Abstract—This paper investigates the potential savings using improved motor and power electronic technology and improved motor control, for different heating ventilation and air-conditioning load profiles. Different energy labels (eff1-eff3) and different voltage/frequency (V/Hz) control have been investigated. The general conclusion is that economical savings will be made, both for an Induction Motor (IM) and frequency converter replacement. The analysis also shows that the choice between an eff2 and eff1 IM, for the given load profiles, always generate the highest saving for the eff1 IM. It is also shown that losses introduced by the commonly over dimensioning of the motor can result in increased energy efficiency with appropriate converter control compared with the use of a motor with lower rating, which is opposite to the case with a grid connected IM.

Keywords- Energy savings, HVAC load profiles, Induction motor, Frequency converter

I. INTRODUCTION

The large assortment of different drive systems on today's market results in a difficult task in making the correct decision for a given Heating Ventilation and Air-conditioning (HVAC) application. The differences in potential savings between different concepts have not been established and are far from common knowledge by an installer or consumer.

The induction motor (IM) is the most commonly used motor today and studies have been made on optimal control regarding IM efficiency, [1,2,3]. Focus has been placed on different control methods in order to obtain optimal operation and evaluation of the resulting IM efficiency improvement. Furthermore, different loss models have been proposed, [4,5], in order to include all the loss components in the IM together with an evaluation of its validity.

Another aspect worth to consider is the dimensioning of HVAC systems. An example taken from [6] showed that, approximately 40% savings were possible for a Constant Air Volume (CAV) system delivering 20% higher flow than needed. One of the reasons for this poor efficiency is that IM have a low efficiency at light load. An interesting issue is accordingly if these "over dimensioning losses" can be reduced by using modern converter technology.

Induction motors sold in the EU are classified by an energy label, eff1 eff2 or eff3, where eff1 is the most energy efficient. This classification was introduced 1998 by the EU and CEMEP (the European Committee of Manufacturers of electrical Machines and Power electronics). The motors included in this classification are two and four pole IM in the range 1.1kW-90kW representing 75-80% of the European market in number of units [7]. The goal of CEMEP was to decrease the number of eff3 motor sales by 50% during 1998-2003. CEMEP had 36 members during this period, which together sold 20 million units in Europe. The result was that, the eff2 label took most of the market share (86%, and eff1 8%). This can be explained by the increased cost of an eff1 motor, (20% higher compared to eff2), and that 80-90% is sold to OEM companies (original equipment manufacturer) [7].

But which is the best option from a cost point of view, and what are the energy savings for various motors and inverter control strategies?

The purpose of this paper is to analyze the potential savings using various eff class motors as well as improved power electronic technology and improved control methods for different HVAC load profiles. The focus is placed on a 4kW 4-pole IM. In addition, a purpose is to investigate the influence of over dimensioning when it comes to pump/fan drives with frequency converters.

II. HVAC LOAD PROFILES

This section will describe two basic load profiles obtained from the literature, two fictive profiles and a case study on an HVAC application in an office building. The load demand refers to the demanded flow from a pump or fan. The torque demand can then be calculated using the affinity laws, [8], assuming that the efficiency of the pump and fan is constant. It should be noted that the profiles only show how a certain load can operate and that deviations can, and will, occur from case to case.

A. Load Profiles A-D

Load profile A describes a two level load operating at 100% for two thirds of the time and at 50% for one third of the
time. This profile can be found for Constant Air Volume system (CAV) using part time reduced flow [9]. Load profile B is taken from [10] and refers to a typical load profile for a Variable Air Volume (VAV) system. Two fictive load profiles are also considered in order to illustrate an extremely low and high load distribution respectively. Profile C describes a load with 30% load demand for 80% of the time and 100% for 20% of the time and profile D describes a constant load demand. Fig. 1 shows the annual load demand of the profiles.

**B. Case Study**

Measurements have been carried out on a pump serving a cooling coil in an office building. The pump is a dry rotor pump of variable speed type with an IM, rated at 1.5kW. Fig. 2 shows the input power distribution for the time period of June 2006 to April 2008. It should be noted that the rated value for dry pumps are given for the mechanical output power of the motor. Hence, it can be noted that the motor is over dimensioned by far more than 100% referred to the electrical input power need. Hence, it is of major interest to investigate the consequences of motor dimensioning.

