Real time estimation of measurement uncertainty for Power Drive Systems with respect to EN 50598-2

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Abstract

This paper investigates the impact of the measurement uncertainty on efficiency of motors, drives, and power drive systems. According to European standard EN 50598-2, efficiency class definitions of motor and power drive systems should include the uncertainty of measuring instrumentation. This renders the choice of the uncertainty estimation model crucial, in order to guarantee a reliable class declaration. The proposed methodology follows the guidelines presented in EN 50598-2 for input-output technique, and accounts for the contribution of measurement uncertainty related to the accuracy specifications of the instruments and sensors. A LabVIEW based tool for automated sequencing and efficiency measurement is developed. The tool accounts for configuration of instruments, basic control of the drives for testing at different operating conditions, data acquisition, efficiency class declaration and online uncertainty calculation based on the method proposed in this paper. A series of tests are carried out on an actual motor drive system test bench for the experimental validation of the analysis. The tests allowed for precise evaluation of the feasibility of the test procedures described in the standard, especially in the case of motor drive testing. The analysis highlights the necessity of a well-defined uncertainty calculation methodology to ensure a reliable declaration of the efficiency class of the product (PDS) under test.

Keywords: - *EN 50598-2, IEC60034-30-1, IEC60034-30-2, IEC60034-2-1, IEC 60034-2-3, Direct input-output efficiency measurement, uncertainty of efficiency measurement methods*

Introduction

In the field of industrial sustainability, the European Commission (EC) has demanded the implementation of regulations in terms of Eco-design, in order to meet the requirements of the European plan 2020 and create a competitive market with innovative and qualitative products [1]. This process was initiated in 2005 for general "energy-using" appliances [2] and was improved in 2009 with the commission regulation [3] for electric motors. In line with this direction, the commission's actions can be summarized in the production and harmonization of series of standards. IEC Standards 60634-30 and 60034-2-1 are the main references for efficiency class definition and efficiency testing for line-operated AC motors [5], [7], whereas similar standard is now published for measurement of efficiency of for converter-fed AC motors [6]. IEC 60034-2-1 includes reference values for efficiency, requirements on measurements and efficiency class definitions.

Due to technological innovations in motor materials, design methods and better cooling concepts, it is now possible to reach higher efficiency levels, which also demands for definition of higher efficiency classes for motors, but then the gaps between the newly defined efficiency classes becomes narrower. This puts stringent requirements on the accuracy levels of measurement instruments used for classification of motor efficiency levels. The next logical step was to regulate the overall efficiency of motor drive system together rather than individual component level: in this effect European standard series EN 50598 are published now which describe efficiency requirements regarding converters and converter driven products. In this aspect, the information on energy efficiency classes and test methodologies for Complete Drive Modules (CDM) and Power Drive Systems (PDS) is provided in [8. As per definition, a PDS is the combination of a motor and a CDM.

The major change in [8] as compared to previously defined standards is that now the uncertainty of efficiency is specifically required to determine the efficiency class of the PDS. EN 50598-2 describes mathematical models, power loss calculation, test methods, requirements for user's documentation and general guidelines for uncertainty calculation of CDM and PDS [8]. As basis for PDS classification in terms of efficiency, a reference model, named reference power drive system (RPDS), is defined. Beside the RPDS, a PDS includes all the auxiliaries that are necessary for the ordinary operation of the system. Mathematical models allow the evaluation of the efficiency class in cases where actual measurements cannot be carried out and define the so-called reference losses associated to RPDS. The use of reference values and standardized tests allows for an easy comparison between different products and renders the combination of different parts possible, in order to derive the efficiency of the extended product. According to [8], when losses of a PDS are measured at full load test point, the efficiency class is defined by the following ratio:

$$\frac{p_{L,PDS}}{p_{L,RPDS}} = \frac{\frac{P_{L,\mathrm{PDS},meas} + u(P_{L,\mathrm{PDS},meas})}{P_{r,M}}}{p_{L,RPDS}} \tag{1}$$

where $p_{L,PDS}$ indicate the relative power losses of the PDS under test. $P_{L,PDS,meas}$ is the actual power loss, to be associated to the PDS, and $P_{L,\mathrm{PDS},meas}$ is the measured power loss. The quantity $p_{L,RPDS}$, defined as relative power losses of the RPDS, is stated in [1] and it is associated to the apparent rated power of the motor $P_{r,M}$. $u(P_{L,PDS,meas})$ indicates the uncertainty related to measured power losses PDS. This is the main differences between earlier standards and EN50598-2 [8]. Equation (1) shows how the uncertainty is accounted for in the final definition of the efficiency class, and should be clearly defined in order to enable direct comparisons between different product's efficiencies.

This paper analyses the testing procedure and efficiency class definitions including measurement uncertainty as described in EN50598 and shows that the measurement uncertainty evaluation as described in standard results in suboptimal performance. An improved method, which takes into account the state of the art of the uncertainty theory and the actual accuracies of the motor testing instrumentation, is described afterwards and its performance is compared with the earlier described methods. The impact of individual instrument uncertainty on the overall efficient class declaration of the motor drive systems is also analyzed in the end.

Uncertainty estimation background

The main reference for uncertainty calculation is JCGM 100:2008 [9], which presents definitions, basic concepts of statistical distributions and practical examples of measurements. In general, the measured value can be influenced by different parameters. The most influential parameters of a measurement are: errors by operator, measurement inaccuracies caused by instruments (accuracy from the datasheet), wrong settings of instruments, errors in setup configuration, environmental conditions and inaccurate calculations. According to the definitions of [9], these parameters give information on the available knowledge on the possible variability of the measurand, which defines the type B uncertainty.

Following the guidelines of [9], [8] states that the knowledge of all tolerances of the used measurement method is mandatory and the normal distribution function shall be used for the conversion of the accuracy data of the instrumentation and normal distribution function shall be used for the conversion of the accuracy data of the instrumentation. Evaluation of uncertainty at randomly occurring errors requires calculation of standard deviation of the power losses of the CDM or PDS, ΔP_L, defined as:

$$\Delta p_L = \frac{\Delta P_L}{P_L} = \frac{s_y}{y} = \frac{\sqrt{\sum_{i=1}^{n}\left(\frac{\partial \mathrm{y}}{\partial x_i} s_{x_i}\right)^2}}{y} \tag{2}$$

where s_y is the standard deviation associated to a quantity y. In case, y is function of variables x_i , its derivative with respect to x_i , $\frac{\partial \mathrm{y}}{\partial x_i}$ shall be multiplied into the standard deviation s_{x_i} associated to x_i. The main sources of inaccuracy are not specifically defined in the standard, neither are there provided any sample cases of calculation which can be used as guidelines for deriving such procedures by users.

