

# APPLICABILITY OF TORQUE CALIBRATION ON TEST BENCHES FOR ELECTRICAL MACHINES

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## Abstract:

The traceability of torque measurements on test benches for electrical machines is primarily established by the static calibration of a torque transducer. However, the loading conditions and signal processing methods are generally different for the static calibration and the measurement on a test bench. Therefore, the applicability of the calibration should be clarified before applying the calibration results for further analysis. In this paper, the torque measurement chain using a power analyser on a test bench for electrical machines is compared to the measurement chain used in the standard calibration procedure DIN 51309.

**Keywords:** DIN 51309; torque measurement; torque calibration; power analyser; motor test bench

## 1. INTRODUCTION

On a test bench for electrical machines, the specimen can be operated at customised loading conditions. Mechanical and electrical quantities are measured to evaluate the efficiency and performance of the investigated electrical machines while the test bench is in operation. Among these measurement quantities, torque is usually the one with the highest uncertainty contribution [1]. Therefore, a calibrated torque measurement with minimum uncertainty is essential for the development and testing of electrical machines.

In addition, rotary torque in test benches is coupled with unneglectable ripples and oscillations. Therefore, instead of transferring the static calibration results directly to the test bench, the applicability of these calibration results should be clarified first.

The traceability of the torque measurements on the test bench for electrical machines is primarily established by the static calibration of the torque transducer. In the step-by-step static torque calibration according to DIN 51309 [2], the torque transducer is loaded with a series of predefined torque steps to calibrate the corresponding output

signals. The output signal (usually in the form of mV/V, V or kHz) is processed by the data acquisition (DAQ) system with a lowpass filter, which removes noise and helps to reach a stable reading. The cut-off frequency is usually set between 0.1 Hz to 10 Hz [3], [4] and stated in the calibration certificate. At the Physikalisch-Technische Bundesanstalt (PTB), a 0.2 Hz Bessel lowpass filter is implemented for most torque calibrations.

On test benches for electrical machines, the measurement chain of a torque signal is generally different from the calibration. For the simultaneous measurement of electrical and mechanical power, power analysers are widely used on test benches for electrical machines under constant working conditions. A power analyser processes both electrical and mechanical quantities at the same time interval to enable a continuously performed online efficiency calculation [5]. Within this time interval, the average value of the torque is recorded to avoid noise and oscillation. Compared to the Bessel lowpass filter used in the calibration, the averaging method of a power analyser is a different mathematical process.

In this paper, these two torque measurement chains are connected in parallel with the same torque transducer to investigate the applicability of the static torque calibration result on the test bench for electrical machines.

## 2. COMPARISON IN STATIC TORQUE CALIBRATION

In order to have a direct comparison between the torque values measured by the power analyser and those measured during the calibration, the T12HP torque transducer with a range of 2 kN·m was installed in the 20 kN·m torque standard machine (TSM) at PTB (Figure 1) to perform a static torque calibration according to DIN 51309. As illustrated in Figure 2, the T12HP is loaded by the TSM with defined torque steps and provides a frequency impulse output in the range from 30 kHz (-2 kN·m

clockwise) to 90 kHz (2 kN·m anticlockwise) which will input both measurement chains in parallel for analysis.

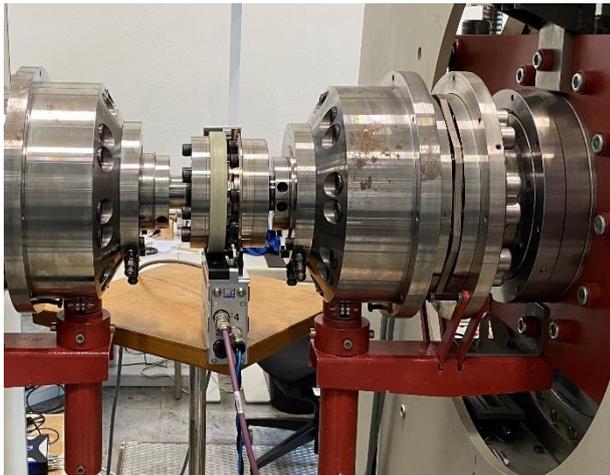


Figure 1: Static calibration of the T12HP torque transducer in the 20 kN·m torque standard machine (TSM) at PTB

The output signal is read by an MGCplus DAQ system with a ML60B measurement card using a 0.2 Hz Bessel lowpass filter with a 10 Hz sampling rate. For each load step, one measurement value is compared to the defined torque load for calibration. This method is named “LP” in the following.

