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About the Physical Interpretation of the Electric Motors Efficiency

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Abstract: Efficiency of induction motors is very much debated these days. Different standards are used in the world, making actual manufacturer numbers hard to compare. Therefore, many motors of 11, 55 and 75 kW have been tested in the machine laboratory of the Electromechanical Engineering department. Special attention was given to the various standards, mainly IEC 60034-2 and IEEE 112 B. The aim was to compare the various motors and to rank them according to their efficiency. Based on these measurements, it was determined that the present IEC standard is not reliable and does not offer the possibility for consumers to make an instructed choice. The reason for this is that the additional load losses, formerly referred to as stray load losses, are not properly taken into account. Comments on the new proposed IEC 61972 standard are included.

Key words: Efficiency, induction motors, additional losses, interpretation, IEC

INTRODUCTION

In the past, many authors have performed studies to assess the losses in induction motors. The losses are split into a number of loss terms, linked with specific parts of the machine. The efficiency may be defined from these individual loss terms:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{loss}}{P_{in}} = 1 - \frac{P_{loss}}{P_{in}} \qquad (1)$$

Therefore, in principle three types of efficiency measurements may be used:

- Direct measurement of electrical input and mechanical output power.
- Direct measurement of the overall losses and the input power.
- Measurement of the individual loss components and the input power.

The measurement of input power is required in all three methods. Generally, electric power can be measured very accurately, as power meters with accuracy of class 0.2 have been available since the very early stages of alternating current technique. However, the assessment of the mechanical power was more difficult. Nowadays, it is possible to measure torque and speed sufficiently accurate in order to obtain correct efficiency values, as shown further on. The measurement of the overall losses is based on calorimetric techniques. Such measurements are very difficult to perform and the accuracy obtained is comparable to the one found by the direct measurement of the output power. Manufacturers prefer the measurement of the individual loss components, as this method in theory does not require loading the machine, being an obvious advantage. Another advantage that is often stated is the fact that errors in individual loss components do not influence the error on the overall efficiency too much. The main advantage is in fact that a correction for a different ambient temperature is made possible. The individual loss components are the following:

$$P_{loss} = P_{J1} + P_{J2} + P_{mech} + P_{iron} + P_{additional} \qquad (2)$$

- P_{J1}: Stator joule losses, obtained from the measurement of the stator resistance, corrected for temperature.
- P_{J2}: Rotor joule losses, obtained from the slip, again corrected for temperature.
- P_{iron}: Iron losses, mostly situated in the stator iron, obtained from a no-load test.
- P_{mech}: Mechanical friction and windage losses, obtained from the no-load test at different voltages.

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- $P_{additional}$: Additional load losses: i.e. losses not covered by the other loss components, formerly also referred to as stray load losses or supplementary losses.

The first four power loss components are not much debated. The last component, the additional load losses, has been the subject of many scientific papers and parts of many textbooks. The efficiency data provided by manufacturers are measured or calculated according to certain standards. These standards use different ways to incorporate the additional load losses. In the existing IEC (1972) 60034-2 standard a constant percentage of the input power is used, being 0.5% at rated load and proportional to the square of the current. This percentage is independent of the motor ratings or any other motor data (e.g. speed, voltage). The Japanese JEC 37 standard simply neglects this kind of losses. In the IEEE 112-B (1991), the additional losses are assessed by measuring the input and output power; the losses not covered by the 4 other loss terms are supposed to be the additional losses. Efficiency values obtained from different testing standards can differ by several percent. At this instant, a new IEC standard is being worked out. The proposed standard presents two lines of thought regarding the assessment of the additional load losses. The first one is a determination by means of the measured output power, the second one attributes a fixed amount to every motor of the same rated power, the percentage being a function of the motor rating. The main question is whether or not it is worthwhile to change procedures dramatically. The answer to this question can only be found by looking at actual values for the additional load losses. Therefore, a limited overview of literature data is given in the next chapter. In the subsequent chapter a large number of test results will be discussed.

An overview of the literature devoted to the subject of additional losses is a massive task. Therefore, the review given here will be limited to some key books and papers, indicating the fact that the fixed 0.5 % number given in the IEC standard has no scientific basis whatsoever. Even more, it will become clear that the assessment of additional losses using fixed numbers is an impossible task.