The important influence of uncertainty on efficiency measurements, as utilized in EN50598-2 [8], intensively encouraged the investigation on uncertainties for efficiency evaluation in the last years. Various earlier prior art, such as [10], focuses on the uncertainties for different measurement methods are presented, matching the uncertainty trends indicated EN50598-2 standard, based on Monte-Carlo simulations. The result shows that errors related to the input electrical power and torque measurements are the most critical as they have largest influence of final loss and efficiency variations. Interesting effects of PWM supply are presented in [11], underlining its impact on the efficiency accuracy. However, in the proposed methodology, distribution functions and combined standard uncertainty were not used in [11], and not all the inaccuracy sources were considered. However, the results are useful for a qualitative comparison between line-fed and converter-fed efficiency evaluations.

Proposed method of uncertainty estimation

Uncertainty calculation is subject to the test setup and other factors, so an accurate model is difficult to be defined. A model must take into account all sources that contribute to the final uncertainty value. The impact of some important factors for the uncertainty calculation, pointed out in the prior art, and the extensive theory of [9] can be used as basis to present a step-by-step approach suitable for efficiency and loss uncertainty calculation for PDS testing. According to the datasheets of the instrumentation, the accuracy of the instrument is usually defined as a percentage of measured quantities (ε_{read}), a percentage of ranges (ε_{range}) or constant errors (ε_{cst}). All of these errors should be considered in the calculation of the uncertainty for a certain quantity x_i, as follows:

$$a_{meas.}(x_i) = \varepsilon_{read} * (\mathrm{x}_{i\_rdg}) + \varepsilon_{range} * (\mathrm{x}_{i\_rng}) + \varepsilon_{cst} \tag{3}$$

where x_{i_rdg} is the measured value, as seen on the instrument's display, x_{i_rng} is the range set on the instrument, and $a_{meas.}(x_i)$ is the interval of confidence in which the measurement x_i may occur. Apart from the accuracy which is directly related to the measured quantity, there are errors caused by other influential conditions (i.e. room temperature, parasitic effects), which can alter the accuracy of the measurement. These errors are usually expressed as percentage of the measured quantity, giving a measure of the variation of the basic accuracy when those conditions occur. The combined uncertainty $u_{TOT}(x_i)$ related to the quantity x_i, influenced by other parameters q_i, is defined by:

$$u_{TOT}(x_i) = \sqrt{u(x_i)^2 + \sum_{j=1}^{n} (\frac{\partial x_i}{\partial q_j} u(q_j))^2} \tag{4}$$

All the parameters x_i that contribute in the definition of power losses have to be combined in order to obtain the final loss uncertainty $u_{TOT}(P_l)$ to be included in the corrected losses as follows:

$$u_{TOT}(P_l) = \sqrt{\sum_{i=1}^{n} (\frac{\partial y}{\partial x_i} u_{TOT}(x_i))^2} \tag{5}$$

Where y can be replaced by the measured loss, or the calculated efficiency in case of efficiency uncertainty evaluation.

Development of efficiency measurement and uncertainty estimation tool (EMUET)

A system including measurement instruments and software to interface with these instruments is developed for efficiency measurement and uncertainty estimation (PDS EMUET). PDS EMUET allows the real-time estimation of the efficiency, power losses, IE/IES definition and uncertainty of CDM, motor and PDS. The set of software tools is developed using National Instrument's LabVIEW and DIAdem development tools [21]. PDS EMUET can be connected with up to three measurement instruments and two electric drives and can send commands for initialization of instruments, acquire and manipulate data for the uncertainty and efficiency calculation and automatically create test reports for all the measurements and processed data.

The main structure of the PDS EMUET is shown in Figure 1 and it consists of five main parts, as follows:

1. Initialization: This action is required in order to initiate the communication with the instruments and to configure the respective settings. For each instrument, a customized window

reproduces the actual setting screen, allowing the operator to change basic and advanced settings.

2. Drive control and measurement monitoring: Drive control can be performed along with electrical and thermal measurements. The control is customized on the drive model and its programming requirements. Main references (torque and speed) and customized parameters can be controlled from the tool through a MODBUS communication adapter attached with the drive which is interfaced to LabVIEW acquisition computer via Ethernet connection. A temperature logger and two power analyzers are connected via Ethernet as well, and their measurement can be visualized on the main frame as numeric values or graphs.

3. Test sequencing: Automated tests can be performed as the tool provides the option to visualize the test points on a speed Vs toque matrix.

4. Efficiency class and uncertainty evaluation: The acquired data are manipulated in order to evaluate the efficiency and the uncertainty of the products as per EN 50598-2. PDS, CDM and motor efficiencies and losses are calculated and visualized on the screen through graphical indicators. The calculation of efficiency and uncertainty can be performed accurately if all the information regarding the experimental setup is available for the tool. Information on the instrument configuration, accuracy datasheets, nameplates with rated values, tolerances are available automatically or as manual inputs for the operator. Datasheets of accuracies, tables with the reference losses of CDM and PDS, test point requirements for the CDM are available in the program sources directory. The tool combines the available data with the acquired measurements, performing a real time calculation of efficiency, losses, uncertainties and providing information and alarms if limits are exceeded or requirements are not met

5. Data logging: Measurements from the instruments, outputs from the drives and results of calculations can be all logged into a singular *.tdms file, organized in sheets as a common spreadsheet that can be edited in Excel or DIAdem.