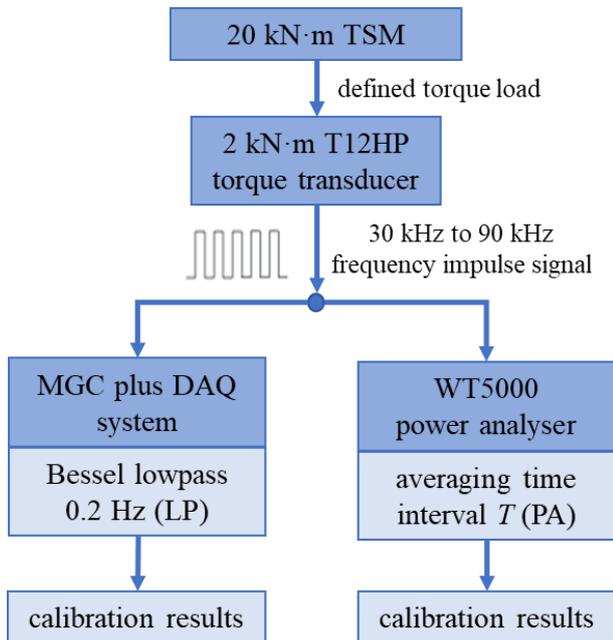
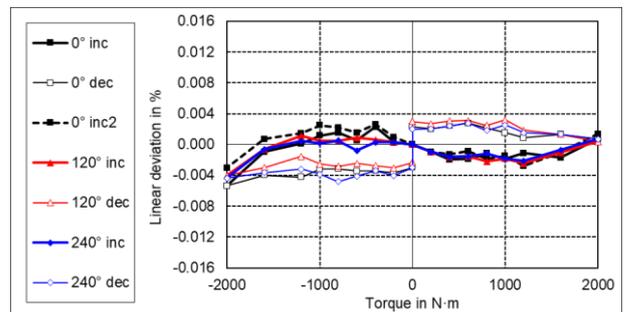


Figure 2: Calibration setup for the T12HP torque transducer according to DIN 51309 with additional power analyser measurement

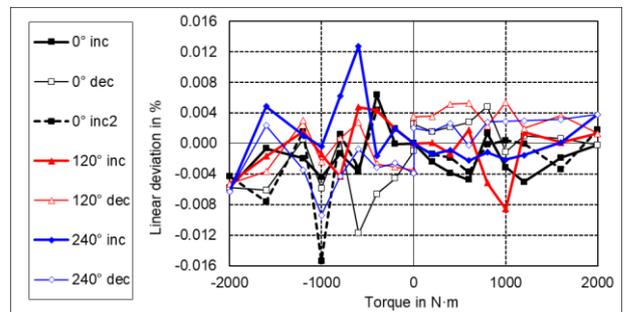
In addition to this so-called traditional measurement chain, the transducer output signal is fed into the Yokogawa WT5000 power analyser in parallel, so that this measurement chain can be calibrated simultaneously. The power analyser processes the transducer’s frequency signal in the megahertz sampling frequency range and

continuously records the average value over the specified time interval  $T$ . This method is named “PA” in the following. For each load step, the torque signal is recorded after a 33 s dwelling time in both measurement chains.

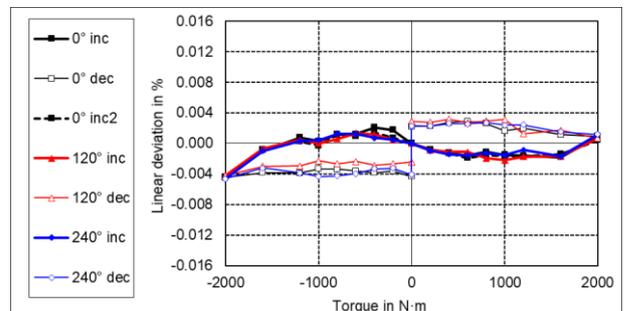
The calibration results according to DIN 51309 using the different recording methods are presented in Figure 3. Each curve represents the linearity deviation of the transducer output signal relative to the maximum calibrated torque for both increasing and decreasing load steps (inc and dec). Meanwhile, clockwise (quadrants I and IV) and anticlockwise torque (quadrants II and III) are repeated respectively for three different mounting positions ( $0^\circ$ ,  $120^\circ$  and  $240^\circ$ ).