Glew (1997) presents in his contribution to the book edited by A. Almeida, P. Bertoldi and W. Leonhard, a qualitative overview of statements on additional losses. The only conclusion that can be drawn from this review is that no realistic values are found from either theoretical studies or specially designed tests aiming at measurements without actually loading the machine.

In different countries, other basic textbooks are used.

Richter (1954) states that in the standards the figure of 0.5 % of the full load input power is found for the additional losses. He immediately adds that different authors have found higher figures in practice, going from 0.8-4.8 % with an average value of 2 %. In the books by Nürnberg (1963, 1987), the figure 0.5 % of the mentioned output power is found. He also indicates, without any further details, that higher values may be found in practice.

Schuisky (1960) presents some detail. He also starts with the figure of 0.5 % of the rated input power, a figure he says, that has been around for 40 years (i.e. from 1920). For squirrel cage induction motors, he assumes 1-2 % to be more realistic, going up to 5 %. He also discusses the relationship between the number of rotor and stator slots and the additional losses.

Kostenko and Pietrovsky (1969) also present the figure of 0.5 % of the input power. They state that "this is an average figure, found experimentally and from which considerable deviations are often observed."

Levi (1984) gives a different approach. He states that 6 % of the losses are additional losses. He also presents difficult empirical formulae to estimate them in the design stage.

Say (1983) does not present any figure at all. He is skeptical to both theoretical and specifically designed experimental approaches.

Alger (1970) gives a review of the test procedures. He states additional loss figures between 0.5-3 % of the full load input power, or higher for poorly designed motors. He also presents analytical formulae.

Engelmann and Middendorf state additional losses typically 1-2 % of the output power, "but values as low as 0.5 % and as high as 4 % are not uncommon."

In (Jimoh *et al*., 1985) a very detailed literature overview is given; 69 references are discussed. The authors come to the conclusion that "the lack of agreement among measurement approaches and between measured and calculated values suggests that there is a need to devise better methods for experimental determination of these losses."

Taegen and Walczak (1987) present a major study of the different influencing parameters (number of stator and rotor slots, slot openings, Y and Δ). Furthermore, a classification of stray losses between no-load and full-load losses is made. For 11 kW motors, the full load additional load losses vary between 166 and 433 W, i.e. 1.5-3.9 % of the output power.

From this overview it becomes clear that the 0.5% figure of the IEC standard is too low and should be regarded as a bottom limit of the additional losses, not as a realistic value. Furthermore, any constant figure is very much debatable.

MATERIALS AND METHODS

Additional load losses: Measured additional load losses vary from 1.5% of input power for the 11 kW motors tested (7 motors), from 0.4-3.0% for the 55 kW motors

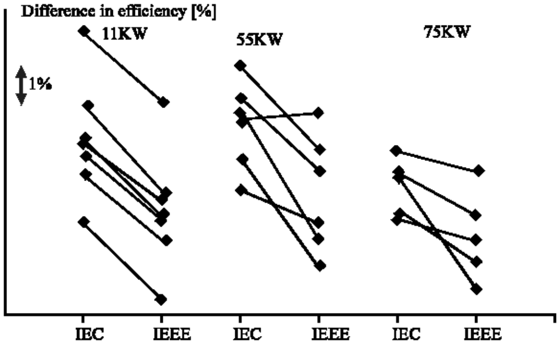

Fig. 1: Ordering of motors based on IEC and IEEE full load efficiency

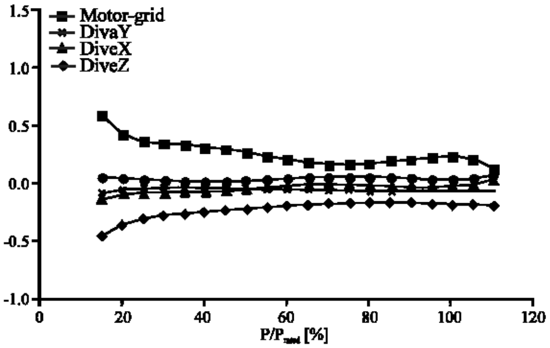

Fig. 2: Deviation from average for 5 measurements on one motor

(6 motors) and from 0.9-2.7% 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 Glew (1997).

