit nodes.

Based on the calculations carried out, it is shown that the use of SynRM for a typical operational cycle of a pump unit can reduce the power consumption by 23.5% as compared to IM.

II. EVALUATION OF THE PUMP UNIT ENERGY CONSUMPTION.

The main technological characteristic, which the pump unit should ensure in most cases, is the flow rate Q [1], [7], [8]. In many cases, the flow rate should significantly change during the process cycle within the range of 25-100% of the rating value Qreq. Meanwhile, all the system components, such as a pump, a FC and a motor, should also work far from rated modes.

The consumed energy of a pump unit E_c depends not only on the efficiency values of pump unit nodes, but also on the pump load profile Q(t), the corresponding required hydraulic head H and the Q control method (via throttling or motor speed adjustment) [1]:

$$E_c = \sum_{i=1}^{N} \left[ \Delta t_i \cdot \frac{\Delta H_i}{\eta_{pump} \cdot \eta_{motor} \cdot \eta_{conv}} \cdot \frac{H_{req}}{H_{pump}} \right]$$

where \( \Delta t_i \) is the i-th time interval duration; \( \Delta H_i \) is the i-th hydraulic head change; \( \eta_{pump} \) is the pump efficiency; \( \eta_{motor} \) is the motor efficiency; \( \eta_{conv} \) is the frequency convertor efficiency.

A wide variety of possible operation cycles and designs of a pump system makes it difficult to estimate the real power consumption of a pump unit in a particular application in the event, when only the motor and FC efficiency classes are known, along with the MEI for the pump's hydraulic part, which specify only the nominal rating efficiency [1].

At the same time, as it can be seen from (1) and the analysis of typical pump loading cycles (Fig. 1), the efficiency of a pump unit at fractional loads is of no less importance for the assessment of a resultant power consumption than the rated loading efficiency [1].

![Fig. 1. A typical pump load distribution in an operating cycle [1]](image)

It should be noted that when assessing the efficient energy use by calculating the E_c (1) value, as compared to the assessment based on the MEI, IE and IES classes, the following factors should be also taken into account [1]:

- selection of components with the best efficiency, both at full and fractional loading;
- optimization of pump mode at an operating point and of the Q control method;
- optimization of control when several pumps are used in a pump unit.

III. USAGE OF A SYNCHRONOUS RELUCTANCE MOTOR TO REDUCE THE PUMP UNIT POWER CONSUMPTION

The known disadvantages of an induction motor (IM), which is commonly applied for the pump unit drives, are the presence of significant electrical losses (up to 30% of the total amount of losses) in a rotor and the difficulty in optimal magnetic flux control when changing the torque T and the rotational speed n. The above disadvantage lead to the fact that the efficiency of IM as a part of the pump unit is greatly reduced under the drop of a required flow rate and a decline in the motor load [7], [8].
One way to reduce power consumption of a pump unit is to select the motor with higher efficiency, including the cases with low loads. The consumed energy $E_c$ of the entire unit in each of the load modes is inversely proportional to the motor efficiency $\eta_{motor}$. The low value of $\eta_{motor}$ can level the effect of all other measures on the reduction of power consumption. In contrast, selecting a motor with higher efficiency within a wide range of modes can significantly reduce the $E_c$ value.

A significant increase in the pump unit efficiency is achievable through the use of a synchronous reluctance motor (SynRM) instead of IM. The SynRM has no rotor windings and the electrical losses in rotor associated therewith. This greatly reduces the value of total losses in a motor [7], [8], [9]. Currently, the leading European manufacturers offer the SynRM coming with a frequency convertor (FC) for the applications, where the use of a variable frequency drive (VFD) ensures a significant energy-saving effect (for example, for pumps, fans and compressors).

The International ABB Concern ("ASEA Brown Boveri") produces two series of SynRMs for industrial pumps, compressors and fans: the IE4 motors as well as the high output IE3 motors. The energy-efficient IE4 SynRMs are supplied by the German company KSB ("Klein, Schanzlin & Becker") as part of its pump units. The Siemens Company also introduced a range of motors of this type to the market.

A three-phase SynRM drive compares favorably with other energy efficient solutions (permanent-magnet motors) due to a simple design of the electromechanical converter and FC, the absence of permanent magnets in the design that have a high cost and significantly complicate the manufacture, maintenance and repair, as well as the maximum unification of the SynRM manufacturing process as compared to the IM production.

This paper compares the power consumption of a 0.75 kW 3,000 rpm pump unit under application of the IE5 SynRM developed by the authors and the serially produced IE3 IM. The aspects of the development and test results for the 0.75 kW, 3,000 rpm SynRM designed to achieve the IE5 class use are described in [13].