**III. INDUCTION MOTOR MODELING**

A steady-state model of the IM including the core losses and stray losses has been proposed in [4] and the Y-equivalent circuit representation from this article is presented in Fig. 3. The difference compared to the more common representation of the equivalent circuit is the resistance in parallel with the rotor leakage inductance, \( L_{\sigma r} \). This resistance, \( R_{\text{stray}} \), represents the stray losses in the rotor circuit. This results from studies made on the stray losses [5], showing that the stray losses are proportional to the square of the shaft torque. In addition, [5], has further shown that the stray losses are proportional to the operating frequency. Hence, \( R_{\text{stray}} \), can be expressed as

\[
R_{\text{stray}} = R_{\text{stray,50Hz}} \frac{f}{50}
\]

The iron losses are represented by \( R_c \) and are also dependent on the frequency. The value of \( R_c \) as a function of the frequency is calculated from a no load test according to [11]. Fig. 4 shows the calculated iron losses for different frequencies, determined from a series of no load measurement. The remaining components are also determined according to [11].

**IV. INDUCTION MOTOR SETUP**

\[\text{A. Parameter Determination of eff1-eff3 Motors}\]

This section will focus on the difference between the efficiency using IM motors labeled eff1-eff3. Parameter identification according to Section III has been performed on a 4-pole 4kW standard induction motor (eff3).
The parameters are now modified in order to suit an eff1 and eff2 IM. The efficiency at 75% rated output power operating at rated voltage/frequency should increase 2% for an eff2 and 4.1% for an eff1 motor respectively [7], compared to the eff3 IM. It should be noted that the limits states a difference between the eff3 and eff1 of ≥ 4.1%. Here the border value has been used. The following assumptions have been made:

- \( R_c \): For an eff1 IM, the value of \( R_c \) is reduced with 37%. The value for an eff2 IM is unchanged
- \( R_r \): For an eff1 and eff2 IM, more copper is used in the stator winding, resulting in a reduced stator resistance. It is assumed to be 20% and 15% lower for an eff1 and eff2 IM respectively.
- \( R_s \): The rest of the increased efficiency is tuned in by increasing \( R_s \). This can be motivated the assumption of thinner laminations and different core material.
- \( R_{	ext{stray50Hz}} \): The stray losses are still assumed to be 2% of the rated output power. However, the value needs to be modified since the operating condition has changed due to the modified motor parameters
- The inductances are assumed to be unchanged.

The resulting parameters are presented in Table I where parameter identification of a 4kW eff1 IM has been performed for verification of the assumptions. It can be noted that the measured value of \( R_r \) and \( R_c \) results in lower losses while the \( R_s \) is slightly higher.

**TABLE I. MOTOR DATA**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Eff3</th>
<th>Eff2</th>
<th>Eff1</th>
<th>Eff1 meas</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_c )</td>
<td>1.50 Ω</td>
<td>1.28 Ω</td>
<td>1.20 Ω</td>
<td>1.0 Ω</td>
</tr>
<tr>
<td>( R_r )</td>
<td>1.30 Ω</td>
<td>1.30 Ω</td>
<td>0.82 Ω</td>
<td>1.0 Ω</td>
</tr>
<tr>
<td>( R_{	ext{stray50Hz}} )</td>
<td>606 Ω</td>
<td>760 Ω</td>
<td>900 Ω</td>
<td>984 Ω</td>
</tr>
<tr>
<td>( R_{	ext{mesh}} )</td>
<td>9.89 Ω</td>
<td>8.13 Ω</td>
<td>9.50 Ω</td>
<td>-</td>
</tr>
<tr>
<td>( L_{\text{in}} )</td>
<td>8 mH</td>
<td>8 mH</td>
<td>8 mH</td>
<td>7 mH</td>
</tr>
<tr>
<td>( L_{\text{dc}} )</td>
<td>8 mH</td>
<td>8 mH</td>
<td>8 mH</td>
<td>7 mH</td>
</tr>
<tr>
<td>( L_{\text{m}} )</td>
<td>140mH</td>
<td>140mH</td>
<td>140mH</td>
<td>140mH</td>
</tr>
<tr>
<td>( P_{	ext{total}} )</td>
<td>4 kW</td>
<td>4 kW</td>
<td>4 kW</td>
<td>4 kW</td>
</tr>
<tr>
<td>( n_{	ext{m}} )</td>
<td>1435 rpm</td>
<td>1445 rpm</td>
<td>1435 rpm</td>
<td>1455 rpm</td>
</tr>
<tr>
<td>( U )</td>
<td>3x400 V</td>
<td>3x400 V</td>
<td>3x400 V</td>
<td>3x400 V</td>
</tr>
<tr>
<td>( I )</td>
<td>9.1 A</td>
<td>9.0 A</td>
<td>8.9 A</td>
<td>8.9 A</td>
</tr>
</tbody>
</table>

