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The Instrumentation Influence on the Motor Loss Determination Uncertainty

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***Abstract*—The input-output method is the most frequently used and, in practice, the only viable alternative to determine the losses of all electrical machines regardless of the supply type or motor technology. However, the losses obtained with the input-output method are sensitive to power measurement uncertainties of the input and output powers. The power measurement uncertainty is formed by two parts: type A uncertainty is related to the variations in the measurement data and type B uncertainty is related to measurement instruments. The variations in the data can be controlled using data processing techniques and the type B uncertainty can be controlled using accurate measurement devices and choosing correctly rated measurement instruments for each task. In practice, the range of the instruments is limited and it is not always possible to perfectly match the instruments to the measured values. In here, the effect of the ratings of the instruments on the loss measurement uncertainty when using the input-output method is studied using a set of induction motors with rated powers from 7.5 kW to 355 kW. The specifications of the measurement instruments available at Electric Drives laboratory at LUT-University are used to derive the theoretical loss measurement uncertainty for the motors. The detailed uncertainty analysis includes the electric and mechanical powers, and as a result, loss measurement uncertainty is given. The results can be used to get an overview about the level of the expected measurement uncertainty for motors with different power ratings and its effect on the determination of efficiency.**

Keywords—electric power, efficiency, induction motor, measurement uncertainty, mechanical power

I. INTRODUCTION

A method of determining losses and efficiency based on direct measurements of input electrical power and output mechanical power is widely used. The method is also simple and fast, and in principle, applicable to all motor types regardless of technology. The method, however, is highly sensitive to the accuracies of the electric power and mechanical power measurements – especially when testing modern high-efficiency machines. This is because when efficiency approaches unity, the relative uncertainty of losses approaches infinity [1].

Measurement uncertainty consists of type A uncertainty and type B uncertainty. Type A uncertainty value is based on the standard deviation of the mean of repeated measurement results. Type B uncertainty covers the (in)accuracies of the measurement instruments. Type A and type B uncertainty have been covered in detail in [2], where electric power measurement uncertainty in frequency converter loss determination is studied. The electrical machine loss uncertainty and its determination have been investigated in several previous publications. The uncertainty of the losses determined with the input-output method is analyzed for three different induction motors over a wide operating range in [3]. The uncertainties of input-output methods used in industry for induction motor measurements are assessed in [4]. The uncertainties of the input-output method and the indirect loss segregation method are analyzed with scientific and numerical methods in [5]. In [6], realistic perturbation-based estimation (RPBE) –method is used for analyzing the efficiency measurement uncertainty. The influence of the measurement error on the uncertainty of the indirect loss segregation method is analyzed using Monte Carlo simulations in [7]. In [8], the uncertainties of the input-output and loss segregation methods of the standard IEC 60034-2-1 are analyzed and suggestions for future standards are given. The uncertainties of the input-output and loss segregation methods in permanent magnet synchronous machine measurements are investigated in [9].

According to the results shown in [1], the efficiency of the measured motor (or any other device under test) is one of the two most important factors affecting the uncertainty of the input-output losses. The second one is how well the ratings of the measurement instruments match with the measured values. The latter one is further investigated in this paper. Uncertainty analysis for the theoretical input-output efficiency measurements of twelve induction motors with different power ratings is performed. A set of measurement instruments with rated values in the range suitable for the motors is used in the analysis. The main goal is to clarify the importance of matching the ratings of the instruments with the measured quantities, as it is not always possible to use perfectly matched instruments for every tested motor. Three cases are analyzed: The first analysis includes only the measurement instrument uncertainties (type B uncertainty). The second analysis includes type A uncertainty that is estimated based on previous work. In the third analysis, the number of instruments with different ratings is reduced to simulate a case where no optimally rated instruments are available. The analysis is carried out using the nameplate data of the motors and the accuracy specifications of the measurement instruments. Only the rated operating point is considered here because it is used for energy efficiency classification. For reference, motor loss uncertainty behavior in partial operating points has been analyzed and discussed in [3].

