Determining the Efficiency of Induction Machines, Converters and Softstarters

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Electric motors account for approximately 50 % of the overall electricity use in industrialized countries. Although this energy conversion has a high efficiency, a small improvement in efficiency by the choice of more efficient motors can lead to significant energy savings. The efficiency of several induction motors and frequency converters, from 11 to 75 kW, has been determined under various load conditions in the laboratory of the Electrical Engineering department at the KULeuven. It is also investigated whether energy savings are possible by using soft-starters.

1. Introduction

Three phase, low voltage squirrel cage induction motors are the most commonly used electric motors in industry. They can be found from a few hundred watts up to several megawatts. The induction motors are characterised by data provided by the manufacturer as rated speed, power, voltage, current, power factor and efficiency. In the past, the efficiency value was of minor importance. Nowadays, with the growing emphasis on energy conservation the efficiency value has become very important and even dominant for applications in industry. Efficiency data by manufacturers are measured or calculated according to certain standards. The main differences between these standards are discussed in this paper.

Furthermore, various ways to save energy are investigated. Rational use of energy begins with the appropriate motor choice. Overdimensioned motors must be avoided, since this has a bad influence on the efficiency.

2. Efficiency Standards

Worldwide, there exist several standards for testing electric machinery. For induction motors, the three most important ones are IEEE Standard 112 [1], JEC 37 (Japan) and IEC 34-2 [2]. At this instant, a new IEC standard, the IEC 61972, is under development [3]. In most European countries, the standards are harmonised to IEC 34-2.

The efficiency value obtained from the different testing standards can differ by several percent, as will be shown by the measurement results. This seems in contradiction with the theoretically simple definition of the efficiency:

$$\eta = \frac{\text{power out}}{\text{power in}} = 1 - \frac{\text{overall losses}}{\text{power in}} \tag{1}$$

The second form allows the correction to a specified ambient and reference motor temperature, by correcting the individual loss components.

The first four loss components are stator and rotor RI^2 losses (P_{stator} and P_{rotor}) iron losses (P_{Fe}) and friction and windage losses ($P_{fr,w}$).

P_{Fe} and $P_{fr,w}$ are determined by a no-load test, the copper losses are calculated based on stator resistance, slip and input power measurements under load. The values of the copper losses are corrected to the reference motor temperature.

Additional load losses have been the subject of numerous studies. In fact, these are all the losses that are not covered by the above mentioned loss components and therefore, they may be expressed as:

$$P_{addit} = \left(P_{in} - P_{out}\right) - \left(P_{Fe} + P_{stator} + P_{rotor} + P_{fr,w}\right) \tag{2}$$

The main difference between the standards emerges from the way in which the fifth loss component, the additional load losses, is treated.

Since a direct measurement of the additional load losses requires the rotor to be removed, the only correct and practical method is to measure both input and output power, and to calculate the difference between the overall loss and the four known loss components, using (2). This is the method used in IEEE standard 112 - Method B. The calculated values at various load levels are linearised as a function of the torque T_{shaft} squared according to

$$P_{addit} = AT_{shaft}^2 + B \tag{3}$$

and corrected for measurement errors to

$$P_{addit,corr} = AT_{shaft}^2 \tag{4}$$

since at zero load the additional load losses are zero.

Historically the torque measurement required by this method was difficult, and therefore the IEC 34.2 standard assumes a standard value for the additional load losses at rated load of 0.5% of the input power, proportional to the current squared at lower load levels. The new proposed IEC 61972 standard gives two possibilities for the assessment of the additional load losses. The first one is a determination by means of the measured output power, as in the IEEE 112-B , the second one attributes a fixed amount to every machine of the same rated power.

The Japanese JEC standard 37 completely neglects the additional load losses.

3. Measurement set-up

The experimental set-up for testing induction machines up to 100 kW at 1500 rpm is shown in Fig. 1. A DC motor equipped with a four quadrant rectifier feeding the energy back to the supply loads the machine. The test rig is also used to assess the efficiency of speed controlled, inverter supplied induction motors, using two power analysers with specific PWM measurement functions.