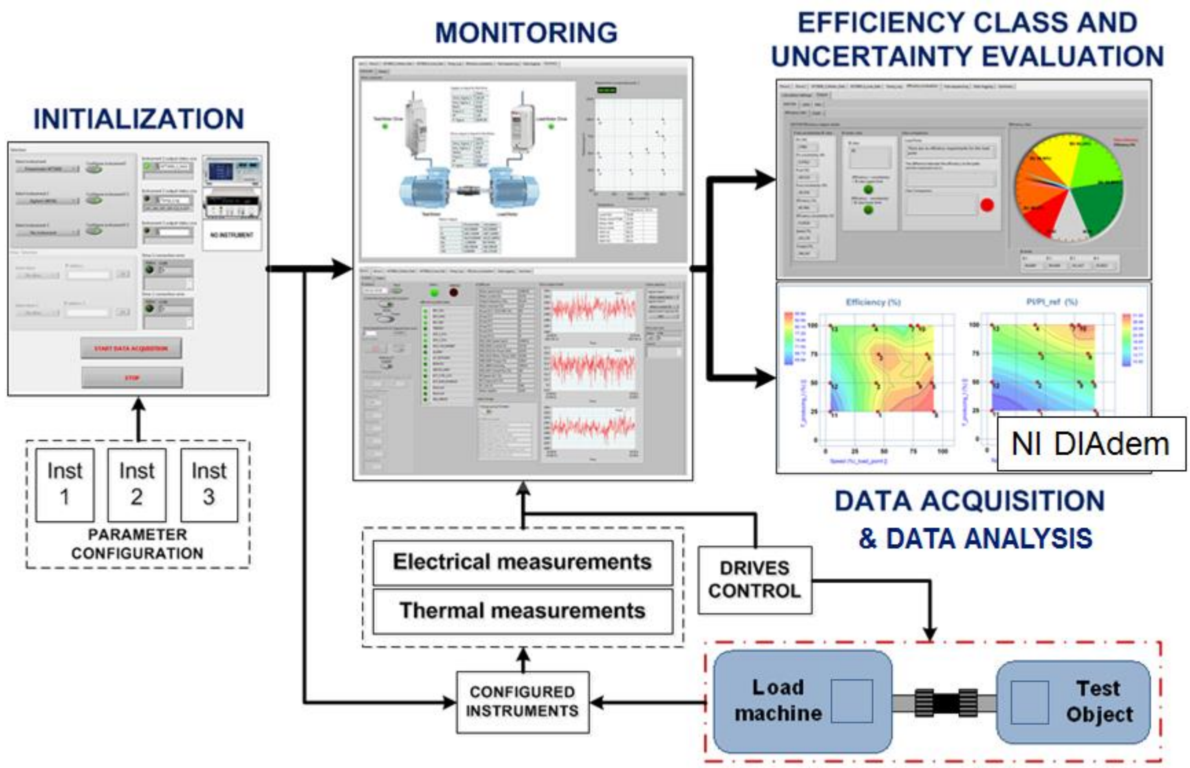

Figure 1: Structure of the online efficiency measurement and uncertainty estimation tool (EMUET)

Experimental measurements of PDS efficiency and online uncertainty

estimation

Test setup

In order to evaluate the efficiency of motor, CDM and PDS, three different test series have been carried out. The test bench is the same for the three tests as shown in Figure 2. For the purposes of the investigation, all measurements are carried out on a converter-fed motor. The motor is fed with a 400 V supply and is connected to a 22 kW drive with 44 A rated output current. The drive connected to the test motor is the test CDM for which efficiency is to be measured. The test motor is coupled to a load machine and a torque transducer is utilized for the measurement of the associated mechanical quantities. The load motor is connected to a drive that provides the control of the torque to be applied at the shaft. Two power analyzers (Yokogawa WT3000) are employed in order to simultaneously perform electrical power input measurements to test drive and test motor and mechanical power output at motor shaft. One of the power analyzer, which is connected to measure motor input power is also interfaced with output from torque transducer allowing simultaneous measurement of motor output power. A temperature logger is used for the measurement of the room temperature, and the temperatures of the housing and the winding of the two motors.

The setup follows the guidelines of IEC60034-2-1 [5] and EN50598-2 [8] in terms of accuracy of the instrumentation. Various accuracies related to electrical and mechanical measurements for the above instruments are taken from respective datasheets and are tabulated in Table 1. Errors related to temperature influence and calibration interval are not considered in the uncertainty calculation. Moreover, the line filters in the power analyzers were disabled to include the powers from harmonic components associated with VSD supply.

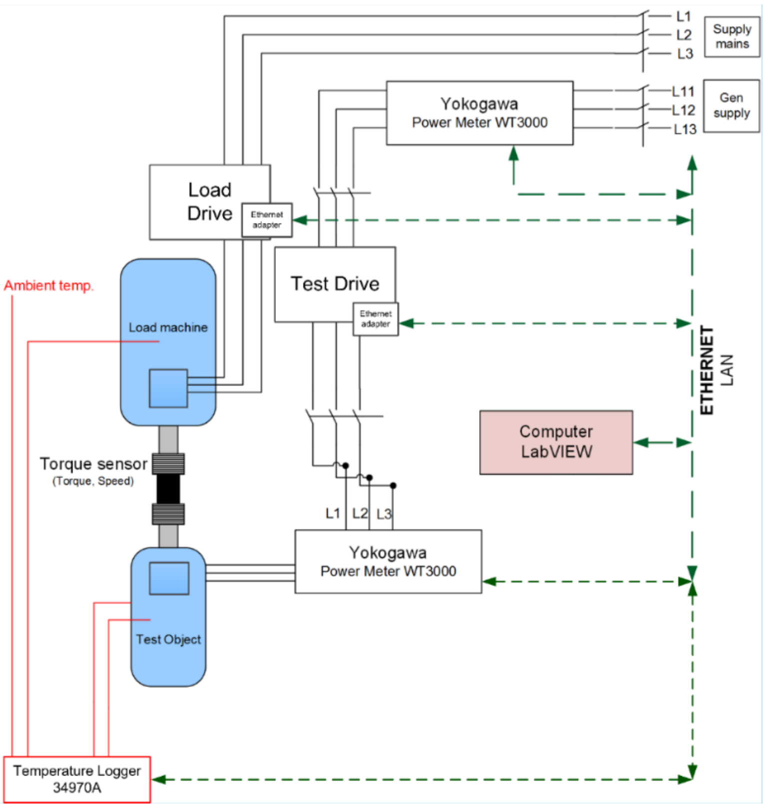

Figure 2: Electrical wiring schematic of measurement setups for input-output method

Measurement Tests

The tests which are carried out are as follows:

1. **Motor and PDS testing at thermal stability as per EN50598-2 [1]:** eight load points have been tested for 30 minutes each. The objective of the test was the measurement of the

performance of the motor and the PDS as per standard. However, the cooling capabilities of the setup were insufficient for the operative points located on the zero speed axis. When a test is performed at speeds greater than zero the natural cooling produced by the rotor compensates for the temperature increase. Therefore, zero-speed load points were omitted from this test. Beside the standard load points, points located on the pump/fan type load (square torque load) curve have been tested. From this test, no evident trends for uncertainties in efficiency and loss have been observed.

2. **Motor and PDS testing on 4x4 matrix:** it was performed in order to facilitate the validation of the typical uncertainty trends presented in [1] and to investigate of the impact of error sources on total uncertainty values. The test points are defined on a 4 x 4 torque v/s speed matrix with 25% speed and load torque increments Figure 5. The thermal stability condition is neglected in this test. Each load point is tested for 10 minutes in order to collect a sufficient amount of samples. The shorter testing time, with respect to test 1, does not compromise the quality or validity of the results and by no means disregards the procedures described in the standard. As stated in [1], measurements over a period of 1 min to 3 min, equivalent of at least several slip cycles, are enough for a later processing. However, the test is not following the standard in terms of sequencing of test points

3. **CDM testing:** thirteen load points were tested, for 5 minutes each, as per where the load for CDM testing is defined by the stator frequency and the torque producing current. In order to run the test with so strictly defined load points, the output current of the drive has to meet the requirements outlined in [1] in terms of relative values and displacement factor. Thus for the test to be valid at one particular load condition (as shown in Figure 6), the test operator has to implement the following steps:

    a. Check the minimum current (torque producing current) and accordingly the load of the machine
    b. Check the load displacement factor and modify other parameters, if possible.