Figure 1 shows the result of an efficiency calculation 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 112-B 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.

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 wanting reliable information on motor efficiency.

Table 1: Efficiency at rated load for four motors of the same design

Partial load [%]	Motor A [%]	Motor B [%]	Motor C [%]	Motor D [%]	Average [%]
125	91.95	92.07	91.75	91.77	91.88
100	92.98	92.86	92.53	93.00	92.84
75	93.75	93.39	93.11	93.84	93.53
50	93.88	93.22	93.19	93.62	93.48

Accuracy: The accuracy of the individual efficiency was determined to be +/- 0.8 % as a worst value, based on the accuracy of the measurement devices used.

From one motor manufacturer, four different motors of the same design were tested. The efficiency values are given in Table 1.

The standard deviation between the measurements is 0.24 %, a value that includes the deviation between the motors due to the manufacturing process.

One motor was tested five times, by professional scientific personnel and by groups of students. The difference with the average result is shown in Fig. 2. The standard deviation between the measurements is 0.12%. These results confirm the fact that a higher accuracy than +/ 0.5% is probably not achievable, even with the highest accuracy in measuring devices.

ADDITIONAL LOAD LOSSES IN THE IEC 60034-2 AND THE NEW IEC 61972 STANDARD

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 (IEC, 1998). This is the only relevant method. The alternative-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 to the customer.

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

An argument to use a fixed amount of additional load losses could be that these kinds 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 base comparison of the motor efficiencies.

Therefore, the use of a fixed but rated power dependent amount of additional load losses in the proposed new IEC standard is therefore, no improvement over the existing IEC standard.

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 0.7-0.9%. The variation in measured losses frequently exceeded 10% of the losses (Bonneville Power Administration, 1993).

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. 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%. This also means that a difference of e.g. 0.2% is not relevant when the difference between two 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 must assume there is indeed a difference.

Temperature and non-perfect power supplies are also 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.

EFFICIENCY AT PARTIAL LOAD

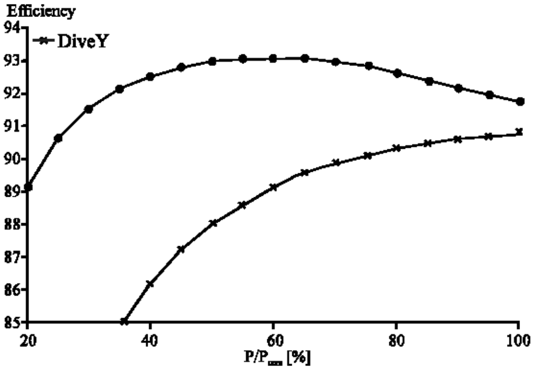

Fig. 3: Efficiency of two motors

Most motors are over dimensioned for safety reasons and because of the standard power ratings. This means motors are usually used in at the range 50-100 % of the rated power. Therefore, it is essential that manufacturers mention the efficiency at 75 and 50% load. Considering the two motors shown in Fig. 3, it is noticed that their rated efficiency differs by 1 %. However, the difference in efficiency at the partial load is more important. In other cases, a motor with a slightly lower rated efficiency has a higher efficiency at partial load. The rated efficiency does not give a good and complete picture of the energy consumption. The efficiency at partial load should be included in all manufacturers' information. In the tests performed, 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 related to 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 labeling could be done, based on such an "average weighted efficiency", reflecting the energy consumption.

PRACTICAL OBSERVATIONS REGARDING THE NEW IEC STANDARD

Load test: In order to measure the stator resistance, the motor has to be shut down. From reading the new IEC standard, it is assumed that the motor is at rated load and then shut down for stator resistance measurement before the highest load point and then loaded at 150, 125, 100, 75, 50 and 25% load. Then the motor is shut down for stator resistance measurement after the lowest load reading. The resistances are assumed to vary according to a straight line between the first and second measurement. However, will the motor temperature not increase slightly when loaded at 150% load? The exact evolution of motor temperature is not straightforward. It depends on shutdown time for resistance measurement, time at 150 and 125% load, size of the motor, thermal time constant of the motor.