The motor under test is first operated at low load in order to loosen the bearings. Then the motor is loaded at rated load until thermal equilibrium is reached. Input and output power are measured at various loads, typically from 125% to 0% of rated load.

The no-load test with uncoupled shaft, performed at different values of the stator voltage, is used to find the value of the iron and the friction/windage losses.

The additional load losses are linearised according to (3) and (4). The value of the offset B is a good indication of the overall measurement error. The average value is 0.02% with a standard deviation of 0.25%.

4. Measurements

18 induction motors of 11, 55 and 75 kW were tested, in a program in collaboration with Laborelec, the Belgian national laboratory for electricity. The motor manufacturers were ABB, ACEC, Brook-Hansen, Leroy-Somer, Samco, Siemens and WEG.

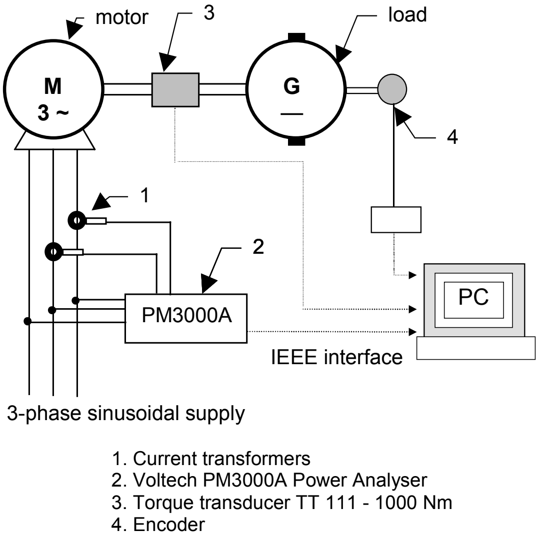


Fig. 1. Measurement set-up

Table 1. Difference in efficiency between measured and catalogue values

	IEEE 112-B	IEC 34.2
11 kW	-2.2 to -4.0%	-0.7 to -2.9%
55 kW	-0.7 to -3.4%	+0.3 to -1.4%
75 kW	-1.2 to -2.9%	-0.7 to -1.5%

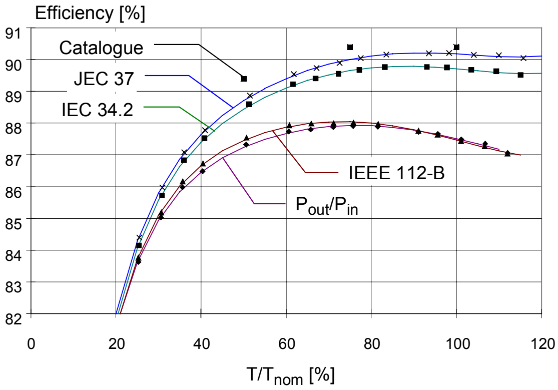


Fig. 2. Catalogue and standard efficiency values

Table 1 shows the difference between the measured efficiency according to IEEE 112-B and IEC 34.2 standards on the one hand, and the catalogue value, normally based on the IEC standard, on the other hand. Although some manufacturers' values are reasonably accurate, most overestimate the efficiency by 3 to 4%.

Fig. 2 shows an extreme example of the difference in efficiency values between the various standards, for a motor with high additional load losses.

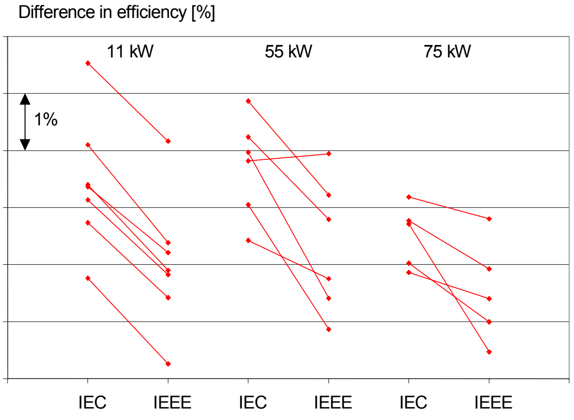
Measured additional load losses vary from 1.5 to 2.3 % of input power for the 11 kW motors tested (7 motors), from 0.4 to 3.0% for the 55 kW motors (6 motors) and from 0.9 to 2.7% for the 75 kW motors (5 motors). Values in the same range were found for some other motors tested in other power ratings. Similar values can be found in [4] and other references.