II. UNCERTAINTY ANALYSIS

The purpose of the analysis presented in this paper was to find out the input-output loss measurement uncertainty for the instruments available at Electrical Drives laboratory at LUT-University when measuring direct-on-line (DOL) motors with different power ratings. Several different motors with different ratings have naturally been tested in the laboratory. For this analysis, all common power ratings that are within the normal capability of the laboratory are taken into account. This results in a total number of twelve 4-pole 50 Hz induction motors from 7.5 kW to 355 kW rated power. Instead of actual measurements, the electrical and mechanical data for the motors are based on the nameplate values, Table I. When analyzing type B uncertainty, there is no need for actual measurement data as long as the (approximate) values that would be measured are known: The rated power (mechanical output power), rated current, rated speed, rated power factor, and rated efficiency are directly given as motor nameplate values. The electric input power is calculated from the rated power P_{m} and the rated efficiency η simply as

$$P_{\mathrm{e}} = \frac{P_{\mathrm{m}}}{\eta} \tag{1}$$

The rated torque is calculated from the rated power and the rated speed n

$$T = \frac{60 \cdot P_{\mathrm{m}}}{2\pi n}. \tag{2}$$

The specifications of the measurement instruments available in the laboratory are used to calculate the theoretical loss uncertainty for each of the motors. Yokogawa WT1600 power analyzer has been used in most of the motor measurements at LUT, and it is suitable for all the 12 motors when equipped with appropriate current transducers. All the current transducers currently used in the laboratory are Hitec CURACC -series and torque transducers are HBM T12 -series. In Table II, the measured quantities of the 12 motors are matched with the current and torque transducers that would be used in actual measurements in the laboratory. In addition to the ratings, the rated current and torque values of each motor are compared with the transducer ratings in Table II. The relative values ($\%I_{\mathrm{nom}}$ and $\%T_{\mathrm{nom}}$) illustrate well the need for this analysis: the percentage varies from a very good transducer match in the range of 80% to over 90% in several cases, down to as low as 22% for the current transducers' match with 7.5 kW motor. Overall, the match of the torque transducers with the motor torque values is better compared to the match of the current transducers. This is expected, because the number of available torque transducers with different ratings is five, while the current transducers are with only four different ratings.

TABLE I. RATED VALUES FOR THE MOTORS.

Frame size	Rated power (kW)	Input power* (kW)	Current (A)	Speed (rpm)	Torque* (Nm)	Power factor	Efficiency (%)
132	7.5	8.3	15.7	1462	49.0	0.76	90.4
160	15	16.3	28.5	1477	97.0	0.82	92.1
225	37	39.4	68.9	1482	238	0.83	93.9
280	75	78.9	133	1485	482	0.86	95.0
280	90	94.5	158	1485	579	0.86	95.2
315	110	115	198	1489	705	0.84	95.4
315	132	138	231	1488	847	0.86	95.6
315	160	167	282	1488	1030	0.85	95.8
315	200	208	351	1487	1280	0.86	96.0
355	250	260	435	1491	1600	0.86	96.0
355	315	328	550	1491	2020	0.85	96.0
355	355	370	616	1490	2280	0.86	96.0

Common for all motors: 4 poles, 400 V, 50 Hz, IE3 efficiency class

*Calculated from nameplate values.

TABLE II. THE CURRENT AND TORQUE RATINGS FOR THE MOTORS AND FOR THE BEST MATCHING MEASUREMENT INSTRUMENTS AVAILABLE.