Certainly, the aimed at accuracy in terms of temperature seems to be very high. Is a single measurement of rated load temperature not sufficiently accurate. A difference in temperature of 10K leads to a difference in efficiency of only +/- 0.1%. Also, for larger motors, the thermal time constant becomes longer and temperature fluctuations less significant.

No-load test: Allowing the motor to reach a stable temperature at no-load is preferable from the theoretical point of view, assuming that the iron and friction losses are indeed temperature independent. The proposed method will significantly increase the overall time needed for the various measurements. In practice, the no-load test can be performed immediately after the load test. The stator resistance measurement can be performed before and after the no-load test and an average value can be used. This average resistance should be accurate enough, compared to the extra cost of the theoretically more accurate method.

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 calculated by dividing the output by the input power.

Most converters have efficiencies of 95-98%, 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.

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. 4. This shows the grid connected motor efficiency of an 11 kW motor, together with the efficiencies of three converters and the total 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 used. The difference becomes more significant at partial load. Converters that make use of flux optimization, like converter X, diminish 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.

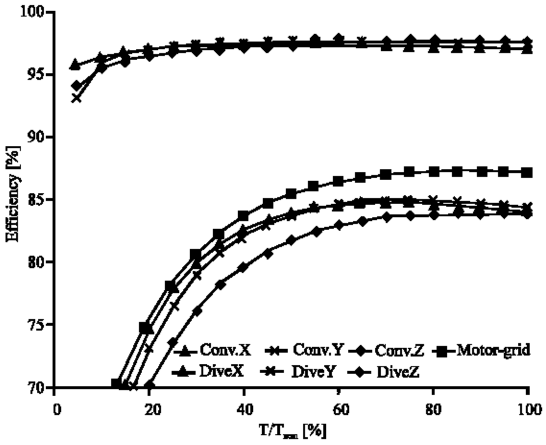

Fig. 4: Converter, grid connected motor and total drive efficiencies

CONCLUSION

The main conclusions from this study are the following:

- The efficiency determination according to the European IEC standard 60034-2 is not reliable.
- The additional load losses must be measured and can in no way be replaced by any kind of fixed allowance, as the difference in additional load losses between motors of the same rating is 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.

REFERENCES

Alger P.L., 1970. Induction machines; their behaviour and uses, (2nd Edn.), Gordon and Breach Science Publishers, New York.

Glew C.N., 1997. Efficiency Measurement testing standards stray losses, the key to efficiency determination. In: Anibal de Almeida: Energy efficiency Improvements in Electric Motors and Drives. Springer, Berlin, pp: 249-265.

IEC Std 34-2, 1972. Rotating electrical Machines-Methods for determining losses and efficiency of rotating electrical machines from tests.

IEC Std 61972:1998: Method for determining losses and efficiency of three-phase, cage induction motors.

IEEE Std 112-1991: IEEE Standard Test Procedure for Poly phase Induction Motors and Generators. IEEE Power Eng. Society, New York.

Jimoh, A.A., R.D. Findlay and M. Poloujadoff, 1985. Stray losses in induction machines; Part II Calculation and reduction, PAS-104, 6: 1506-1512.

Kostenko, M. and L. Piotrovsky, 1969. Electrical Machines, Vol. II: Alternating current machines, MIR Publishers, Moscow.

Levi, E., 1984. Polyphase motors; a direct approach to their design, John Wiley and Sons, New York.

Nürnberg, W. and R. Hanitsch, 1987. Die Prüfung elektrischer Maschinen, 6. Auflage, Springer Verlag, Berlin.

Nürnberg, W., 1963. Die Asynchronmaschine, Springer Verlag, Berlin, 2. Auflage.

Richter, 1954. Elektische Maschinen. Vierter Band: Die Induktionsmachine, Verlag Birkhäuser, Basel/ Stuttgart.

Say, M.G., 1983. Alternating current machines, (5th Edn.), Pitman.

Schuisky W., 1960. Berechnung elektrischer Maschinen, Springer-Verlag, Wien.

Taegen, F. and R. Walczak, 1987. Experimental verification of stray load losses in cage induction motors under no-load, full-load and reverse rotation test conditions, Archiv für Elektrotechnik, pp: 255-263.

The Bonneville Power Administration United States Department of Energy, 1993. Energy-efficient Electric Motor Selection Handbook.