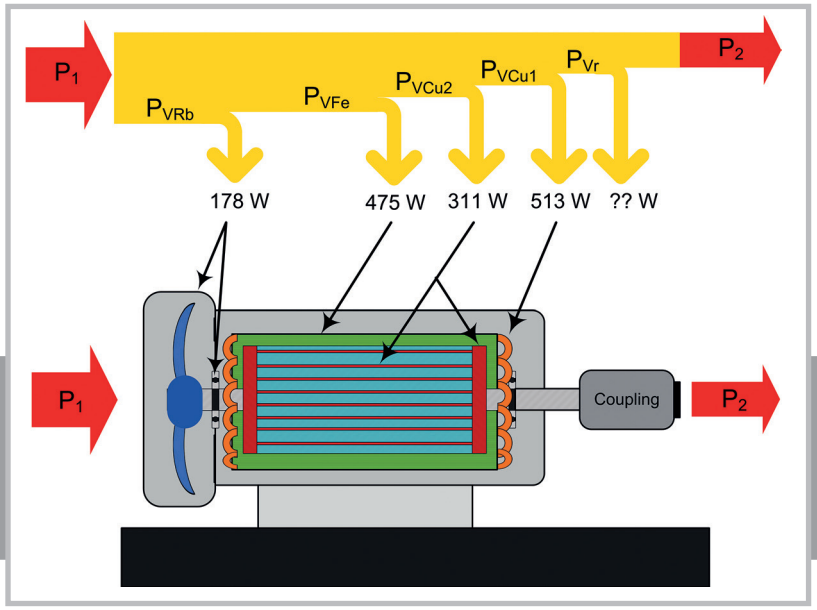
Efficiency determination on (explosion-protected) electric machines – a survey under measurement uncertainty aspects



01 Losses occurring in an induction machine, numerical values as example

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Due to increasing energy prices, increasingly scarce resources and EU requirements for energy-operated products which require for the future power-related minimum efficiencies for induction machines which are marketed within the EU [1], ever increasing importance is attached to the efficiency determination on electric machines. In this article, different procedures for determination of the machine efficiency are compared and their properties are assessed. An important aspect also is the evaluation of the measurement uncertainty of the final result „efficiency" as a function of the procedure used for its determination.

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1 Approaches for the determination of the efficiency of electric machines

The machine efficiency is defined as

$$\eta = \frac{P_2}{P_1} \qquad (1),$$

P_1 relating - in the case of motors - to the consumption of electric power and P_2 being a measure of the mechanical power dissipated via the shaft. Thereby, the power dissipation of the machine is defined as:

$$P_v = P_1 - P_2 \qquad (2)$$

For an assumed efficiency of $\eta = 0.9$ this means that the power loss amounts to only 10 % of the power P_1 and that the power loss as the difference from two values - which are each time larger by approx. one order of magnitude - thus particularly depends on the measurement uncertainties during the electric and mechanical power measurement. This influence increases with increasing rated power of the machine, as the machine efficiencies usually increase with increasing rated power.

1.1 Direct measurement of the efficiency

The possibility of determining the efficiency of electric machines which is probably most plausible and evident at first sight is the direct method of measurement. In this method, the measurands „consumed electric power" and „dissipated mechanical power" are related, and the efficiency is calculated directly. This

procedure is also admissible according to standard EN 60034-2-1 [3]. It is, however, only recommended for machines with a maximum rated power of $P_N \leq 1$ kW. This is due to the relatively large measurement uncertainty of the mechanical power measurement which enters - in the case of the direct measurement - directly into the measurand „efficiency". This has already been explained in detail in [2].

1.2 Indirect measurement of the efficiency

For induction machines in the rated load range of 1 kW < P_N, standard EN 60034-2-1 recommends the indirect method of measurement (single loss procedure). In this procedure, the losses occurring in the individual machine parts are separately determined in accordance with [3] and then subtracted from the measured, consumed electric power to determine the dissipated mechanical power. The losses occurring in the machine and the residual losses P_{LL} searched for are shown **Figure 01**.
Here, the iron losses P_{fe} and the friction losses P_{rb} are calculated via the no load characteristic determined during the execution of the no load test. The electric potential difference, for which the iron losses are calculated, is the reduced electric potential difference U_r, calculated in accordance with [3]. Hereby, the voltage drop via the resistive stator winding resistance, which is also increasing with increasing loading and increasing machine current, is also taken into account.