Rated Power (kW)	Rated current (A)	Current transducers* (A)	$\%I_{\mathrm{nom}}$ (%)	Rated torque (Nm)	Torque transducer (Nm)	$\%T_{\mathrm{nom}}$ (%)
7.5	15.7	100	22	49.0	100	49
15	28.5	100	40	97.0	100	97
37	68.9	300	32	238	500	48
75	133	300	63	482	500	96
90	158	300	74	579	1000	58
110	198	300	93	705	1000	71
132	231	600	54	847	1000	85
160	282	600	66	1030	2000	51
200	351	600	83	1280	2000	64
250	435	2000	31	1600	2000	80
315	550	2000	39	2020	5000**	40
355	616	2000	44	2280	5000**	46

*Rated with peak current value.

**Currently not available at LUT's lab.

The power analyzer measurement accuracy is given in percentages of the reading and range values in the specifications. The power analyzer input current range affects the effective current measurement range of the power analyzer (Table III) and the related range error. The output signal of CURACC system is 1 A (peak) when measuring the rated current of the transducer. Therefore, the power analyzer input range selection provides flexibility when the measured currents are far below the transducer rating. The motor rated current to power analyzer current measurement range ratio ($I_{\mathrm{N}} / I_{\mathrm{range}}$) is included in Table III. After the power analyzer input range selection, only 7.5 kW motor has a I_{N} to I_{range} –ratio of less than 50%. A more suitable range for 7.5 kW motor is not available, as the next smaller range would be 200 mA, which would cause $I_{\mathrm{N}} / I_{\mathrm{range}}$ to exceed 100%. Here, in practice, the power analyzer input range match is much more important in the uncertainty point of view than the current transducer match because the current range accuracy of the CURACC system is 25 times as high as the power analyzer current range accuracy (see specifications in Table V).

A. Type A uncertainty

Type A uncertainty arises from the variations in the measured values. Typically, motor measurements are performed taking several readings of the same operating point. The standard deviation of the mean value of these readings is the type

TABLE III. YOKOGAWA WT1600 CURRENT MEASUREMENT RANGE.

Rated Power (kW)	Rated current, I_{N} (A)	WT1600 input range (A)	Measurement range, I_{range} (A)	$I_{\mathrm{N}} / I_{\mathrm{range}}$ (%)
7.5 kW	15.7 A	0.5	35.4	44
15 kW	28.5 A	0.5	35.4	81
37 kW	68.9 A	0.5	106	65
75 kW	133 A	1	212	63
90 kW	158 A	1	212	75
110 kW	198 A	1	212	93
132 kW	231 A	1	424	54
160 kW	282 A	1	424	66
200 kW	351 A	1	424	83
250 kW	435 A	0.5	707	62
315 kW	550 A	0.5	707	78
355 kW	616 A	0.5	707	87

A standard uncertainty. The type A uncertainty analysis is covered in detail in [2].

Here, the type A uncertainty is estimated based on average relative type A uncertainty values from previous measurements, Table IV. In previous measurements, the relative type A uncertainties have been rather consistent regardless of the measured motor. Therefore, we can assume that using similar measurement instruments, the type A uncertainty values are at a similar level as in the previous analyses. In addition, the effect of the type A uncertainty on the overall uncertainty has been very small in LUT measurements. This is mainly because of a high number of recordings (typically 100) taken for each test point, which reduces the type A uncertainty [2], [3]. Hence, using the average values from previous measurements is well sufficient for the purpose of this analysis.

B. *Type B uncertainty*

The type B uncertainty analysis is performed similarly as in [3], where the full analysis procedure is covered thoroughly with example calculations. Type B uncertainty covers the uncertainty contribution of the measurement instruments. The accuracy specifications for the power analyzer and the current and torque transducers are given in Table V. As we are considering DOL measurements in this analysis, only the accuracy specifications for the band around 50 Hz grid-frequency are included for the power analyzer. Typically, the accuracy of the power analyzers is lower when operating at frequencies below or above the optimum range. The accuracy values for the power analyzer and the current transducers are given as percentages of reading and range. The HBM T12 speed sensor has a system accuracy of 150 ppm of the speed, and as the resolution of the speed signal is a rather modest 0.1 rpm, the effect of the resolution is taken into account in the uncertainty analysis.