Table 1: Accuracies of instrumentation and standards requirements

Instrument	Measured quantity	Error source	Accuracy	Requirements from standards
Digital power analyzer	Mechanical power	Torque input (Analog)	±0.1%reading error + , 0.1% measurement range error)	Minimum class 0,2 [IEC 60034-2-1]
		Speed input (pulse)	±0.05%reading error + 1 mHz	<0,1 rpm [IEC 60034-2-1]
	Electrical measurements	Current, Voltage	±(0,1% reading error + 0,05 % measurement range error)	0,2 % of rated apparent power S_{equ} (0,3 % of S_{equ} for limited bandwidth), including external sensors [EN 50598-2]
		Power	±(0,15% reading error + 0,1% measurement range error + tanφ*0,3% of reading)	
	Line filter influence (DISABLED)	Current	0,5% of reading	Shall not be used [EN 50598-2]
		Voltage	0,2% of reading	
		Power	1 % of reading	
	One year accuracy (not considered)	1,5 times 6 month accuracy		
	Temperature coefficient (Valid for range 5 to 18°C or 28 to 40°C)		Add ±0.02% of reading /°C	
Torque transducer	Torque	Accuracy	± 0,1% reading	Standards are not setting requirements on torque transducers:
		Rotating Speed influence	0,01% per 1000 rpm	
		Linearity + hysteresis	±0,1 % rated torque	
	Speed	Accuracy	-	
Current Transducer	Current	Accuracy	±(0,05% reading + 30 µA)	Shall not be used[EN 50598-2]
		Conductor position effect	± 0.01% of reading	

Influence of measurement conditions on the final results

Even though measurement procedures met most of the requirements described in EN50598-2 standards, the motor testing could not be carried out efficiently for all the load points. Three main limitations were incurred in order to meet the measurement guidelines given in EN50598-2 standard. This is summarized in Figure 3 and in Figure 4.

The first problem concerns the zero speed load points (encircled red in Figure 3) and is related to the thermal condition that could stress the machine. The second problem is related to partial load point conditions (encircled green in Figure 3 and in Figure 4). For these operation points, it has been noticed that the sensitivity of the instrumentation, which is scaled for nominal point measurement of the motor drive setup, was not sufficiently high to detect signals of low amplitude such as power factor and others. This fact has consequences on the calculation of parameters as uncertainties and efficiencies of test objects. The last problem is related to the change of the load point ((encircled gray in Figure 3 and in Figure 4). Such a change affects the measurement and the data processing because of the consequent transients. When the auto-range function is enabled, the power analyzer changes the range automatically according to the measured value. The power analyzers produces null measurements during recalibration period and it reflects in infinitive peaks or null samples for all the quantities during these times. Proper sampling and averaging of measurement data is required in such instances. But the first two problems cannot be resolved leading to loss of measurement at this points. The EN50598 standard should specifically describe the proper guidelines to follow at such measurement conditions.

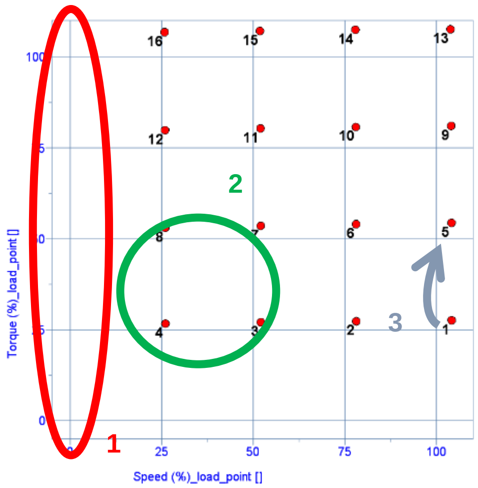

Figure 3: Critical test conditions

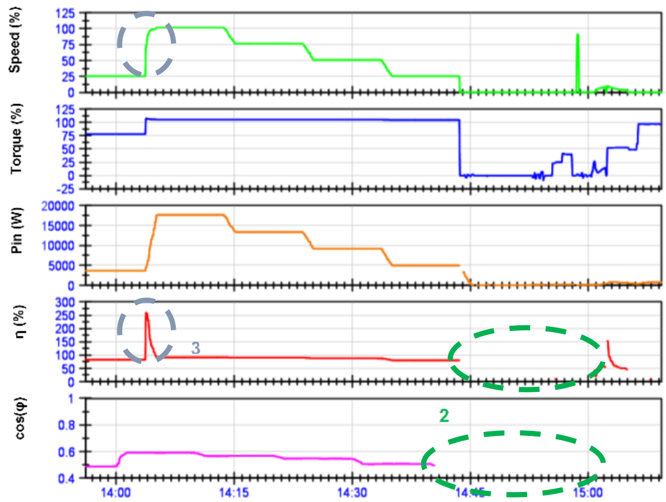

Figure 4: Effects of critical conditions

Measurement analysis

Efficiency and loss trends for test 2 with 4 x 4 load point matrix

This sections describes the efficiency and power loss values for each load point have been acquired in test 2 only, since it gives enough test points to derive the trends in measurement uncertainty and its dependence of various measurement quantities. The respective trends and numeric values for each load point are presented in Figure 5- Figure 8. All the logged values presented here are sampled every 5 seconds and averaged over 7 minutes in order avoid any errors due to spurious measurements and random noise. The relative losses for PDS and CDM are illustrated in Figure 7 and Figure 8. As expected, power losses are increasing for higher loads. In PDS testing, losses for partial load point are erroneously calculated by the tool, giving null values, due to the problem related to the sensitivity of the instruments, discussed in the previous section.

Similarly, the motor efficiency uncertainty is evaluated online by EMUET tool for all measurement points based on the procedure described above. The typical variation of the uncertainty for the operation points is shown in Figure 9. It is evident that the uncertainty is higher for low torque and high speed values. A similar trend can be recognized in Figure 10 for the uncertainty of losses in PDS. This reflects the fact that both the quantities are related to the measurement of electrical and mechanical power, and the difference between the input powers of the two products is affected only by the losses of the drive. Therefore, uncertainties in efficiency or losses and other parameters, are equivalent. As far as CDM losses are concerned, as depicted in Figure 11, the resulting uncertainty values are highly influenced by the operating frequency (speed) and are less affected by the current variation.