The machine slip s (this information is needed to calculate the rotor losses [2]) is determined by means of a slip coil, whereupon the periodic time of the rotor magnetic field detected with the slip-frequent is determined.
In the following calculations, the dissipated mechanical power of the machine then corresponds to:

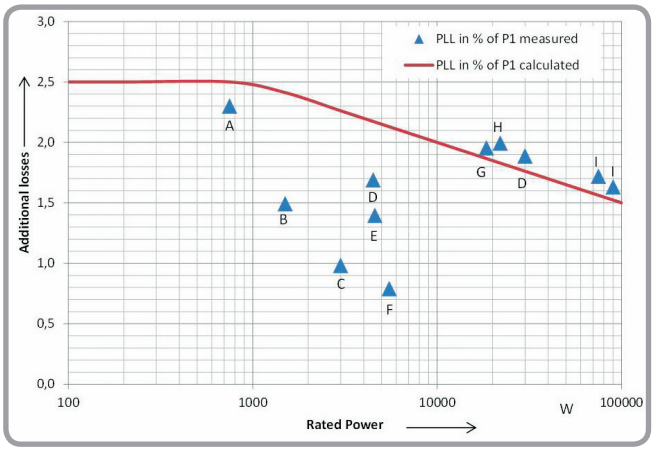
$$P_2 = P_1 - P_{Cu\,1} - P_{Fe} - P_{LL} - P_{Cu\,2} - P_{Rb} \quad (3)$$

This relationship is identical for the two indirect procedures described in the following; the differences are due to the way in which the required load-dependent additional losses P_{LL} are determined.

2 Determination of the load-dependent additional losses

The residual losses can, on the one hand, be estimated computationally via a mathematical function, as described in [3]. The input parameter of this function is the consumed electric power P_1 of the machine. The calculation instruction changes as a function of the rated power P_2 of the electric machine. For the power range $P_2 \leq 1$ kW, a constant fraction of the electric power P_1 is assumed for the additional losses:

$$P_{LL} = P_1 \cdot 0.025 \quad (4)$$



02 Representation of the measured and calculated residual losses for machines of the manufactures A – I related in percent to P_1

In the range 1 kW < P_2 < 10 000 kW, the following is valid:

$$P_{LL} = P_1 \cdot \left[0.025 - 0,005 \log 10 \left(\frac{P_N}{1kW} \right) \right] \quad (5)$$

For the range $P_2 \geq 10\,000$ kW it is assumed that

$$P_{LL} = P_1 \cdot 0.005 \quad (6)$$

The power of all machines observed here lay in the range between 0.75 kW and 30 kW.

The second way of determining the additional losses is based on the determination of the residual losses for different points of the load characteristic in the range from 0.25 times to 1.5 times the rated torque of the machine.
For this procedure, the iron and the friction losses of the machine, the stator winding resistance achieved in operation with rated load in the thermal steady state, and the stator winding resistance after the load characteristic has been determined are required. Another parameter is the coolant temperature during the test.

After operation has been performed with rated load and continuous operation has been reached, the load characteristic is usually recorded for the machine for 6 load points in the range from 1.5 M_N...0.25 M_N. This procedure is described in detail in [2].