**B. Energy Optimal Control of the Induction Motor**

The most simple control technique of an IM is to use constant V/Hz control, meaning that the ratio of the voltage and frequency is kept constant. As a result, the magnetic flux in the motor is kept constant which makes it possible to load the IM with its rated torque even at low frequencies. However, each operating point can be achieved with an infinite number of V/Hz ratios and this choice will have an influence on the efficiency of the IM. Fig. 5 shows an example of the core losses together with the resistive losses for a constant operating point, \((T,n)=(3.7\text{Nm},800\text{rpm})\), as a function of frequency. The efficiency of the IM is also presented and it can be seen that the maximum efficiency occurs, approximately, when the core and resistive losses intersects. The phase voltage at this operating point has been reduced from 126.5V, operating at constant V/Hz, to 76.4V. Many loads have a lower torque demand at lower speeds, especially pumps and fans. Hence, it is possible to make substantial energy savings by controlling the motor to its optimal V/Hz.

**V. CALCULATION RESULT OF DIFFERENT DESIGN AND CONTROL TECHNIQUES**

The efficiency has been calculated for an eff3 and eff1 IM, controlled with constant V/Hz and the eff1 IM with optimal V/Hz. The motor was loaded with a load torque \( T=b\omega^2 \), where \( b \) is a constant resulting in rated torque at rated speed and \( \omega \) is the speed in rad/s. Fig. 6 shows the efficiency with the quadratic load demand. It should be noted that the voltage is limited to its rated value of 400V. From an energy efficiency point of view it would be favorable to use a higher voltage at high loads. As a result, the optimal V/Hz control has less or no impact at high load due to the voltage limitation.

**VI. POTENTIAL SAVINGS**

The annual energy consumption of a drive system can be calculated as

\[
W = \int_0^{8760} p_o(t) dt
\]

where \( p_o(t) \) is the power demand as a function of time and 8760 is the number of hours during a year. The electric input power to the drive system and the time duration of each load situation will be determined from load profiles A-D. Each profile consists of a different number of constant levels resulting in different power demands. Given each power demand and time distribution, the energy consumption can be calculated as

\[
W = \int_0^{t_1} P_1 \, dt + \int_{t_1}^{t_2} P_2 \, dt + \ldots + \int_{t_n}^{t_{n+1}} P_n \, dt
\]

where \( t_1, t_2, \ldots, t_n \) is the time duration of the electric power input \( P_1, P_2, \ldots, P_n \).

![Figure 5. Core losses and resistive losses in the stator and rotor for a given operating point,(T,n)=(3.7Nm,800rpm), and the resulting efficiency of the IM](image)
The loss model valid for different energy labels, eff1-eff3, using constant and optimal V/Hz control will be used in order to estimate the potential savings for different load profiles. It is assumed that the pump/fan speed is proportional to the flow, according to the affinity laws. This means that it is assumed that the torque demand of the pump/fan is proportional to the square of the flow. Assuming a constant pump/fan efficiency, the torque speed demand of the driving motor can be derived from a given load profile, $Q$.

$$n = n_N \frac{Q}{Q_{\text{max}}} \quad (4)$$

$$T = T_N \frac{Q^2}{Q_{\text{max}}} \quad (5)$$

where $n_N$ and $T_N$ is the rated speed and torque respectively and $Q_{\text{max}}$ is the maximum flow resulting in rated motor operation. In order to investigate the influence of IM dimensioning, the load demand will be decreased, using the same pump/fan speed, meaning that the torque demand of the pump/fan will be decreased. The dimensioning will be referred to as the percentage of the original flow demand, e.g. a dimensioning of 80% corresponds to a decrease of the flow to 80% which means that the torque will decrease to 64% of its original value.

It should also be noted that in order to compare the different types of energy labels, identical operating points needs to be considered. Hence, the input parameters are the speed and torque demand, where the maximum power operating point is set to 1435 rpm and 26.6Nm corresponding to rated operation for the eff3 IM.