The torque accuracy specifications, however, are a much more complex case where several different sources of inaccuracy exist. The torque accuracies are given related to either the transducer nominal torque T_{nom}, the torque being measured T_{act} (torque reading), or the torque span in the measurements ΔT. In this case, where each motor is measured at rated load, ΔT is equal to the rated torque value as in standstill before the test, torque value is zero and the maximum measured value is the rated torque value of each motor. The accuracy value of parasitic loads is related to the stresses other than torque that are affecting the transducer in an actual measurement setup. The parasitic loads are compensated in the transducer [10] and they do not therefore directly affect the torque reading. However, the parasitic loads have an effect on the uncertainty of the measurement [10]. The accuracy value of 0.3% corresponds to the maximum limit of total parasitic loads. Here, based on the previous work, the parasitic loads for each transducer are assumed as 25% of the limit in a setup where the transducer rated torque is measured. This value is further scaled down by the motor rated torque to transducer rating –ratio ($\%T_{\mathrm{nom}}$) given in Table II, because in smaller motor setups also the parasitic stresses can be considered to be lower. Therefore, the effect of the parasitic loads on the torque accuracy is assumed here as

$$\text{Parasitic loads accuracy} = 0.3\% \times 25\% \times \%T_{\mathrm{nom}}. \qquad (3)$$

TABLE IV. TYPE A RELATIVE UNCERTAINTY VALUES USED IN THIS ANALYSIS. THE VALUES ARE BASED ON PREVIOUS MEASUREMENTS.

Quantity	Type A relative uncertainty
Electric power	0.035%
Speed	0.009%
Torque	0.031%

TABLE V. ACCURACY SPECIFICATIONS FOR THE MEASUREMENT INSTRUMENTS.

Device / Specification		Accuracy
Yokogawa WT1600		
Power accuracy, 45 Hz ≤ f < 66 Hz		0.15% of reading + 0.05% of range
Power factor influence, 45 Hz ≤ f < 66 Hz		power reading × tan φ × 0.15%
Hitec CURACC		
Current accuracy		0.01% of reading + 0.002% of range
HBM T12 torque accuracy		
Temperature influence on zero value, per 10 degree deviation from 23°C		0.02% T_{nom}*
Temperature influence on span, per 10 degree deviation from 23°C		0.03% T_{act}**
Linearity and hysteresis	0…20% T_{nom}	0.006% T_{nom}
	20…60% T_{nom}	0.013% T_{nom}
	60…100% T_{nom}	0.02% T_{nom}
Repeatability		0.01% ΔT***
Sensitivity tolerance		0.05% T_{act}
Parasitic loads		< 0.3% T_{nom}
HBM T12 speed accuracy		
Measurement system accuracy		0.015% (reading)
Resolution		0.1 rpm

* Transducer nominal torque

** Active torque being measured

*** Difference between the highest and lowest (or negative) torque values being measured in the system

C. *Combined uncertainty, mechanical power uncertainty, and loss uncertainty*

For the final electrical power, mechanical power, and motor loss uncertainty values, the uncertainty sources are combined. As type A and type B uncertainties do not correlate, the combined uncertainty can be calculated as the square root of the sum of squares

$$U = \sqrt{{U_{\mathrm{A}}}^2 + {U_{\mathrm{B}}}^2} \qquad (4)$$

where U_{A} is type A uncertainty and U_{B} is type B uncertainty. To combine the speed and torque uncertainties into mechanical power uncertainty, the method of partial differentials has to be applied. This is presented with example calculations in [3]. The loss uncertainty, in turn is calculated from the input and output power uncertainties as the square root of the sum of squares assuming that the power uncertainties do not correlate:

$$U(P_{\mathrm{l}}) = \sqrt{U(P_{\mathrm{e}})^2 + U(P_{\mathrm{m}})^2} \qquad (5)$$

where $U(P_{\mathrm{e}})$ and $U(P_{\mathrm{m}})$ are the electric power uncertainty and mechanical power uncertainty, respectively.