Fig. 3 shows the result of using a measured value for additional load losses. For the 11 kW (a), 55 kW (b) and 75 kW (c) motors. On the left are the IEC 60034-2 values, on the right the IEEE values for efficiency at full load. The vertical scale is 1% between the marks. The IEC overestimates the efficiency (with one exception), but this is not the most important point. More important is the fact that from one motor to another, the additional load losses differ significantly.

5. Additional load losses in the IEC 60034-2 and the new IEC 61972 standard

Based on the proposed new IEC standard, the additional load losses would be taken as 1.9% of input power for the 55 kW motors. This may be a good average value, but the efficiency of one motor of the tests would be overestimated by 1.1%, whereas the efficiency of another motor would be underestimated by 1.5%, with all possible values in between. Clearly, this method is extremely unfair to the motor manufacturers, and to the customers who want reliable information on motor efficiency.

In the new proposed IEC standard, the additional load losses are preferably determined by means of the measurement of the output power, as in the IEEE method. This is the only relevant method, since additional load losses can differ significantly between motors of the same rating. Table 2 shows the average additional load losses of the tested motors, ranging from 0.4 up to 3%, with an average of 1.7% of input power. The alternative in the new IEC standard – with a fixed allowance – can not be defended. It is not important what average value would be used: it is the difference in additional load loss among motors of the same rating that is relevant.



(a) (b) (c)

Fig.3. Ordering of motors based on IEC and IEEE full load efficiency

Table 2. $P_{\text{additional load}}$ in % of P_{in}

	$P_{\text{additional load}}$
11 kW	1,5 to 2,3%
55 kW	0,4 to 3,0%
75 kW	0,9 to 2,7%

For example: motor A, labelled as a high-efficiency motor, may have a 93% efficiency according to the IEC standard. The real efficiency could be e.g. 91%, because the additional load losses are actually 2.5% for this motor. Motor B of the same power rating may have an IEC efficiency of 92%, and a real efficiency of also 92%, because the additional load losses happen to be 0.5%. The comparison of both motors according to a method using an assumed or average value for the additional load losses is futile. This comparison would indicate motor A to be the "best". In fact, motor B is clearly more efficient.

An argument to use a fixed amount of additional load losses could be that these kind of losses are supposed to decrease during the first six months of operation. This assumption is debatable for several reasons: firstly, these changes are based on manufacturing techniques that were relevant 30 years ago. Nowadays manufacturing tolerances have become smaller.

Secondly, all motor manufacturers use similar designs and materials. For the user it is irrelevant with respect to the 'ab initio' comparison of the motor efficiencies. Therefore, the use of a fixed amount of additional load losses in the proposed new IEC standard is no improvement over the existing IEC standard.

6. Accuracy

In the American Energy Policy Act of 1992, the measurement error is taken into account. A round robin test involving 9 test facilities showed a measurement error of 0.7 to 0.9%. The variation in measured losses frequently exceeded 10% of the overall loss [5].

Motor efficiencies according to the NEMA nameplate labelling standard MG1-12.542 are determined based on the average value of a series of measurements on motors of the same design. Then the closest lower value in a standardised list is taken. This list contains the values 98.0 – 97.8 – 97.6 – 97.4 – 97.1 – 96.8 – 96.5 – 96.2 – 95.8 – 95.4 – 95.0 – 94.5 – 94.1 – 93.6 – 93.0 – 92.4 - …. Associated with this list is a second list of minimal efficiencies at rated load, voltage and frequency. Any motor of the same design must have at least this efficiency. For a 93.6% motor, the minimal efficiency is 92.4%. This constitutes a significant safety margin that may be larger than required. The method prevents users from assuming an undue accuracy in the efficiency determination. We would advise a similar list to be included in the IEC standard.