3 Comparison of the metrologically and computationally determined additional losses

As the determination of the additional losses via the load characteristic implies an increased effort, the additional losses are - in practical applications - often calculated as described in

Quantity	Value	Standard uncertainty	Degree of freedom	Sensitivity coefficient	Uncertainty contribution	Contribution to the overall uncertainty
M	96.00 Nm	0.409 Nm				
Mm	96.00 Nm	0.289 Nm	Infinite	$9.7 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$	47.5 %
Ma	0.0 Nm	0.0289 Nm	Infinite	$9.7 \cdot 10^{-3}$	$280 \cdot 10^{-6}$	0.5 %
Mk	0.0 Nm	0.289 Nm	Infinite	$9.7 \cdot 10^{-3}$	$2.8 \cdot 10^{-3}$	47.5 %
n	2965.4 min^{-1}	1.15 min^{-1}				
nm	2965.4 min^{-1}	1.14 min^{-1}	Infinite	$310 \cdot 10^{-6}$	$360 \cdot 10^{-6}$	0.8 %
na	0.0 min^{-1}	0.0289 min^{-1}	Infinite	$310 \cdot 10^{-6}$	$9.1 \cdot 10^{-6}$	0.0 %
P_1	32048.0 W	27.0 W				
Pm	32048.0 W	27.0 W	Infinite	$- 29 \cdot 10^{-6}$	$-780 \cdot 10^{-6}$	3.7 %
Pa	0.0 W	0.289 W	Infinite	$- 29 \cdot 10^{-6}$	$- 8.4 \cdot 10^{-6}$	0.0 %
P_2	29811 W	128 W				
π	3.14159265					
eta_{dir}	0.9302	$4.06 \cdot 10^{-3}$	Infinite			

Explanation of the quantities used

M	Torque	P_1	**Electric Power**
Mm	Measurement value of the torque	Pm	Measurement value of the el. power
Ma	Resolution error of the torque	Pa	Resolution error of the electric power
Mk	Constant error of the torque measurement	P_2	Dissipated mechanical power
n	Speed	eta_{dir}	Motor efficiency
nm	Measurement value of the speed	na	Resolution error of the speed

Result		
	Measurand	eta_{dir}
	Value	0.9302
	Expanded measurement uncertainty	$\pm 8.1 \cdot 10^{-3}$
	Coverage factor	2.0
	Coverage	t-Tabelle 95 %

Table 1: Measurement uncertainty budget for the efficiency in the case of direct measurements

equations **(4)** to **(6)**, in particular if the efficiency achieved complies with the desired IE classification. The resulting question now is to what extent the calculated additional losses agree with those which have been determined metologically via the load characteristic. For the machines observed here, these relationships have been metrologically investigated by applying both procedures to the machines available at PTB (years of construction: 2006 – 2010) and comparing the results of the efficiency determinations.

These investigations have not yet been completed. Therefore, the result shown in the following can reflect only an intermediate state which is not yet representative.

Procedure	Direct n measured	Direct s measured	Indirect n measured	Indirect s measured
P_1	32048 W	32048 W	32048 W	32048 W
P_2	29811 W	29853 W	29909 W	29951 W
P_{Vtotal}	2237 W	2195 W	2139 W	2097 W
η	0.93	0.932	0.933	0.935
Expanded measurement uncertainty (k=2), from GUM	$8.1 \cdot 10^{-3}$	$8.1 \cdot 10^{-3}$	$3.3 \cdot 10^{-3}$	$3.3 \cdot 10^{-3}$
IE class	IE2	IE2	IE3	IE3

Table 2: Comparison of different procedures for efficiency determination, example for the machine with a rated power of 30 kW

Up to now, only machines in the rated power range from 0.75 kW to 30 kW have been investigated. The machines of the rated powers 3 kW (C) and 30 kW (D) were equipped with copper die cast rotors. **Figure 02** shows the results obtained so far for the determination of the additional losses P_{LL} related in percent to the consumed electric power P_1 at rated operation:

Due to the small number of electric machines which have been investigated so far with respect to the additional losses, a statistic evaluation and the safe detection of relations for the design of the machines has not been possible. Two facts have, however, already become apparent:

- Between the numerical values which have been calculated and metrologically determined for the additional losses, partly large deviations occur (here up to a factor of 2.7), but with $\eta = 0.904$ to $\eta = 0.893$, the impact on the efficiency is also small in this case.
- The larger differences detected so far have a negative impact on the efficiency determined, in the positive direction, only a maximum deviation of the efficiency determined of $\eta = 0.880$ to $\eta = 0.882$ has been determined - this can be regarded as negligible.

Figure 03 shows the impacts on the machine efficiencies detected for the calculated and the measured residual losses.