III. UNCERTAINTY RESULTS

The results are divided into three sections: First, only type B uncertainty is taken into account. Second, type A uncertainty is included and the combined uncertainty results are presented and discussed. Third, the number of the current and torque transducers available is reduced to find the bare minimum amount of transducers with different ratings required to get usable results with the input-output method. All the uncertainty results are presented as expanded uncertainties at coverage factor $k = 2$, which corresponds to 95% level of confidence.

A. *Type B uncertainties of the input and output powers*

The electrical power type B relative expanded uncertainty values at the rated operating points of all 12 motors are shown in Fig. 1 together with motor rated current to current measurement range ratio (I_N / I_{range}). The uncertainty values show a clear inversely proportional dependence of the I_N to I_{range}-ratio, which is expected as the power analyzer range accuracy is higher when the match of the range is better. The uncertainty values – except 7.5 kW motor value – are over a quite narrow range between 0.16% and 0.19%. The uncertainty value of 7.5 kW motor being notably higher at approximately 0.24% shows illustratively how quickly the uncertainty starts to rise when the I_N to I_{range}-ratio falls.

The mechanical power type B relative expanded uncertainty values at the rated operating points of all 12 motors are shown in Fig. 2 together with motor rated torque to transducer nominal torque ratio (T_N / T_{nom}). Inversely proportional dependence of the torque uncertainty from the T_N to T_{nom} –ratio is clear, and the mechanical power uncertainty values vary only on a rather narrow range between 0.105% and 0.125%.

B. *Motor loss type B and combined uncertainty*

When combining the electric power and mechanical power uncertainty values illustrated in Figs. 1 and 2, the motor loss uncertainty can be calculated using (5). First, this is done only for the type B uncertainty values to obtain the motor loss type B uncertainty. Second, the type B uncertainties of electric power, torque, and speed are combined with the type A uncertainty values from the previous work (Table IV) to get the combined uncertainties. The motor loss type B relative uncertainty, the motor loss combined uncertainty, and the motor efficiency are presented in Fig. 3. The difference between the type B uncertainty curve and the combined uncertainty curve shows that the type A uncertainty is practically insignificant here. Fig. 3 shows in a practical manner, how the loss uncertainty rises with the motor efficiency. The loss uncertainty values are in general at a very good level; from a bit below 3% for small motors up to slightly over 5% for motors with higher power ratings. Both the current and torque range mismatches show only as slight variations in the loss uncertainty curves because of a much wider scale of the uncertainty shown in the plot. It is notable, that although the electric power uncertainty was significantly higher with 7.5 kW motor compared to other motors – and also the mechanical power uncertainty was one of the highest with it – the lower motor efficiency mitigates the difference. As a result, 7.5 kW motor loss uncertainty is actually the second lowest of all the 12 motors.

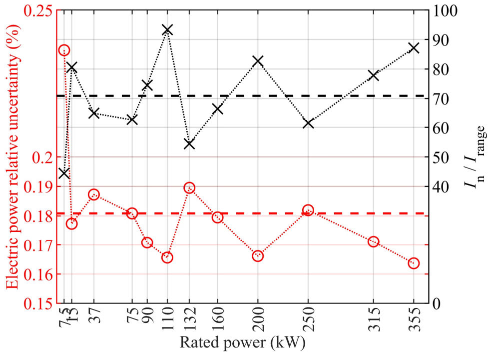

Fig. 1. The electric power type B relative uncertainty for the 12 motors in rated operating points (red), and the motor rated current to current measurement range ratio (black). The 12 motor average values are indicated with dashed lines. The uncertainty values are presented at coverage factor $k = 2$ which corresponds to 95% level of confidence.