Measurement errors of 10% of the overall losses are perfectly possible. However, this 10% error for a 93.6% efficient motor, means an uncertainty of only 0.6% on the efficiency value, becoming 93.6 +/- 0.6%.

When comparing two motors, a difference of e.g. 0.2% is not relevant. Such a difference would also not be maintained after selecting a rated efficiency from the list. The difference between motors labelled at 93.6 and 93.0% may not be significant. However, when two motors are labelled as 93.6 and 92.4%, one can assume there is indeed a difference.

Temperature and non-perfect power supplies are important problems with respect to the efficiency and losses during operation. However, they are irrelevant with respect to the accurate assessment of the efficiency for comparison of motors by users. All motors will suffer from these problems in the same way.

7. Efficiency at partial load

Most motors are overdimensioned for safety reasons, and because of the standard power ratings. This means motors are usually used at the range 50–75-100 % of rated power.

It is essential that manufacturers mention the efficiency at 75 and 50% load. The efficiency curves clearly show that the difference in efficiency between the motors varies with the load condition (Fig. 4). This means that a motor with a high rated efficiency does not guarantee a high efficiency at partial load. This is especially the case for motors with relatively high iron losses. The rated efficiency does not give a good picture. The efficiency at partial load should be included in all manufacturers' information.

In the tests performed at the KULeuven, the motors were ordered based on the average weighted efficiency between 25 and 100% load, using the partial load as weighting factor. In this way, the ordering is based on the energy consumption.

A possible "average weighted efficiency" could e.g. be defined as (1 x Eff_{100} + 0.75 x Eff_{75} + 0.5 x Eff_{50})/2.25, or if one wants to stress the efficiency at 75% load, (0.75 x Eff_{100} + 1 x Eff_{75} + 0.5 x Eff_{50})/2.25, or something similar. Perhaps motor efficiency labelling could be done, based on such an "average weighted efficiency", reflecting the energy consumption.

8. Energy savings

Three ways to save energy are treated in this chapter: energy saving by the appropriate motor choice, by a frequency converter or by special softstarters.

Energy savings by appropriate motor choice

The choice of a motor with higher efficiency leads to energy savings. A difference in efficiency of a few percent may lead to significant energy savings, particularly when the relatively small purchase price is compared to the far more significant energy cost.

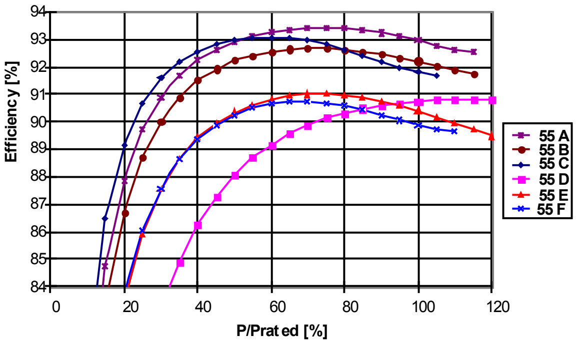


Fig. 4. IEEE 112-B efficiency; 55 kW

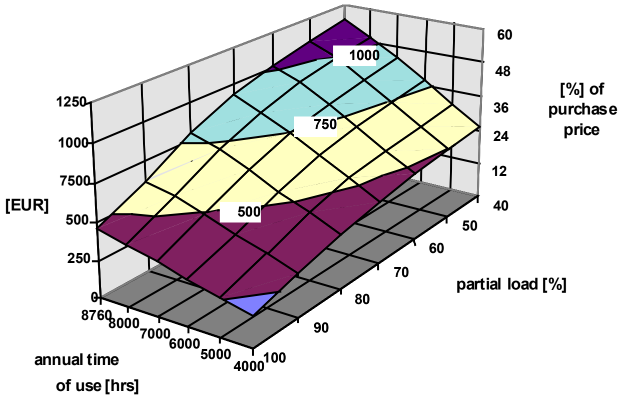


Fig. 5. Cost saving, motor 55 C vs. 55 D

Fig. 5 shows the relative cost saving when using motor 55 C instead of 11 D. The lower energy cost, due to the 2 to 3% higher efficiency, is expressed relative to the typical purchase price of approximately 40 EUR/kW, and this in function of both the average partial load and the annual time of use. The energy cost is taken as 0,075 EUR/kWh.