Due to the fact that the additional losses represent only a relatively small share in the total machine losses, the impact on the measurement result „efficiency“ is - with a maximum deviation of 1.49 % related to the efficiency determination with the residual losses determined metrologically - to be referred to as small; it may, however, be decisive for the IE classification of the machine.

Hereby, it must also be taken into account that the efficiency of the machine is - like all other measurands - afflicted with measurement uncertainties which even superimpose with the results of Figure 03. For the machine with a rated power of 30 kW, the measurement uncertainties were analyzed in detail in [2]. Here, the results of the analyses according to GUM [4], [6] are summarized again.

4 Consideration of the measurement uncertainty

The approach described here covers the measurement uncertainties of the electric voltage measurement, of the current measurement, of the determination of the power factor, of the torque determination and of the speed measurement. The measurement uncertainties for the current, for the electric potential difference and for the power factor can be summarized in one indication of the measurement uncertainty for the power measurement. For the direct efficiency determination in accordance with **Table 1**, an evaluation of the measurement with the aid of GUM showed the following result:

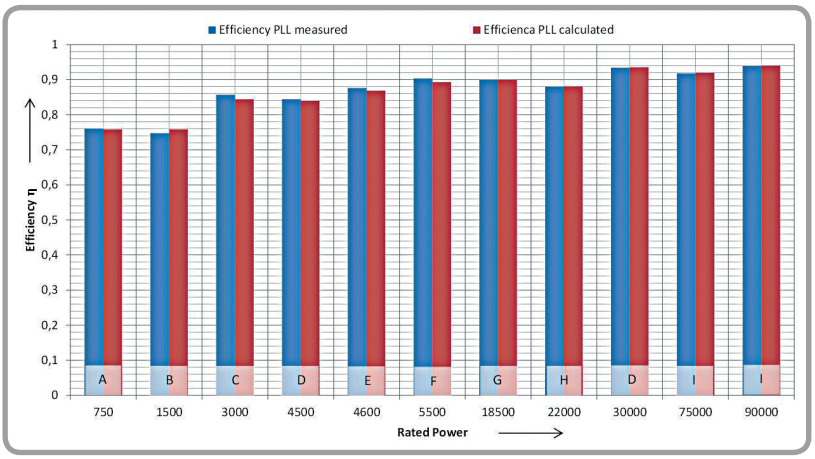
Here it turned out very clearly that the torque measurement (with 95 %) makes - by far - the largest uncertainty contribution to the overall measurement uncertainty.

If the residual loss procedure acc. to [2] is, however, applied to determine the efficiency, an efficiency of $\eta = 93.5$ % is obtained for a consumed power of $P_1 = 32\,048$ W and a dissipated power of:

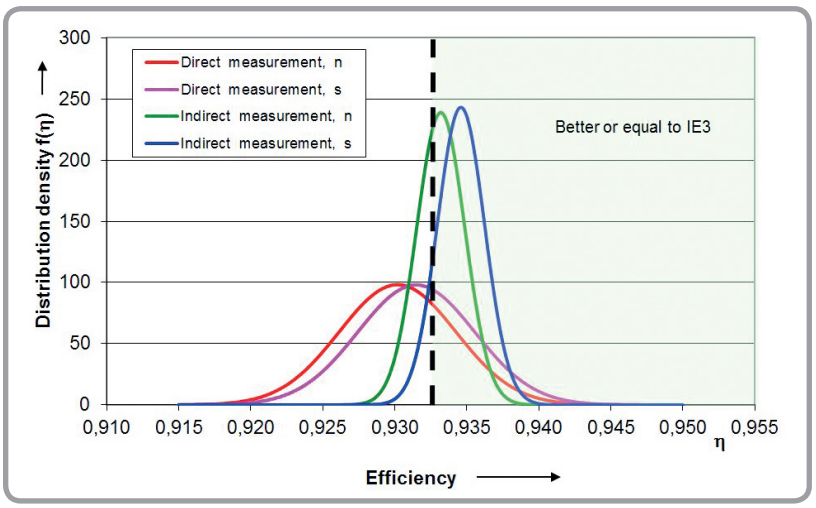
$$P_2 = P_1 - P_{Fe} - P_{Cu\,1} - P_{Rb} - P_{Cu2} - P_{LL} = 29951.5\ \text{W} \qquad (7)$$

This corresponds to classification IE3 [1].