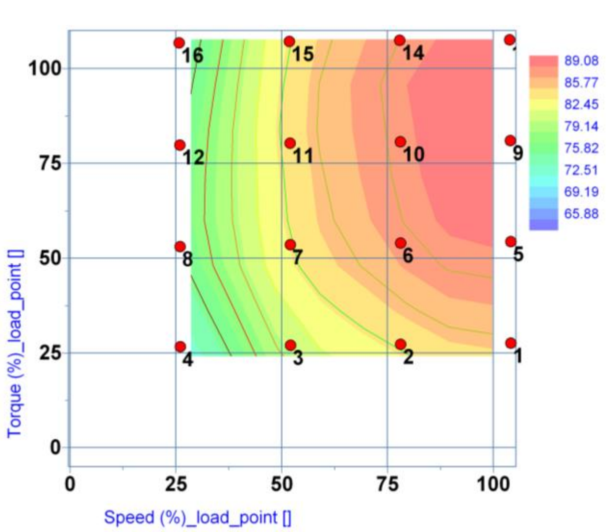

Figure 5: Test 2 - PDS efficiency

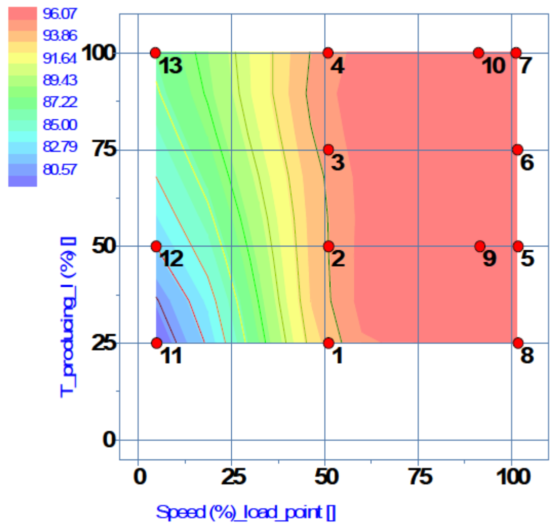

Figure 6 Test 3 - CDM efficiency

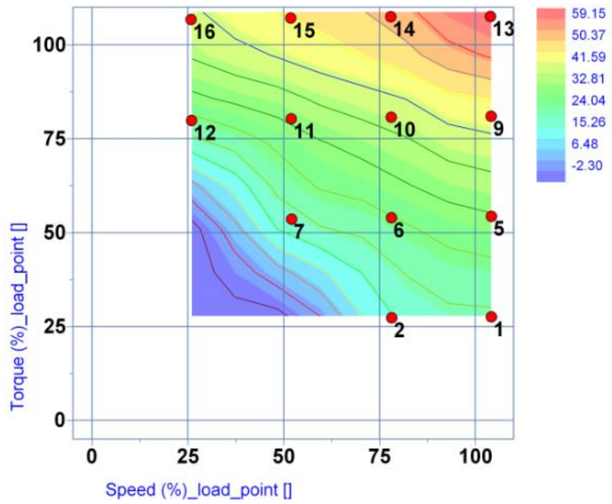

Figure 7: Test 2 - Relative losses for PDS

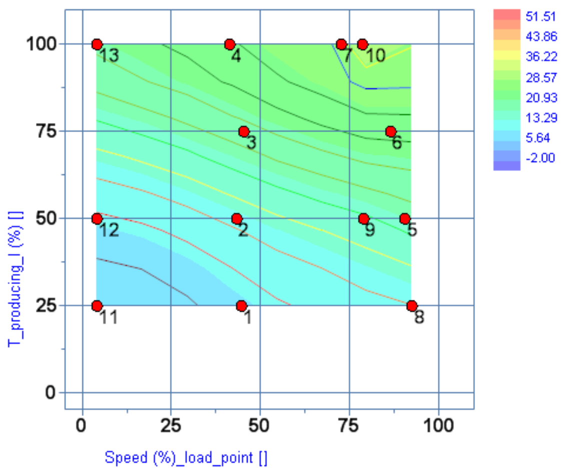

Figure 8: Test 3 - Relative losses for CDM

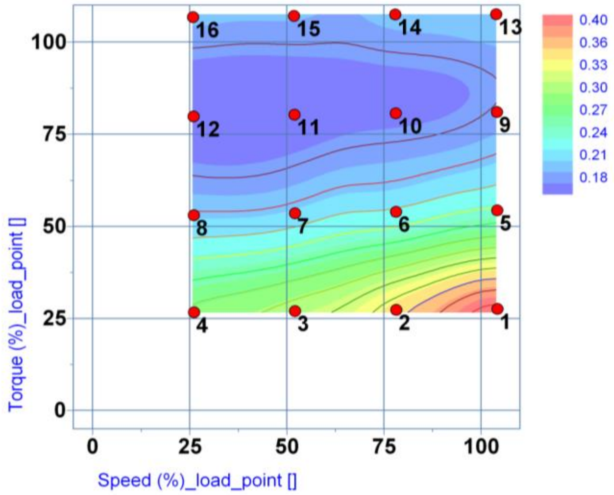

Figure 9: Test 2 - Relative uncertainty of efficiency of motor

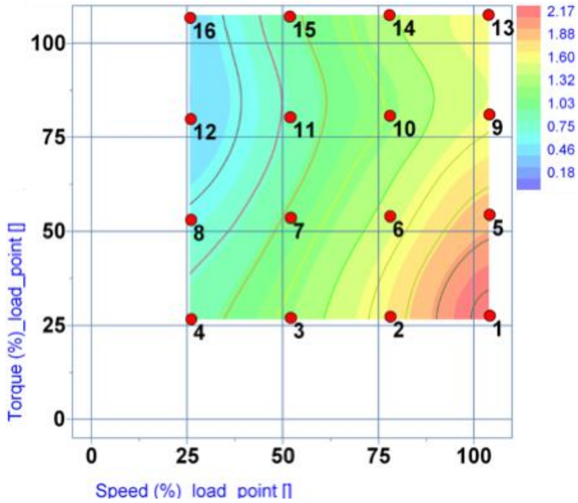

Figure 10: Test 2 - Relative uncertainty of complete PDS loss of PDS

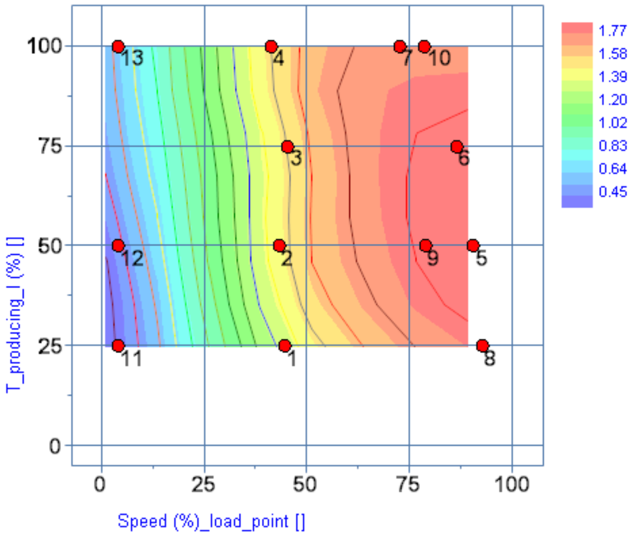

Figure 11: Test 3 - Relative uncertainty of CDM power loss

The influence of actual efficiency of motor on relative estimation uncertainty is analyzed as shown in Figure 12. It can be seen that the uncertainty in motor efficiency is not proportional to the actual efficiency of the motor. This is due to the fact that a motor can have the same efficiency for different load points. In the calculation of uncertainty in efficiency, apart from the accuracy related to measured quantities, there is the contribution of instrument range related errors which causes a non-linear relation between the measurements and uncertainty. A direct correlation between efficiency and uncertainty can be identified when the load torque is kept constant. For these operating points, the uncertainty in efficiency increases with the increase in the efficiency of the motor. It can be pointed out that the relative uncertainty is higher for lower torque values due to lighter loading of instrumentation which still have larger contribution of instrumentation range related uncertainty.

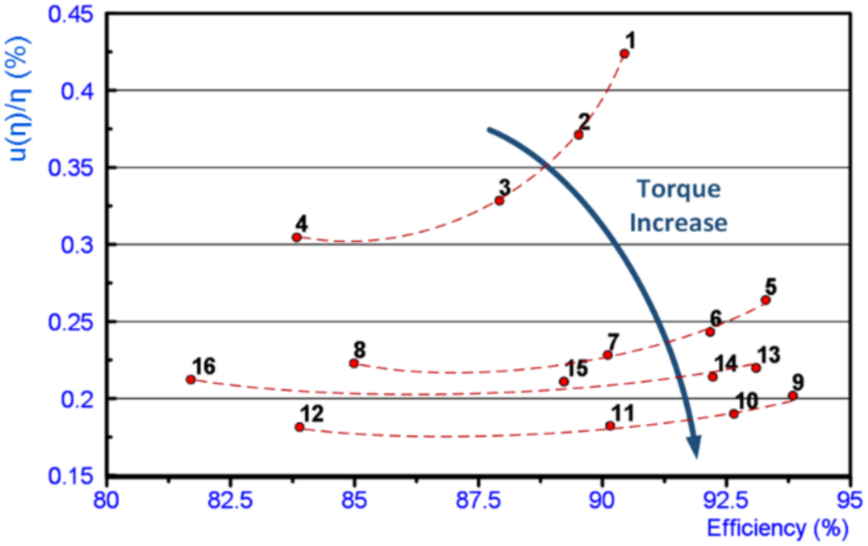

Figure 12: Test 2 – Relative efficiency versus efficiency (numbers indicate the measurement point as shown in Figure 5)