For continuous use at full load, the annual saving in this example is ± 10% of the purchase cost, but at partial load it can be as high as ± 50%.

So-called high efficiency motors, sold at a price premium of 25 to 40%, can justify this price difference, provided that they have indeed a higher efficiency than standard motors. Unfortunately, this is not always the case, as discussed earlier.

Energy savings with variable speed applications

A variable speed drive, using a standard induction motor and a frequency converter, can lead to annual energy savings of up to 50%, e.g. in pump and ventilator drives, when compared with fixed speed on/off, throttle or bypass systems. At present, no standards are available to determine the efficiency of these drive systems. In this study, the efficiency of a drive is found by dividing the output by the input power.

Most converters have efficiencies of 95 to 98%, even at relatively small loads. The average drive efficiency is 2% lower than the grid connected motor efficiency. However, this is less important than the energy saving potential.

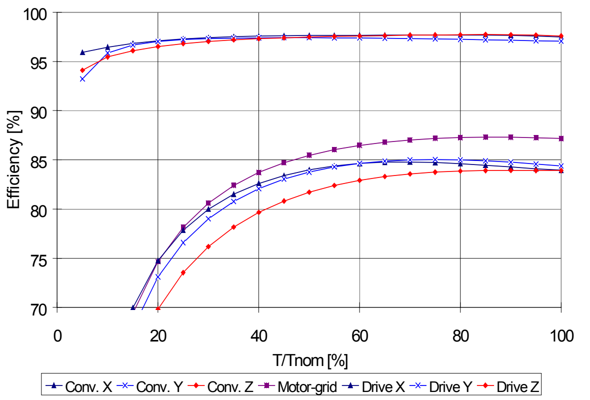


Fig. 6. Converter, grid connected motor and total drive efficiencies

Between the various drive combinations of the same power rating, differences in average efficiency up to 4% are found. However, there is no general rule at hand, as to which converters are best for a particular motor.

One interesting result is shown in Fig. 6. This shows the grid connected motor efficiency of an 11 kW motor, together with the efficiencies of three converters and the overall drive efficiencies of these converters with the same motor. This illustrates the influence of the converter on the efficiency.

The efficiency of the drive at full load is nearly the same for all of the converters. The difference becomes more significant at partial load. Converters that make use of flux optimisation, like converter X, reduce the iron losses in the motor. At small loads, the efficiency of the drive can be equal or even higher than the grid connected motor effiency.

Energy savings with softstarters

The principle used in the soft-starters with an energy saving functions is in fact a simplification of the flux-optimisation used in field oriented control. At low load conditions, the motor current is reactive to build up the magnetic field in the airgap. Iron losses are the main loss component. They are a quadratic function of the flux and the voltage (the function is somewhat less than quadratic for hysteresis losses). In each case, it is evident that lowering the supply voltage decrease the iron losses.

The energy saving function of a soft-starter controls the voltage so that the current needed to provide a certain torque is always minimal. In practice, this is realised by phase-cutting, using two thyristors in anti-parallel. No DC-link is required, resulting in a lower cost in comparison to a frequency converter. A disadvantage of the phase cutting is certainly the harmonic distortion of the current, which can reach 30 %.

The performance is determined by measuring the efficiency (calculated as the division of the output power by the input power) with and without the device. It is essential that the mechanical power is measured because the voltage reduction has an influence on the torque and the output power. In some case studies performed by manufacturers using the energy saving capabilities as a selling argument, this measurement is omitted.

Different soft-starters of various power ratings are tested. As an example, the power savings of an 11 kW motor are treated in this paragraph. The efficiency of the 11kW motor, with and without the soft-starter, is given in Fig. 7. It can be seen that a significant improvement in efficiency is only possible at less than 40 % of rated load. At full load the soft-starter has a negative effect on the efficiency due to the losses in the soft-starter.