To consider the energy characteristics, the observed motors were tested within a wide range of modes according to IEC 60034-2-3 (Edition 1.0 2013-11, Method 2-3-C: Input-output method). The results cover from 25% to 100% of rated speed and from 15% to 110% of rated torque. The test results of the serially produced IE3 IM and the IE5 SynRM were presented in the form of two-dimensional dependences $\eta_{drive} = f(P_{shaft},n)$ (Fig. 2), where $\eta_{drive} = \eta_{motor} \cdot \eta_{conv}$ is the electric drive efficiency; $P_{shaft}$ is the shaft power transmitted to load by motor, $W$; $n$ is the rotational speed of a motor, rpm.

The motor efficiency at the points, which have no experimental data, was calculated through bilinear interpolation. Fig. 2 shows the experimental dependences of $\eta_{drive} = f(P_{shaft},n)$ for the IM and SynRM drives.

![Fig. 2. The $\eta_{drive} = f(P_{shaft},n)$ dependence for IM (a); the $\eta_{drive} = f(P_{shaft},n)$ dependence for SynRM (b)](image)

Fig. 3 shows a comparison of the efficiency for both motors (IM and SynRM) at working with a quadratic torque on speed dependence.

![Fig. 3. The $\eta_{motor}$ dependence on $P_{shaft}$ at operation on load with a quadratic dependence $T$ on $n$ for both motors (IM and SynRM)](image)
Fig. 4 shows the comparison of the IM and SynRM drives efficiency (motor + FC) for the same case.

IV. CALCULATION OF A PUMP UNIT POWER CONSUMPTION BY USING IM AND SYNRM

This section describes the calculation of a pump unit power consumption by using the efficiency data of the motors considered as well as the nameplate data and the model of the pump's hydraulic part.

A particular industrial pump unit with the "Calpeda NM 32/12DE" 0.75 kW pump is considered. It is assumed that the considered pump is used for pumping the liquid with the density of $\rho = 1,000$ kg/m$^3$. The maximum pump load according to the required flow rate of water is equal to the rated value of 12 m$^3$/h. Fig. 5 shows the H(Q) and $\eta_{\text{pump}}(Q)$ pump characteristics when operating at rated speed (2,900 rpm) reported by the manufacturer [12]. A 0.75 kW, 3,000 rpm motor should be used for the pump drive.

The drive-consumed power is determined according to (1), in assumption of $H_{\text{req}} = H_{\text{pump}}$, because the adjustment of speed and not throttling is used to change the feed. To calculate the pump's power consumption, it is necessary to determine the pump mode in terms of H and Q at given rotational speed n. The point $(H_{\text{req}}, Q_{\text{req}})$ is determined as the intersection point of the pump's H-Q diagram at given speed and the characteristic of hydraulic load (2) (Fig. 6).

The hydraulic head H, which is required by the hydraulic system to ensure a certain flow rate Q value, is calculated according to the following formula:

$$H_{\text{req}} = H_{\text{stat}} + k_{\text{loss}} \cdot Q_{\text{req}}^2,$$

where $H_{\text{stat}}$ is the static head required to maintain the desired level of liquid at $Q_{\text{req}} = 0$; $k_{\text{loss}}$ is the coefficient of losses in a pipeline.

During the calculation, it is possible to approximate the experimental pump's head vs flow curve at a fixed speed with a sufficient accuracy with the following function: $H = a - b \cdot Q^2$ [10], [11], where $a = \text{const}$; $b = \text{const}$. In this case, in the assumption of meeting the affinity law:

$$Q_1 / Q_2 = n_1 / n_2, \quad H_1 / H_2 = (n_1 / n_2)^2,$$

The head vs flow curve is easily converted for a lower rotational speed $n$ [11]:

$$H_{\text{req}} = H_{\text{fict}} \left( \frac{n}{n_{\text{rate}}} \right)^2 - S_{\text{fict}} \cdot Q_{\text{req}}^2,$$

where $H_{\text{fict}}$ is a "fictive pump's head" at $Q = 0$; $S_{\text{fict}}$ is a "fictive pump's hydraulic resistance"; $n_{\text{rate}}$ is a pump's rated speed.

For this case, the dependence of the rotational speed $n$ on the flow Q looks as follows:

$$n_{\text{req}} = n_{\text{rate}} \cdot \sqrt{1 - \frac{H_{\text{stat}}}{H_{\text{fict}}} \left( \frac{Q_{\text{req}}}{Q_{\text{rate}}} \right)^2 + \frac{H_{\text{stat}}}{H_{\text{fict}}}},$$

where $Q_{\text{rate}}$ is the pump's rated flow.
For this calculation, let us assume the value of the static head $H_\text{stat} = 0.32 H_\text{fict}$, which is a typical value in industrial application [11]. The coefficient of losses in a pipeline $k_\text{loss}$ is selected so that the rated value of flow $Q_\text{rate}$ is ensured at a rotational speed of 3,000 rpm.