(a) Rel. linearity deviation with LP (using MGCplus and 0.2 Hz Bessel lowpass filter)



(b) Rel. linearity deviation with PA (using power analyser  $T = 1$  s)



(c) Rel. linearity deviation with PA (using power analyser  $T = 8$  s)

Figure 3: Comparison of the torque calibration results using the different recording methods

The torque deviation measured by the power analyser with one second averaging time ( $T = 1$  s) is shown in Figure 3 (b). It is observed that the torque

is measured with significantly higher and randomly distributed deviations. This leads to the conclusion that the 1 s averaging time is not capable of reducing noise and oscillation down to the same level as the 0.2 Hz Bessel filter. However, with an 8 s averaging time ( $T = 8$  s), as presented in Figure 3 (c), the torque can be measured with comparable accuracy as in the static calibration.

### 3. COMPARISON ON THE TEST BENCH FOR ELECTRICAL MACHINE

To expand the comparison of the two measurement chains from static to rotary conditions, the statically calibrated torque transducer is mounted on a 200 kW test bench for electrical machines at PTB (Figure 4). The specimen on the left is connected to the DC load motor on the right through a universal joint and the torque transducer between them. Besides torque measurement, the transducer also measures the rotational speed via an optical incremental encoder.



Figure 4: The 200 kW test bench with a specimen on the left and a DC load motor on the right as well as the torque transducer in between

For comparison, the same measurement chains as in Figure 2 are implemented on the test bench except for the MGCplus being replaced by a QuantumX MX460b with comparable measurement principles and accuracy. To visualise this process more clearly in the power analyser, a half second averaging time interval is selected ( $T = 0.5$  s). The averaged data are then processed with an additional 16 point moving average filter. Ultimately, the measurement chain is equivalent to the  $T = 8$  s setting as in Figure 3 (c).

During the measurement, a characterisation map is performed to investigate the relation between the

measured torque and the rotational speed. The characterisation map is developed based on the previous work in [6] to cover a wider operation range of the specimen. In Figure 5, the measured rotational speed and the raw torque data are presented as well as the lowpass filtered signal (LP) and the averaged signal with the power analyser (PA).

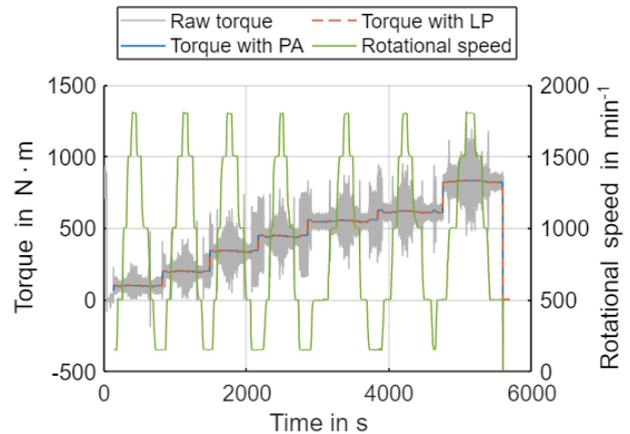


Figure 5: Performed characterisation map consisting of measured torque and rotational speed

#### 3.1. Stability of the measurement points

It can be observed in Figure 5 that the torque is associated with a large amount of oscillation in this test bench setup. The oscillation is identified as torque ripples in the rotary shaft and is particularly severe at the upper and lower speed limits. To investigate the behaviour of LP and PA under torque ripples, two representative load steps are considered below.

##### Case A: load step at 830 N·m and 1000 min<sup>-1</sup>

The complete course of the load step is presented in Figure 6 (a). In Figure 6 (b), the time axis is enlarged in (zoom area (b)), and in Figure 6 (c), the torque axis is enlarged in (zoom area (c)).

At this load step, the amplitude ratio of the torque ripples is smaller compared to other steps. Therefore, both LP and PA can reduce the torque ripples and achieve good stability.