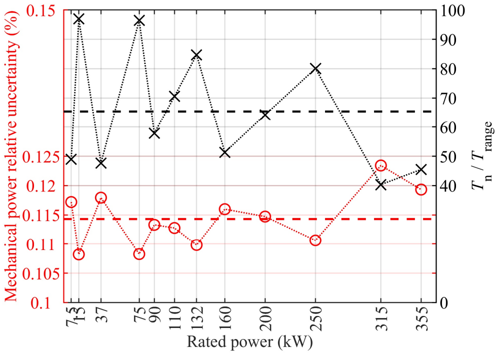

Fig. 2. The mechanical power type B relative uncertainty for the 12 motors in rated operating points (red), and the motor rated torque to the transducer nominal torque ratio (black). The 12 motor average values are indicated with dashed lines. The uncertainty values are presented at coverage factor $k = 2$ which corresponds to 95% level of confidence.

It can be concluded from the results shown in Fig. 3 that even when we have almost perfectly matched high accuracy measurement instruments, the loss measurement uncertainty rises above 5% with the high power ratings. This shows how significant the influence of the efficiency is in the loss measurement uncertainty value. All motors considered here are rated for IE3 efficiency class, which is currently the minimum requirement by EU commission [11]. It should be kept in mind that for motors with higher efficiency classifications type B uncertainty is even higher. Motor efficiencies are continuously rising; IE4 motors are well available and IE5 motors are in the market.

C. *Uncertainty when using a limited number of current and torque transducers*

It is not always possible to acquire the best matching current and torque transducers for the measurements of every motor. Here, the lowest possible number of transducers with different ratings from Hitec CURACC and HBM T12 series were selected in such a way that usable loss and efficiency results could still be achieved. Therefore, the following uncertainty results show a hypothetical situation, where only a single set of 2 kA-rated CURACC transducers, and only two HBM T12 transducers rated for 500 Nm and 5 kNm would be used to measure all 12 motors from 7.5 kW to 355 kW. Table VI shows the transducers used for each motor and the ratios of motor ratings to transducer ratings. The rated current of 7.5 kW motor is only approximately one percent of 2 kA CURACC current rating. The rated torque to transducer nominal torque ratios are down to around 10% in the worst matching cases. For the largest motors, the transducers are naturally the same as before.

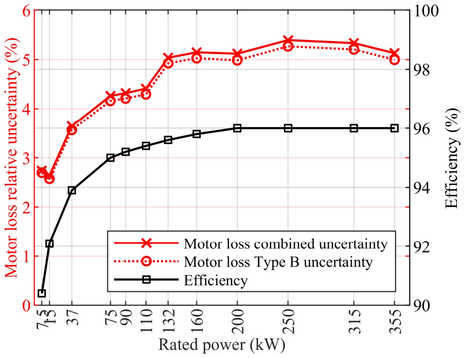

Fig. 3. The motor loss type B relative uncertainty and combined relative uncertainty for the 12 motors in rated operating points (red curves), and the rated efficiencies of the motors (black curve). The uncertainties are presented at coverage factor $k = 2$ which corresponds to 95% level of confidence.

When only a single set of current transducers is used, the power analyzer input range can, however, be adjusted according to the output level of the current transducers when motors with different current ratings are measured, Table VII. This results in very good effective measurement ranges for the WT1600 across all 12 motors.

In Fig. 4, the electric power type B uncertainties when using only 2 kA current sensors are compared with the uncertainty results obtained using all the current transducers with different ratings. According to the comparison, the uncertainty rises notably with some motors, but with two motors the uncertainty is even lower. The lower uncertainties with 75 kW and 132 kW motors are explained by considerably better matching with the power analyzer current ranges, which improves the uncertainty more than using the larger transducer deteriorates the uncertainty. For the three largest motors, the results are naturally equal as the 2 kA transducers are used in both cases.

The mechanical power uncertainties when using only the 500 Nm and 5 kNm transducers are compared with the uncertainty results obtained using all torque transducers with different ratings in Fig. 5. The comparison shows that the torque uncertainty increases more rapidly the further the transducer match is from optimal. Using two transducers for the whole range of motors, the uncertainty rise is limited to approximately twice the uncertainty level compared to when the whole T12-series is utilized (red curve).

