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

Christian Lehrmann, Uwe Dreger, Dr.-Ing. Frank Lienesch
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.

1 Approaches for the determination of the efficiency of electric machines

The machine efficiency is defined as
\[ \eta = \frac{P_1}{P_2} \] (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:
\[ P_2 = P_1 - P_3 \] (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...
In the range 1 kW < $P_2$ < 10 000 kW, the following is valid:

For the range $P_2$ ≥ 10 000 kW it is assumed that

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

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].

### 1.2 Indirect measurement of the efficiency

For induction machines in the rated load range of 1 kW < $P_1^N$, 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:

$$P_2 = P_1 - P_{Cu1} - P_{Fe} - P_{Cu2} - P_{Ro} \quad (3)$$

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 $P_2$ ≤ 1 kW, a constant fraction of the electric power $P_1$ is assumed for the additional losses:

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

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

$$P_{LL} = P_1 \left[ 0.025 - 0.005 \log \left( \frac{P_2}{1kW} \right) \right] \quad (5)$$

For the range $P_2$ ≥ 10 000 kW it is assumed that

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

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### 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
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 metrologically 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.

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

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Standard uncertainty</th>
<th>Degree of freedom</th>
<th>Sensitivity coefficient</th>
<th>Uncertainty contribution</th>
<th>Contribution to the overall uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>96.00 Nm</td>
<td>0.409 Nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mm</td>
<td>96.00 Nm</td>
<td>0.289 Nm</td>
<td>Infinite</td>
<td>9.7 · 10⁻³</td>
<td>2.8 · 10⁻³</td>
<td>47.5 %</td>
</tr>
<tr>
<td>Ma</td>
<td>0.0 Nm</td>
<td>0.0289 Nm</td>
<td>Infinite</td>
<td>9.7 · 10⁻³</td>
<td>280 · 10⁻⁴</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Mk</td>
<td>0.0 Nm</td>
<td>0.289 Nm</td>
<td>Infinite</td>
<td>9.7 · 10⁻³</td>
<td>2.8 · 10⁻³</td>
<td>47.5 %</td>
</tr>
<tr>
<td>n</td>
<td>2965.4 min⁻¹</td>
<td>1.15 min⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>nm</td>
<td>2965.4 min⁻¹</td>
<td>1.14 min⁻¹</td>
<td>Infinite</td>
<td>310 · 10⁻⁶</td>
<td>360 · 10⁻⁶</td>
<td>0.8 %</td>
</tr>
<tr>
<td>na</td>
<td>0.0 min⁻¹</td>
<td>0.0289 min⁻¹</td>
<td>Infinite</td>
<td>310 · 10⁻⁶</td>
<td>9.1 · 10⁻⁶</td>
<td>0.0 %</td>
</tr>
<tr>
<td>P₁</td>
<td>32048.0 W</td>
<td>27.0 W</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pm</td>
<td>32048.0 W</td>
<td>27.0 W</td>
<td>Infinite</td>
<td>-29 · 10⁻⁶</td>
<td>-780 · 10⁻⁶</td>
<td>3.7 %</td>
</tr>
<tr>
<td>Pa</td>
<td>0.0 W</td>
<td>0.289 W</td>
<td>Infinite</td>
<td>-29 · 10⁻⁶</td>
<td>-8.4 · 10⁻⁶</td>
<td>0.0 %</td>
</tr>
<tr>
<td>P₂</td>
<td>29811 W</td>
<td>128 W</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>π</td>
<td>3.14159265</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ηdir</td>
<td>0.9302</td>
<td>4.06 · 10⁻³</td>
<td>Infinite</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Explanation of the quantities used**

- **M**: Torque
- **Mm**: Measurement value of the torque
- **Ma**: Resolution error of the torque
- **Mk**: Constant error of the torque measurement
- **n**: Speed
- **nm**: Resolution error of the speed
- **P₁**: Electric Power
- **Pm**: Measurement value of the el. power
- **Pa**: Resolution error of the electric power
- **P₂**: Dissipated mechanical power
- **ηdir**: Motor efficiency
- **na**: Resolution error of the speed

### Result

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Value</th>
<th>Expanded measurement uncertainty</th>
<th>Coverage factor</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ηdir</td>
<td>0.9302</td>
<td>± 8.1 · 10⁻³</td>
<td>2.0</td>
<td>t-Tabelle 95 %</td>
</tr>
</tbody>
</table>
The 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 \( P_1 = 32048 \) W and a dissipated power of:

\[
P_2 = P_1 - P_{fe} - P_{cu1} - P_{Rs} - P_{c2} - P_{LL} = 29951.5 \text{ W}
\]

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 (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 \( P_1 = 32048 \) W and a dissipated power of:

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Direct n measured</th>
<th>Direct s measured</th>
<th>Indirect n measured</th>
<th>Indirect s measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_1 )</td>
<td>32048 W</td>
<td>32048 W</td>
<td>32048 W</td>
<td>32048 W</td>
</tr>
<tr>
<td>( P_2 )</td>
<td>29811 W</td>
<td>29853 W</td>
<td>29909 W</td>
<td>29951 W</td>
</tr>
<tr>
<td>( P_{\text{Vital}} )</td>
<td>2237 W</td>
<td>2195 W</td>
<td>2139 W</td>
<td>2097 W</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.93</td>
<td>0.932</td>
<td>0.933</td>
<td>0.935</td>
</tr>
<tr>
<td>Expanded measurement uncertainty (k=2), from GUM</td>
<td>8.1 \cdot 10^{-3}</td>
<td>8.1 \cdot 10^{-3}</td>
<td>3.3 \cdot 10^{-3}</td>
<td>3.3 \cdot 10^{-3}</td>
</tr>
</tbody>
</table>

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

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:

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\[
P_2 = P_1 - P_{fe} - P_{cu1} - P_{Rs} - P_{c2} - P_{LL} = 29951.5 \text{ W}
\]

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-
periods 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 \( \eta \) 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 $\mu$ – here the respective measurement value for the efficiency – and the standard deviation $\sigma$ 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:

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

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.

Literature