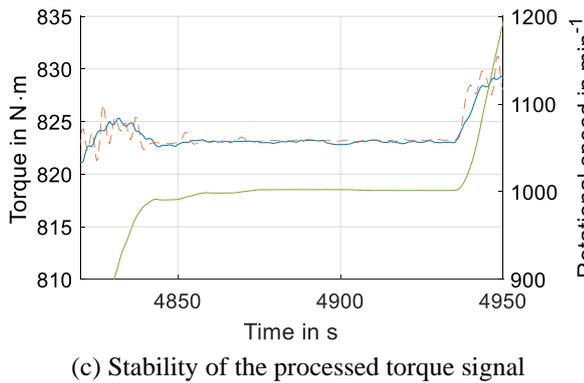
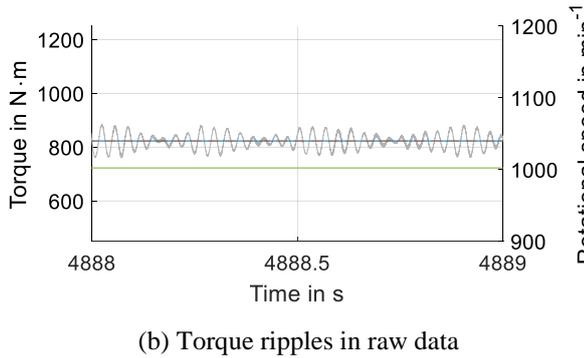
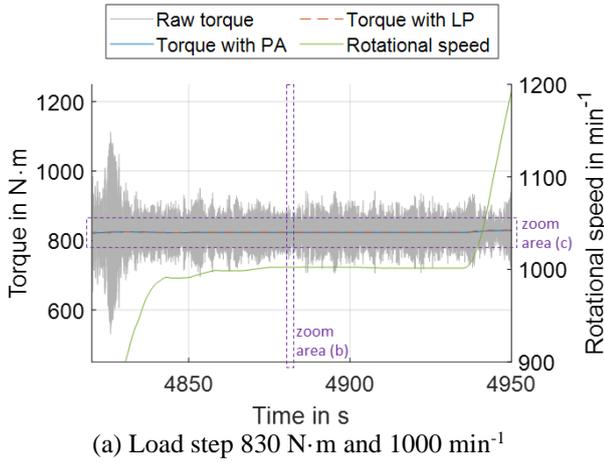


Figure 6: Stability of the torque measurement at load step 830 N·m and 1000 min<sup>-1</sup>

### Case B: load step 830 N·m and 1800 min<sup>-1</sup>

The complete course of the load step is presented in Figure 7 (a). In Figure 7 (b), it is enlarged in on the time axis (zoom area (b)), while in Figure 7 (c), a zoom is shown on the torque axis (zoom area (c)).

At this load step, the amplitude ratio of the torque ripples is much larger compared to other steps. It can be observed that LP can achieve better stability, while the processed signal of PA travels up and down. Part of the reason for the signal travelling is that the averaging method of PA is not capable of reducing the ripples down to the same level as LP. Moreover, the ripples also challenge the control system to keep the load step constant, which is observed by the fact that the mean values of both torque and speed are still changing after dwell.

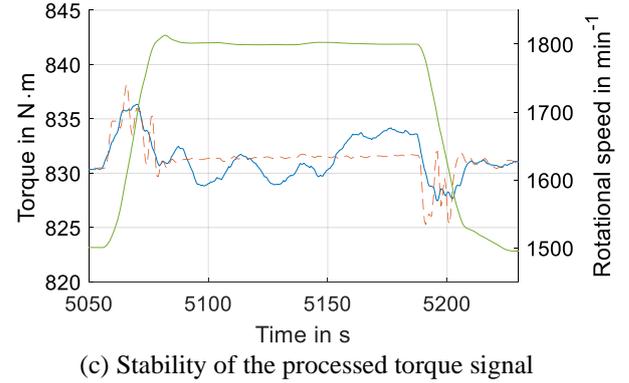
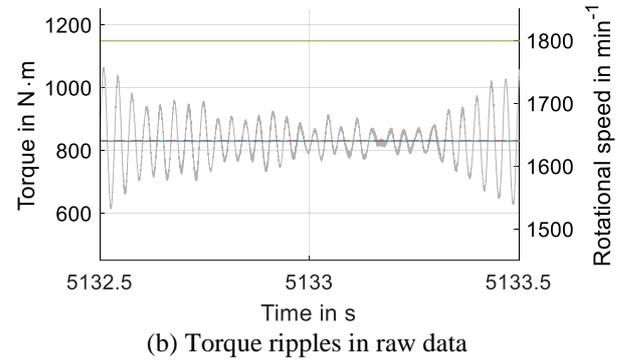
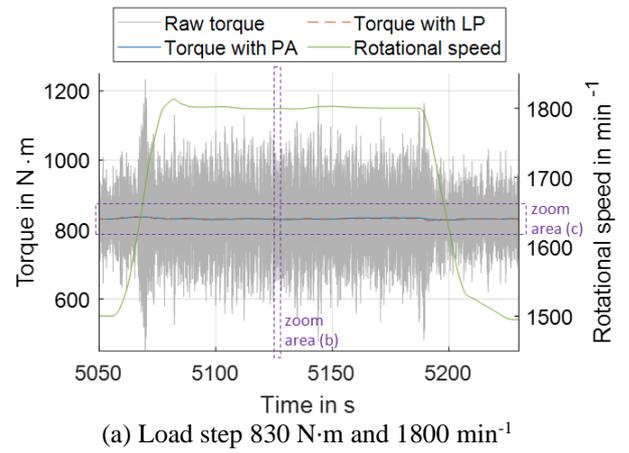