TABLE VI. THE RATIOS OF THE MOTOR CURRENT AND TORQUE RATINGS TO THE TRANSDUCER RATINGS WHEN USING ONLY 2 KA CURRENT TRANSDUCER AND TWO TORQUE TRANSDUCERS.

Rated Power (kW)	Rated Current (A)	Current transducers* (A)	$\%I_{\mathrm{nom}}$ (%)	Rated Torque (Nm)	Torque Transducer (Nm)	$\%T_{\mathrm{nom}}$ (%)
7.5	15.7	**2000**	**1**	49.0	**500**	**10**
15	28.5	**2000**	**2**	97.0	**500**	**19**
37	68.9	**2000**	**5**	238	500	48
75	133	**2000**	**9**	482	500	96
90	158	**2000**	**11**	579	**5000**	**12**
110	198	**2000**	**14**	705	**5000**	**14**
132	231	**2000**	**16**	847	**5000**	**17**
160	282	**2000**	**20**	1030	**5000**	**21**
200	351	**2000**	**25**	1280	**5000**	**26**
250	435	2000	31	1600	5000	32
315	550	2000	39	2020	5000	40
355	616	2000	44	2280	5000	46

*Rated with peak current value.

TABLE VII. YOKOGAWA WT1600 CURRENT MEASUREMENT RANGE WHEN USING 2 KA CURRENT TRANSDUCERS WITH ALL MOTORS.

Rated Power (kW)	Rated current, I_N (A)	WT1600 input range (mA)	Measurement range, I_{range} (A)	I_N / I_{range} (%)
7.5	15.7	**20**	28.3	**56**
15	28.5	**50**	70.7	**40**
37	68.9	**100**	141	**49**
75	133	**100**	141	**94**
90	158	**200**	283	**56**
110	198	**200**	283	**70**
132	231	**200**	283	**82**
160	282	**500**	707	**40**
200	351	**500**	707	**50**
250	435	500	707	62
315	550	500	707	78
355	616	500	707	87

The motor loss uncertainties when using only 2 kA current transducers and 500 Nm and 5 kNm torque transducers are compared with the uncertainty results obtained using all torque and current transducers with different ratings in Fig. 6. The comparison shows a surprisingly modest increase in the loss uncertainty, although the uncertainty behavior with motor power rating and efficiency is not as predictable as it was the case in Fig. 3. At the most unfavorable cases, the loss uncertainty is approximately 1/3 to 1/4 higher for the 90 kW and 160 kW motors compared to situation when all the transducers are utilized.

The uncertainty penalty for using fewer transducers is naturally higher with the lower rated motors as the transducers selected are the suitable ones for the higher rated end of the motor scale. The torque uncertainty starts to rise very rapidly when the measured values are below 10% of the transducer rating and for that reason the whole range from 7.5 kW motor to 355 kW motor cannot practically be measured using a single torque transducer. Either 100 Nm or 500 Nm transducer had to be included in addition to the 5 kNm transducer to limit the torque uncertainty with 7.5 kW and 15 kW motors to sensible levels. Selecting the 100 Nm transducer as the second choice for this analysis instead of the 500 Nm transducer would have meant that the 5 kNm transducer would have been used for the 37 kW motor, and its loss uncertainty would have risen to 9%, hence the 500 Nm transducer was a better choice.

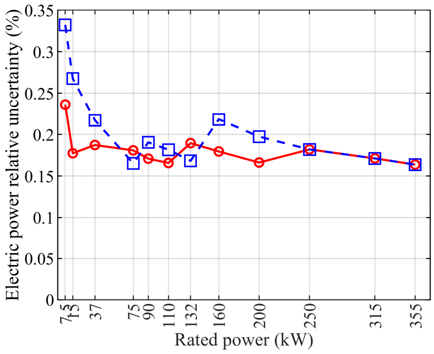

Fig. 4. The electric power type B relative uncertainties for the 12 motors in rated operating points. The red curve with circles shows the original situation, where all current transducers with different ratings are used with matching motors. The blue curve with squares shows the situation, where 2 kA current sensors are used with all motors. The uncertainty values are presented at coverage factor $k = 2$ which corresponds to 95% level of confidence.