Similarly, influence of actual input and output power measurements on efficiency uncertainty u(η) is analyzed by plotting the uncertainty as a function of output and input power uncertainties (Figure 13 and Figure 14). The value of u(η) is loosely related to the input power uncertainty level. However, a linear relationship between uncertainty in efficiency and mechanical losses can be observed, as depicted in Figure 13. The effect of two main measurands contributing to mechanical power- speed and torque measurement values on the uncertainty is shown in Figure 15 and Figure 16, respectively. u(η) is increasing with the speed but the influence of the torque is quite significant. As seen in Figure 15, the variation of the uncertainty is not concretely varying with speed variation, but it is increasing when the torque decreases.

Thus it can be concluded that the torque range related contribution in the power analyzer dominates most on the overall measurement uncertainty

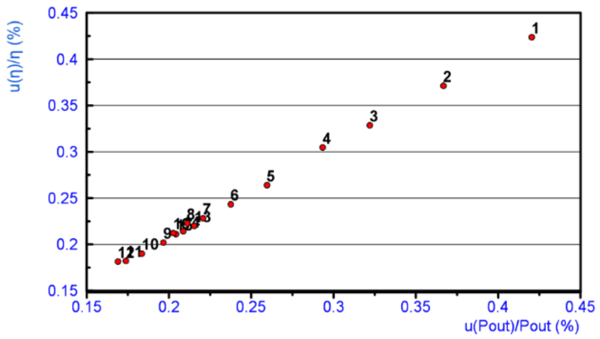

Figure 13: Test 2 - Motor efficiency uncertainty versus mechanical power uncertainty

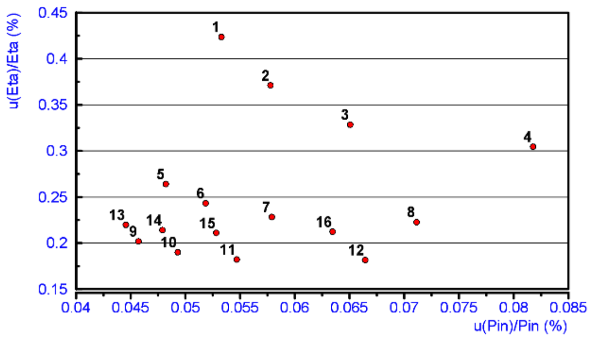

Figure 14: Test 2 - Motor efficiency uncertainty versus electrical power uncertainty

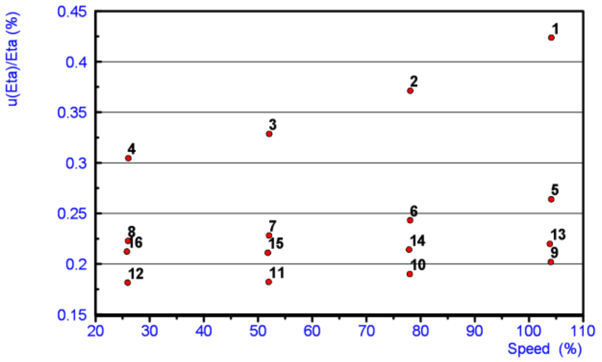

Figure 15: Test 2 - Motor efficiency uncertainty versus speed

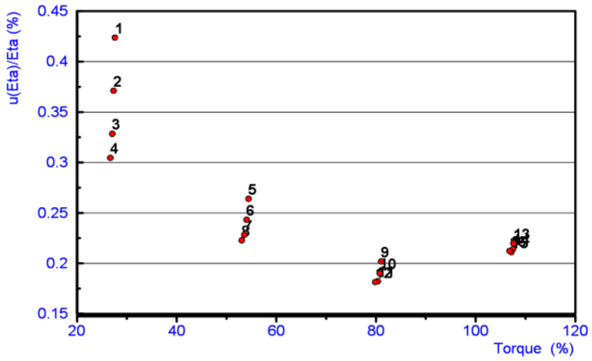

Figure 16: Test 2 - Motor efficiency uncertainty versus torque

Comparison with measurement uncertainty with EN 50598-2 standard

EN 50598-2 [8] describes typical uncertainty trends for different loss determination methods. The uncertainty indicated in the standard is based on a normal distribution for error occurring randomly associated to a total accuracy 0,2% of the rated apparent power S_{equ}. According to the standard, the uncertainty trend in losses has been calculated as