Figure 7: Stability of the torque measurement at load step 830 N·m and 1800 min<sup>-1</sup>

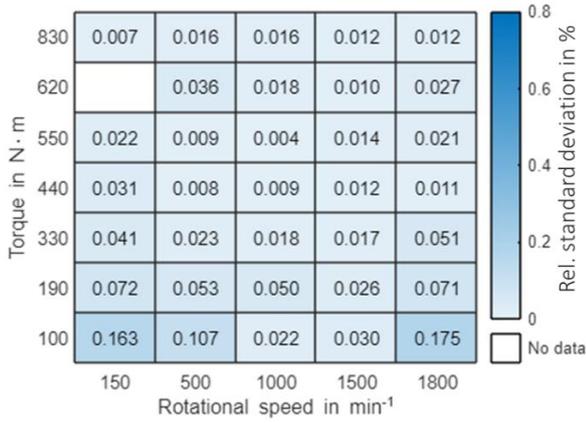
### 3.2. Uncertainty contribution due to instability

To quantify the stability of the torque measurements at each load step, the standard deviation of the processed signal is calculated for the first stable 25 s (approximately fifty measurement points) after dwell:

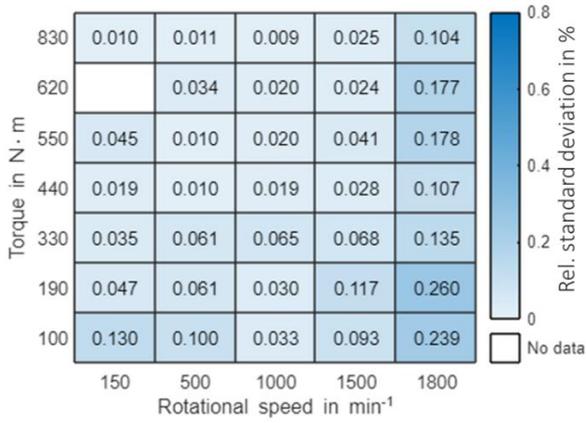
$$\sigma^2 = \frac{1}{N} \sum_{k=1}^N (X_k - \bar{X})^2 \quad (1)$$

where  $N$  is the number of measurement points,  $X_k$  is the individual value and  $\bar{X}$  is the mean value.

The corresponding relative standard deviation with LP and PA for each load step is presented in the characterisation matrix of Figure 8.



(a) Relative standard deviation with LP in %



(b) Relative standard deviation with PA in %

Figure 8: Characterisation matrix of the relative standard deviation with LP or PA for each load step (“No data” means that the load step is too short for analysis)

However, it is important to note that the standard deviation calculation in equation (1) is only valid when all individual measurement points are independently measured. The processed signal of the lowpass filter or the moving average is autocorrelated and therefore equation (1) is not directly applicable.

Based on the method developed in [7], a sample autocorrelation function (ACF) can visualise the autocorrelation between the current measurement point and its previous measurement points (Figure 9). The  $x$ -axis indicates their indexing distance from the current measurement point. The orange dashed line indicates a 95 % confidence limit for uncorrelation. This means the current measurement point is only autocorrelated with the nearest previous points above the limit according to [7].

The cut-off lag  $n_r$  of autocorrelation is 6 for LP and 9 for PA. According to [7], the standard deviation of the measurement data without autocorrelation can be corrected as  $\sigma_c^2$  in equation (2).