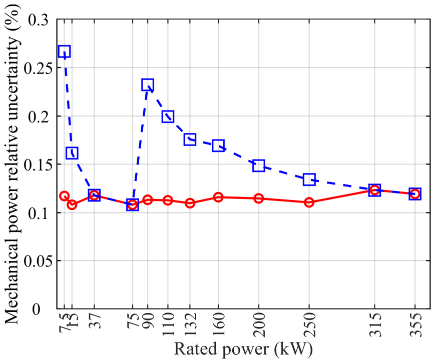

Fig. 5. The mechanical power type B relative uncertainties for the 12 motors in rated operating points. The red curve with circles shows the original situation, where all torque transducers with different ratings are used with matching motors. The blue curve with squares shows the situation, where only the 500 Nm and 5 kNm transducers are used. The uncertainties are presented at coverage factor $k = 2$ which corresponds to 95% level of confidence.

IV. DISCUSSION AND CONCLUSIONS

The proper selection of the measurement instruments has an effect on loss measurement uncertainty. Here, the average total measurement uncertainty of the electrical power was around 0.18% and the average total measurement uncertainty of the mechanical power was around 0.11%. The measurement uncertainty was considered here only at the rated load point and when operating with partial loads, the measurement uncertainty would be increased. However, the measurement uncertainty does not depend linearly from the ratio of the measurement instrument's rating to measured value, since part of the uncertainties are related directly to a measured value rather than to the rated value of an instrument. The selection of the rating of the current measurement device is less important than the torque transducer: there is a wide choice of current ranges available in power analyzers that can be used to match the effective current measurement range to the measured current in order to minimize the measurement uncertainty. In here, it is assumed that data are collected using a digital communication protocol without any voltage and/or frequency conversion. Each A/D conversion or level adjustment will increase the measurement uncertainty. Type A uncertainty is not a problem when enough data samples are used in the analysis and the most dominating factor in the total measurement uncertainty are the instruments and their accuracies. The losses of large induction motors are more demanding to be measured accurately, as they are typically operating with higher efficiency. However, the power factor is increasing as a function of the motor rated power and increased power factor decreases the active power measurement uncertainty (reading value). The power analyzer used here is not a state-of-the-art device but it is equipped with current transducers that are the most accurate ones on the market. With a high-end power analyzer, the total electrical power uncertainty would be much smaller. Based on the analysis here, the input-output method can be used to reliably measure the losses of direct-on-line induction motors if proper instrumentation is used. In practice, only a limited number of instruments are available in laboratories and some mismatch between the measured value and the rated value of the instrument must be accepted. However, if the rated value of the instrument is not far away from the measured value, it should not cause significant problems.

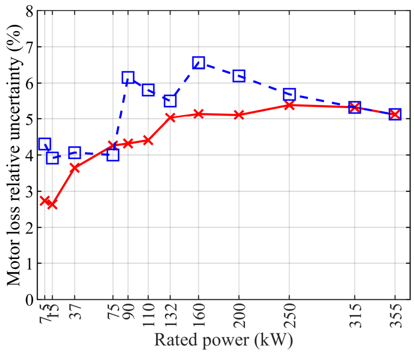

Fig. 6. The motor loss relative combined uncertainties for the 12 motors in rated operating points. The red curve shows the original situation, where all torque and current transducers with different ratings are used with matching motors. The blue curve shows the situation where only the 2 kA current transducers, and 500 Nm and 5 kNm torque transducers are used. The uncertainties are presented at coverage factor $k = 2$ (95% level of confidence).

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