An analysis of the measurement uncertainty showed that - averaged over all load points - the contribution of the torque measurement amounts to only 14.9 %. **Table 2** compares the efficiencies determined with the measurement procedures „direct measurement M and n“, „direct measurement M and s“, „indirect measurement M and n“ as well as „indirect measurement M and s“ as examples for the machine with a rated power of 30 kW. The designations „direct measurement M and s“ and „indirect measurement M and s“ mean that - instead of the torque measurement by means of a speed transmitter - this value has been calculated via the machine slip „s“ and the line frequency in accordance with [5]. The machine slip was measured by means of a slip coil. The time which passes during 10 pe-



03 **Comparison of the efficiencies determined for the test machines of manufactures A – D (additional losses, calculated and metrologically determined)**



04 **Representation of the result of efficiency determinations in the form of the distribution density function**

riods of the electric potential difference induced in the slip coil is determined manually with the aid of a stop watch.

Here it is striking that the differences between the speed measurement „speed transmitter“ and „calculation of the machine slip via the slip coil“ are, in the result of the evaluation - i.e. in the measurement uncertainty - only very small. In this case, the influence of the speed measuring method can, therefore, be regarded as very small.

The situation is, however, basically different when the methods „direct efficiency determination from consumed and dissipated power“ and „determination via the residual loss procedure“ are compared. Here, significant differences in the indicated measurement uncertainty are obtained according to Table 2. In this example, the different efficiencies η determined as a function of the procedure, also lead to the serious consequence that - when the efficiency is determined in accordance with the direct method - the machine could be assigned only to efficiency class IE2 and would - in accordance with EU Ordinance 640/2009 - no longer be admitted for direct mains operation after 1 January 2015.

When the residual loss procedure is applied, the machine reaches, however, energy efficiency class IE3.

The cause for the deviation of the expanded measurement uncertainty represented in Table 2 can be found in the measurement uncertainties of the torque measurement, whose influence on the final result is clearly smaller when the residual loss method is applied for efficiency determination instead of the direct method.

Here, it should, however, be pointed out that in this observation, the measurement uncertainty which results due to the fact that the determination of the slip by means of a slip coil and the measurement of the electric quantities for this measurement point can - due to the principle - not be carried out at exactly the same time, has not been taken into account.

5 Classification of the machine efficiencies calculated with respect to the measurement uncertainties in the IE classification

For a graphic evaluation of the results of the assessments performed here for the machine with a rated power of 30 kW, **Figure 04** shows the distribution density functions of the measurement results. The distribution density function is characterized by the

expected value μ – here the respective measurement value for the efficiency – and the standard deviation σ which corresponds to the standard measurement deviation determined by means of GUM. The section between the two turning points of each function corresponds to twice the standard deviation $\mu \pm \sigma$ (confidence interval 68 %). As an additional condition, the area must be identical in the case of distribution density functions. An increasing standard uncertainty of measurement is indicated by a broadening of the curve shapes with a simultaneous decrease in the curve maximum. For the distribution density function of the efficiency according to Figure 04, the following can be written:

$$f(\eta) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(\eta-\mu)^2}{2 \cdot \sigma^2}} \qquad (8)$$

All efficiencies on the right-hand side of the broken line comply with efficiency classification IE3 or better.

When the measurement value is observed without the associated measurement uncertainty, it turns out that only the measurement procedures investigated here, which are based on the indirect determination of the residual losses, furnish a result for the efficiency which meets the requirements of efficiency classification IE3. For the procedures „direct measurement, n“ and „direct measurement, s“ only efficiency classification IE2 is obtained as the result.