### A. Load Profile A

Fig. 7 shows the energy consumption for different IM setups using an eff3 IM with constant V/Hz control as a reference. First the eff3 IM is replaced by an eff1 IM with the same rating resulting in a 4-7% decrease in energy consumption. The next step is to move from 4kW rating to a lower rating when possible. The difference becomes evident when the dimensioning percentage decreases. Finally, both the IM and control of the IM is changed which results in the largest decrease in energy consumption. It should be noted that the consumption of the 4kW eff1 with optimal V/Hz control becomes almost identical to the smaller ratings with optimal control. This is due to the fact that the calculation for the smaller IM ratings is derived from the 4kW IM. Hence, since decreased IM rating in practice results in a decrease in efficiency, over dimensioning actually results in lower energy consumption if the oversized IM is operated at optimal V/Hz.

![Figure 7. Potential energy savings for load profile A.](image)

The largest saving is provided when both the IM and the frequency converter is replaced. However, this also results in the largest investment. The annual saving between the eff3 and eff1 class in kWh can be found in Fig. 8. The difference between an eff1 and eff2 motor is approximately half of the difference between an eff1 and eff3 motor.

![Figure 8. Potential annual savings in kWh for load profile A.](image)

### B. 6.2 Load profile B

Fig. 9 and Fig. 10 show the energy consumption for the different IM setups and the result becomes similar to that of the load profile A.
C. 6.3 Load profile C and D

The same calculations where performed for load profiles C and D. For profile C, only the maximum load demand is decreased when the dimensioning are considered, since the 20% load demand already is extremely low. The result is analyzed in the next section.

6.5 Cost analysis

The largest energy saving is achieved when both the IM and the frequency converter is replaced. However, this also results in the largest investment. Hence, the energy saving potential must be related to the initial cost. It is assumed that a frequency converter and an eff3 IM costs 100 €/kW and an eff2 IM costs 125 €/kW.

In order to include interest rate in the investment, the following expressions can be used in order to calculate the payback time and the total saving,

\[
T_p = \frac{I_e + \sum_{n=1}^{N} (I_e - I_e^*) n}{W_{\text{save}} W_{\text{cost}}} r \frac{100}{100}
\]  

where \(T_p\) is the payback time (years), \(I_e\) is the investment (€), \(r\) is the interest rate (%), \(W_{\text{save}}\) is the annual saving (€), \(W_{\text{cost}}\) price of 1kWh (€) and \(T_{\text{Life}}\) is the life time of the drive system (years).

Table II presents the payback time and the total savings that can be made assuming 20 years of operation, 5% interest rate and the cost 0.1€/kWh. \(D\) and \(C_T\) denote the dimensioning index and the total energy cost of the drive system during its lifetime.

In the case where the eff2 and eff1 IM are considered, only the price difference between the different choices are accounted for, in order to investigate if there is any reason for choosing an eff2 IM instead of an eff1 IM.

It should be noted that with the extreme case of profile C and a 60% dimensioning, savings can be made.

D. Verification using Measured Parameters

In order to verify the estimations, parameter identification where performed on a 1.5 2.2, 3.0 and 4.0kW eff1 induction motor and used instead of the assumed values. Table III shows the difference in early consumption using the estimated consumption with the assumed values as reference. It can be noted that for almost every case, the previously presented values where underestimated which is a natural consequence since the border values were used in section IV. As a result the potential savings presented will be larger.

VII. CONCLUSIONS

Load profiles A-D cover a wide range of different possible load profiles. The largest saving with an IM replacement was found when the load demand is high. This becomes evident for load profile D where the load demand is high during the whole
time interval. As the load demand decreases, the savings of replacing the IM decreases. The opposite is valid for the optimal control of the IM. However, even if the energy savings are large relative to the constant V/Hz control at light load, the energy cost decreases with decreasing load. Hence, the savings does not necessarily increase as the load decreases.

When the system is to be replaced and the choice of IM is eff2 or eff1, the recommendation falls on eff1. Since the price difference between the different labels are fairly low compared to the possible savings, even for the extreme case with load profile C, savings can be made.

The analysis regarding dimensioning of the IM showed that the potential savings decreases when a smaller IM rating is used, provided that the control is optimal.

Finally, the estimations were successfully compared with calculation using measured motor parameters. The result showed that the consumption decreased resulting in potentially larger savings.

REFERENCES


[10] Danfoss “The drive to reduce costs and improve system control”, May 2000