$$\frac{\Delta P_L}{P_L} = \frac{\sqrt{(k * P_{IN})^2 + (k * P_{OUT})^2}}{P_{IN} - P_{OUT}} = k\frac{\sqrt{1+\eta^2}}{1-\eta} \tag{6}$$

with coefficient k=0,2% related to the total accuracy of power meter, P_{IN} and P_{OUT} are measured input and output active powers. This approach is qualitatively right but too generalized but far simplified from the fact that accuracies are not just function of the reading error, but they include different contributions as described earlier. Thus, an operator who is not familiar with calculation of uncertainties can be misled by the standard guidelines. The results acquired by applying the above-mentioned definition to the measurement data yields the green curve in Figure 17.

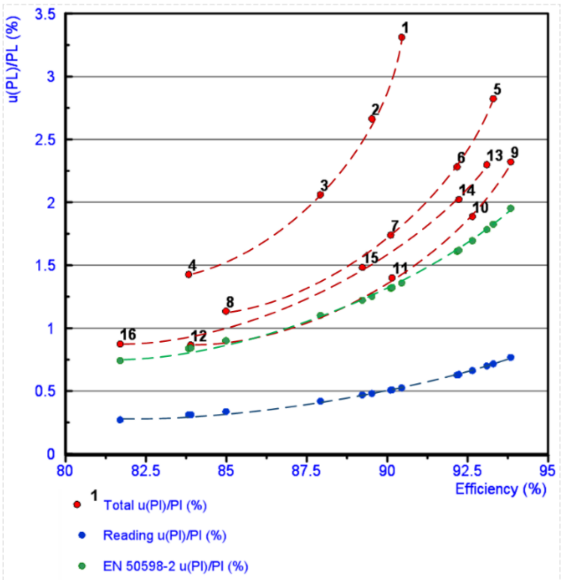

Figure 17: Test 2 - Loss uncertainty for motor

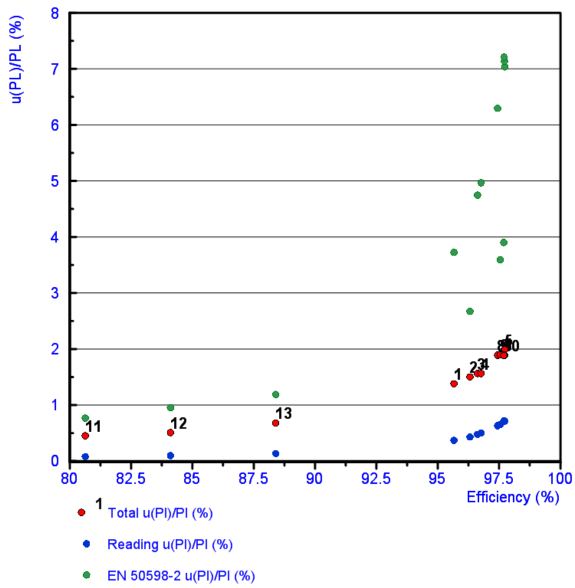

Figure 18: Test 3 - Loss uncertainty for CDM

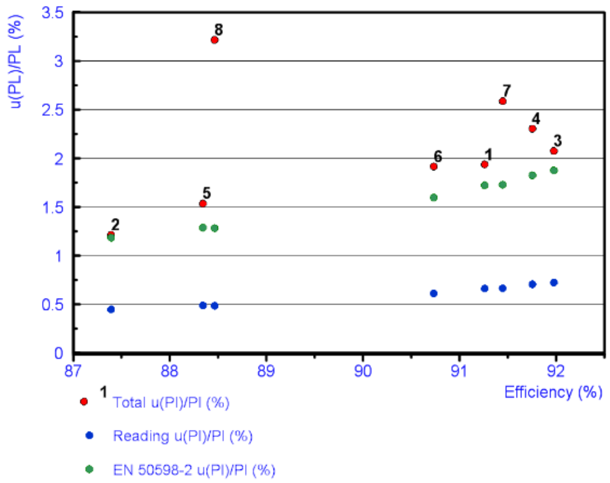

Figure 19: Test 1 - Losses uncertainty for PDS

The same generalized approach of assuming the accuracy as a percentage of the read quantity is repeated on the measurements, applying the actual reading accuracy of the instrumentation.

$$\frac{\Delta P_L}{P_L} = \frac{\sqrt{(k_1 * P_{IN})^2 + (k_2 * P_{OUT})^2}}{P_{IN} - P_{OUT}} \qquad (7)$$

where the accuracy of measured quantity of electrical measurements is k_1=0,02% applied to measured electrical power $P_{el,}$ and total reading accuracy on mechanical measurements is k_2=0,1% of measured mechanical power $P_{mech.}$. This is shown in Figure 17 in **blue** curve, characterized by the application of uniform distribution.

The actual power loss uncertainty which includes both measured quantity errors and equipment range errors is represented by the **red** curves in Figure 17 and is calculated using following equation

$$\frac{\Delta P_L}{P_L} = \frac{\sqrt{u(P_{IN})^2 + u(P_{OUT})^2}}{P_{IN} - P_{OUT}} \qquad (8)$$

where the respective uncertainty of different power measurements are calculated as described in previous sections. The typical values of the estimated uncertainties are higher than the uncertainties presented in the EN50598-2 standard (**green** curve) or the ones related to the only reading errors since the range related errors have larger influence and are function of a mechanical measurement.

The same analysis, as described above, is repeated for test 3 and test 1 and the respective results are shown in Figure 18 and Figure 19. Since all test points could not be measured in test 1, a trend similar to the one reported in Figure 17 for test 2, cannot be easily recognized for test 2. For CDM test (test 3), the uncertainty of the losses is not dependent on the torque value as in motor testing, since the measurements are strictly related to electrical parameters, and the uncertainty are not as much amplified as it happens due to torque transducer used in Test 2 or Test 1. Since the range and the input and output power measurements are not significantly different, equation (8) gives an uncertainty trend coherent with the typical trend of [8], independently on the load torque point.