If the measurement uncertainties resulting for the efficiency are now included in the analysis, it can be seen (Figure 04) that when the measurement is repeated on one and the same machine (e. g. in accordance with the procedure „direct measurement, n“) results will be obtained which - with a certain probability - meet the requirements of classification IE3. When the efficiency is, on the other hand, repeatedly determined with the „indirect measurement n“ procedure, results will also be obtained in the case of which the machine only complies with efficiency classification IE2.

For a better illustration of the result of these investigations, **Figure 05** shows the interval ranges of the 95 % confidence level of the efficiency, determined with the aid of the procedures described here [6]. This indication means that – for an assumed infinite number of measurements, 95 % of the measurement values determined lie within this interval.

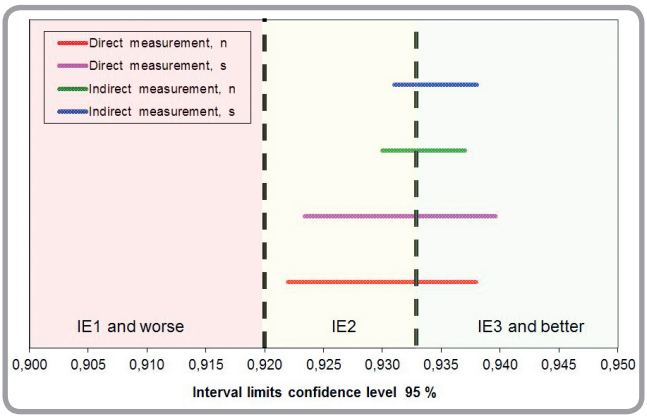
This result shows very clearly the influence of the total measurement uncertainty of the procedure applied on the final result of the observation – i. e. the machine efficiency – and thus also on the IE-classification of the motor investigated. Here, the same machine and the same test are concerned, only different measurands have been evaluated with different procedures.

6 Summary

For the investigated machines of different sizes, Figure 02 shows that partly clear deviations – which also affect the calculated machine efficiency – occur between the additional losses determined by calculation and the additional losses which have been determined metrologically. In almost all cases, this led to an impairment of the machine efficiency compared to the metrological determination of the residual losses; the „improvement“ of the efficiency observed in the case of some machines is very small and lies in the range of the occurring measurement uncertainties. It can, however, be definitely decisive for the IE classification of the motor. This point will also be the subject of further scientific investigations.

As far as the efficiency determination is concerned, it is, therefore, absolutely profitable for the motor manufacturer to make the additional efforts required for the metrological determination of the additional losses.

The assessment of the results with regard to the material of the rotor cage did not, so far, show any clear influence when the rotor cage was designed in copper die cast instead of aluminum die cast.



05 **Representation of the interval limits of the 95 % confidence level**

Literature

[1] Ordinance (EC) No. 640/2009 of the Commission of 22 July 2009 for Implementation of Directive 2005/32/EC of the European Parliament and of the Council in view of the determination of requirements for the environmentally sound design of electric motors [2]Lehrmann, C., Dreger, U., Lienesch, F.; Wirkungsgradbestimmung an elektrischen Maschinen: Gegenüberstellung und Optimierung verschiedener Verfahren (Efficiency determination on electric machines: comparison and optimization of different procedures); Bulletin SEV volume 101 (2010), issue 11, p. 37 - 43 [3] DIN EN 60034-2-1: 2008; Drehende elektrische Maschinen – Teil 2-1: Standardverfahren zur Bestimmung der Verluste und des Wirkungsgrades aus Prüfungen (ausgenommen Maschinen für Schienen und Straßenfahrzeuge) (Rotating electric machines - Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles); Beuth-Verlag, Berlin [4] Pesch, B.; Bestimmung der Messunsicherheit nach GUM (Determination of the Measurement Uncertainty according to GUM; Norderstedt, Books on Demand, 2003 [5] Eckhardt, H.; Grundzüge der elektrischen Maschinen (Basic Features of the electric machines); Teubner-Verlag Stuttgart, 1982 [6] Sommer, K.-D., Siebert, B.R.L.; Praxisgerechte Bestimmung der Messunsicherheit nach GUM; Technisches Messen (Practice-oriented determination of the measurement uncertainty acc. to GUM; Technical Measurements); volume 71(2004), issue 2, p. 52-66