The energy saving are given by the difference between the power loss with and without the soft-starter. It is normalised to the rated output power of the 11 kW motor in Fig. 8. As expected, the energy saving is maximum at no-load. The saving is very small. It is smaller than 2 % and decreases at higher load. Due to the internal losses, power consumption increases when the machine is loaded above 50 %.

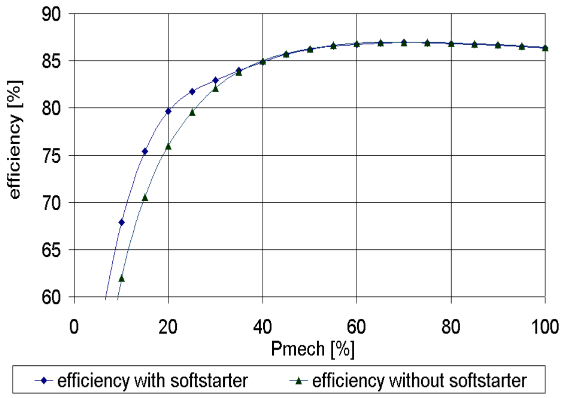


Fig. 7. Efficiency of with and without the 11kW soft-starter

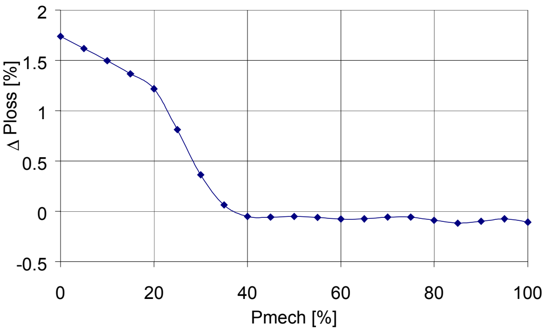


Fig. 8. Difference in loss power with the 11kW soft-starter

Energy saving with phase-cutting has a small positive influence on the power factor at small load conditions. The drawback is the harmonic distortion of the current, which reaches 30 % at no-load. This leads to additional losses in supply transformers and fast ageing of the motor.

Based on the energy savings shown in Fig. 8, the payback time can be calculated. As an example a motor running at 20 % of its rated load is chosen. Obviously, this is a badly chosen motor, but in practice it is not exceptional that motors are overdimensioned.

The energy saving for the 11 kW motor is now 1,25 %. (Fig. 8). The corresponding cost savings turn out to be smaller: 16 % of the purchase price of the soft-starter, with constant operation and an electricity cost of 0.075 EUR/kWh. When the annual time of use is 5000 hrs, an annual cost saving of only 9% of the purchase price is possible, resulting in a pay-back time of more then ten years. When compared to the variable speed drives, these energy savings are extremely small. For partial loads above 40 % no energy savings are possible.

9. Conclusions

The present IEC standard does not provide reliable efficiency values. The additional load losses must be measured, and can in no way be replaced by any kind of fixed allowance, as the differences in additional load losses between motors of the same rating are too significant to be ignored; the difference from one motor to another can exceed 2% of input power, far exceeding the measurement error.

The partial load efficiency is just as important as the full load efficiency with respect to energy consumption. Motors are often overdimensioned. It is demonstrated that a difference in efficiency at partial load can have a large impact on the overall energy consumption. Annual energy savings of 50 % of the purchase cost are possible.

The frequency inverters of the latest generation have typical efficiencies of 95 up to 99 %. For a 50 Hz inverter frequency, the overall drive efficiency is about 2 % smaller, compared to direct supply by the grid. In industrial processes, variable speed drives can reduce the energy by more than 40 %, especially when fans or pumps are used.

The energy savings, realised by soft-starters with an energy saving function is limited; it is smaller than 5 % of the output power. Furthermore, energy savings are only possible if the load is smaller than 50% of the rated value.

Softstarters should not be bought to save energy. It is almost impossible to obtain a reasonable payback time based on the energy savings. Short payback times can only occur if the motor is badly chosen; a smaller motor must then be considered.

The improvement of the power factor with energy saving softstarters is negligible. Moreover this improvement goes together with a strong distortion of the current. The harmonic distortion of the current goes up to 30 % at no-load.

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