It can be concluded that the measurement uncertainty in efficiency or motor losses is generally higher than what is described by the EN50598-2 standard when all error sources related to range related errors are considered in estimation of measurement uncertainty. This consideration is missing in the present formulation of EN50598-2.

Summary of measurement results and recommendations for test procedure

This section summarizes various criticalities pointed out in previous sections as recommendations to further improve the test procedures and other guidelines described in EN50598-2. It shall be noted that the recommendations are based on authors experience with following test procedures for given rating of motor drive system as well as associated instrumentation.

Test type

EN50598-2 [1] indicates that in critical thermal conditions, the measurement test shall be performed over a time period of 10 minutes, involving a cooling system at full performance. For zero-speed load points, temperature could be an issue even with full performance operation of the cooling system. If a separate cooling system is not available, a shorter time period of testing for these particular points is required, such that the temperature rise should not be larger than the rated temperature rise at nominal operating point.

The instrumentation to be selected has to match the accuracy requirements described in EN50598-2 [1], expressed as percentage of S_{equ} [5]. This approach seems not appropriate because the apparent power S_{equ} cannot be used as a reference for the mechanical power accuracy. Furthermore, the apparent power value does not give useful information on the instrumentation choice because most instrument manufacturers display accuracy levels as percentages of reading and range or as constant errors.

Test points for PDS and CDM are defined by different parameters. Due to this measurement tests for a PDS does not provide loss information coherent with the load points defined for the CDM, as the respective requirements for current and power factor cannot be satisfied. Therefore, two tests have to be carried out separately for PDS and CDM.

Calculation of Measurement Uncertainty

EN50598-2 [1] generalizes the uncertainty calculation approach with the use of normal distributions. Since some manufacturers express the accuracy with a specific distribution of standard uncertainty, the inclusion of it can incur problems when the applied uncertainties are calculated for different laboratories that employ different instruments and quantities are measured by instruments using different uncertainty distributions. In case the instrument manufacturer provides uncertainty values calculated with a specific distribution (i.e. uniform), this specific distribution should be used [2].

Introduction of tolerance limits is necessary in order to make comparable loss measurements carried out in different laboratories (different instrumentation or environment conditions). Less accurate instruments, but included in tolerance limits stated in [3], could affect the efficiency class declaration of the product. Additionally, measurable criteria in term of tolerances, as presented in [4] for line fed motor, shall be included for CDM and PDS for both nominal operating points and partial load points. Such criterion can be used as a cross check for acceptance of the test results at different operating points.

All relevant sources of inaccuracies that could affect the uncertainty calculation should be considered as demonstrated in this paper, since some important accuracy contributions from the instruments could be involuntarily neglected, such as transducer contributions or errors related to other influential parameters.

CDM testing

For CDM testing the following remarks can be made:

The use of the rated apparent power of the motor, $P_{r,M}$, shall be revised in the context of testing for CDM. The references on $P_{r,M}$ included in EN50598-2 [1] can potentially create confusion in the choice of the reference values because they are referred to the drive and not to the motor. If information on the rated values of the drive are not available, $P_{r,M}$ is referred to the motor for the actual application. In this case, it can happen that the requirements on the current and displacement factor cannot be achieved and that the losses of the CDM exhibit lower values. Moreover, when the rated power of a drive is significantly different from the respective one for the motor, the requirements on power factor and current cannot be met. A comparison between reference and measured losses, as indicated in the standard is presented in Table 2.

Table 2: Comparison of reference losses with measurements with 44 A drive

Operation point (Torque producing current (%), frequency (%))	(0; 25)	(0; 50)	(0; 100)	(50; 25)	(50; 50)	(50; 100)	(90; 50)	(90; 100)
$P_{L,RCDM}$ (W)	550	633	896	570	689	1072	780	1410
I_{out} (A)	18,4	24,5	40,8	18,4	24,5	40,8	24,5	40,8
$P_{L,CDM}$ (W)	191	236	391	210	277	483	319	536
Actual I_{out}(A)	19,5	25,2	41,4	18,7	25,1	41,9	25,1	41,1
$P_{L,CDM}$ /$P_{L,RCDM}$ (%)	34,7	37,3	43,6	36,8	40,2	45,0	40,9	38,0
Required cosphii	0,49	0,71	0,85	0,49	0,71	0,85	0,71	0,85
Actual cosphii	-	-	-	0,46	0,51	0,57	0,69	0,76

If the actual drive is oversized, the situation is equivalent to the respective observation as previous point. Furthermore, when PDS and CDM tests are performed simultaneously, the strict requirements on the power factor are unlikely to be satisfied. Bigger deviation from the set values should be allowed when the load is the actual motor in the PDS.

The use of an equivalent electronic load is suggested when the CDM testing requirements are not achieved, as per [1]. This testing option is not feasible when a test lab carries out PDS and CDM measurements on the same setup.

Further improvisation of IE/IES definitions for CDM/PDS efficiency classes

The relative losses of the reference drive given in the EN50598-2 [1] are substantially higher than that of the most available drives in the market. Nowadays, electric drives are characterized by higher and higher levels of efficiency. In order to make the IE classification for drives a valid index of efficiency, which is useful for the customer for comparing different products, the class definition limits have to be properly set according to the actual state of the market. Also further efficiency classes need to be defined to segregate the higher efficiency drives, this is missing in the present formulation of efficiency classes for CDM as well as PDS.

Conclusions

This paper presents an investigation on efficiency measurement methods and classification as described in the recently published standard EN50598-2. The in-depth analysis of EN50598-2 [1] has pointed out several unclear definitions and procedures. An explicit calculation method for uncertainties of efficiency and power losses is proposed in this paper, which is not available in the published standard. Tools for automated testing of motor drives as per EN50598-2 were developed and experimental tests were performed on the test motor to further investigate the influence of external factors like measurement uncertainty of individual equipment and the uncertainty estimation of measured efficiency values for CDM and PDS. In addition to the uncertainty analysis, the tests allow for precise evaluation of the feasibility of the test procedures described in the standard, especially in the case of motor drive testing. The impact of this work can be summarized in the development of a set of guidelines by which a general procedure for measurement of efficiency and compliance of the same could be checked. The necessary instrumentation and software tools for automated sequencing of motor and drive testing was developed and proposed method of uncertainty estimation was implemented online so that the efficiency of measurement device i.e. CDM or PDS and its acceptance based on estimated uncertainty could be calculated online. In the end, the paper provides specific guidelines on how the EN50598-2 could be updated to make it more applicable by most of the test laboratories.

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