The efficiency of pump $\eta_\text{pump}$ at the rated mode (at a rated value of flow) is determined using the nameplate characteristics (Fig. 5b). The change of $\eta_\text{pump}$ at a change in the rotational speed $n$ is not considered.

Let us consider an average cycle for the variable speed pumps proposed in [1] (Fig. 1) as the daytime loading cycle under the flow rate $Q(t)$. It is assumed that the unit passes through a full cycle in a non-stop mode for one day.

Table I shows the modes of motor operation corresponding to a certain value of liquid flow within the system $Q$, which are calculated using the above model. Among other things, the calculated IM and SynRM drive efficiency under observed conditions are also indicated.

**TABLE I. MOTOR MODES DURING ONE OPERATING CYCLE (SEE Fig. 1)**

<table>
<thead>
<tr>
<th>Q, %</th>
<th>P2, W</th>
<th>n, rpm</th>
<th>$\eta_\text{drive}$ (IM)</th>
<th>$\eta_\text{drive}$ (SynRM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>719.309</td>
<td>3,000</td>
<td>0.781</td>
<td>0.863</td>
</tr>
<tr>
<td>75</td>
<td>394.846</td>
<td>2,514</td>
<td>0.743</td>
<td>0.837</td>
</tr>
<tr>
<td>50</td>
<td>194.357</td>
<td>2,100</td>
<td>0.646</td>
<td>0.790</td>
</tr>
<tr>
<td>25</td>
<td>76.516</td>
<td>1,806</td>
<td>0.453</td>
<td>0.704</td>
</tr>
</tbody>
</table>

At a year-round operation of a pump unit with an approximately constant daily flow rate timetable, the annual energy consumption can be estimated as follows:

$$E_{\text{c}, \text{year}} = \frac{t_{\text{day}}}{t_{\text{cycle}}} \cdot E_c \cdot 365,$$

The cost of saved energy, in compliance with the current energy cost, is calculated as follows:

$$COST_{\text{energy}} = T_\text{energy} \cdot E_{\text{c}, \text{year}},$$

where $COST_{\text{energy}}$ is the cost of saved energy, euro (€); $T_{\text{energy}}$ is the current energy cost, €/kWh.

$\Delta P_1 = 100 \% \left(1 - \frac{P_{1,\text{SynRM}}}{P_{1,\text{IM}}} \right)$,

where $P_{1,\text{SynRM}}$ is the power consumed by the SynRM drive; $P_{1,\text{IM}}$ is the power consumed by the IM drive.

According to (Fig. 7b), at decreased liquid flow rate $Q$, the savings $\Delta P_1$ in % are significantly increased.

Fig. 7 shows the calculation results for the power $P_1$ consumed by the IM and SynRM drives. Let us determine the power savings expressed in percentage as follows:
TABLE II. THE RESULTS OF CALCULATING THE ECONOMIC EFFECT FROM THE SYNRM DRIVE INSTALLATION

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current energy cost (including VAT and other taxes), ( T_{energy} ) [€/kWh]</td>
<td>0.1974</td>
</tr>
<tr>
<td>Daytime consumption of an IM unit, [kW*h]</td>
<td>7.548</td>
</tr>
<tr>
<td>Daytime consumption of a SynRM unit, [kW*h]</td>
<td>6.113</td>
</tr>
<tr>
<td>Daily energy saving, ( \Delta E_{day} ) [kW*h]</td>
<td>1.435</td>
</tr>
<tr>
<td>Annual energy saving, ( \Delta E_{year} ) [kW*h]</td>
<td>523.636</td>
</tr>
<tr>
<td>Annual energy saving, %</td>
<td>23.5</td>
</tr>
<tr>
<td>Saved energy cost per year, ( COST_{energy} ) [€]</td>
<td>103.37</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The paper shows that the use of SynRM in an industrial pump unit allows reducing the power consumption significantly. According to the calculations carried out, when using the IE5 SynRM [13], power consumption of a pump unit is reduced by 23.5% as compared to the case of using a serially produced IE3 IM in a drive.

Besides, the decrease in SynRM drive efficiency under a reduction in the required flow rate of liquid is significantly slower than in the IM drive efficiency (Fig. 4). This leads to a significant reduction in the power consumption at low flow rates (around 35% at Q = 25%, Fig. 7b).

Thus, considering a specific example for a 750 W pump unit, the paper shows that the SynRM is an effective energy-saving measure for the newly introduced or overhaul-requiring industrial pumping stations.

In further works, it is planned to study the energy saving effect of the SynRM application for the pump units of higher power capacity.

REFERENCES