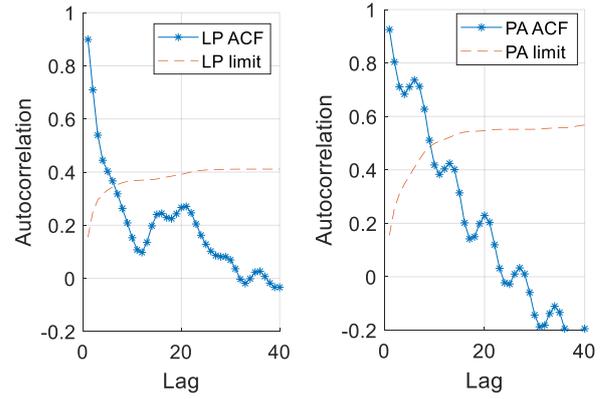
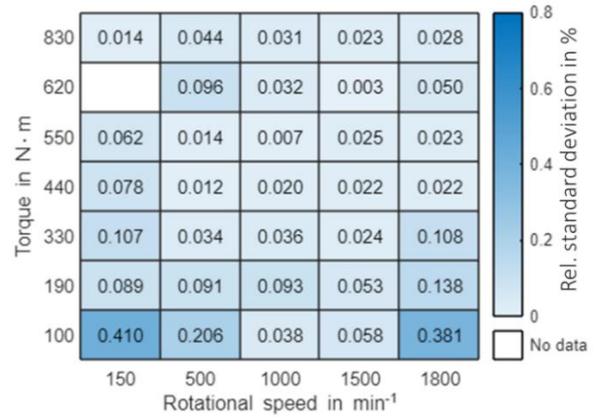


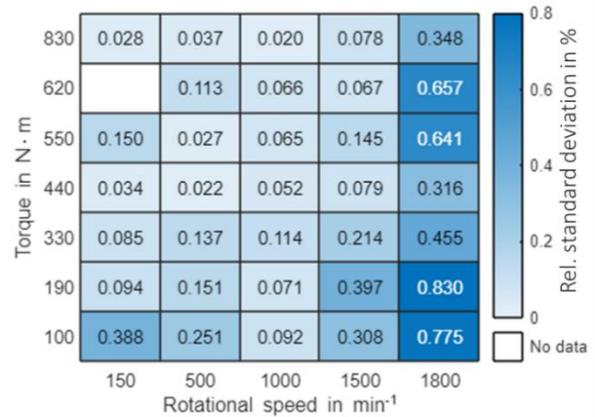
Figure 9: ACF and autocorrelation band for LP and PA

$$\sigma_c^2 = \left( 1 + \frac{2 \sum_{i=1}^{n_r} (N-1) \cdot ACF}{N} \right) \cdot \sigma^2 \quad (2)$$

The corrected relative standard deviation with LP and PA for each load step is presented in the characterisation matrix of Figure 10.



(a) Corrected relative standard deviation with LP in %



(b) Corrected relative standard deviation with PA in %

Figure 10: Characterisation matrix of the corrected relative standard deviation with LP or PA for each load step (“No data” means that the load step is too short for analysis)

Compared to the characterisation matrix in Figure 8, the uncorrelated relative standard deviation is approximately twice as large. For most load steps, the corresponding deviations are even

larger than the accuracy class (0.02 %) of the implemented torque transducer.

In conclusion, the torque deviation should be considered as an additional uncertainty contribution to the torque measurement on a test bench due to the instability of the load steps. This contribution is not negligible, particularly under severe torque ripples.

#### 4. EFFICIENCY DETERMINATION

One of the primary purposes of torque measurements on test benches for electrical machines is to determine the efficiencies. It is undertaken through the ratio between mechanical and electrical power. The efficiency mapping measured by the power analyser is presented in Figure 11. Since the specimen is a commercial industrial motor designed mainly for the nominal load, lower efficiencies are measured at reduced torque and rotational speed.

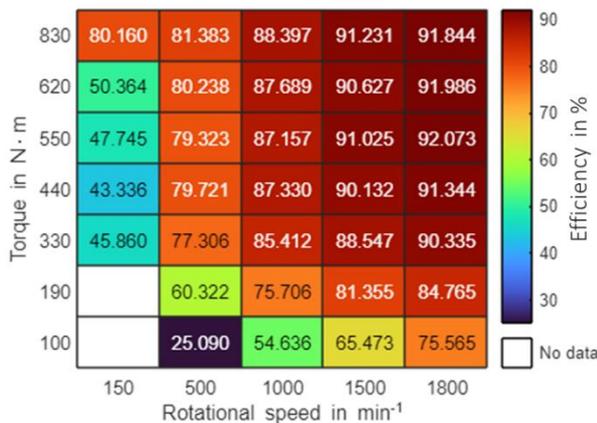


Figure 11: Efficiency mapping measured by the power analyser

It is important to point out that the suggested additional torque measurement uncertainty due to the torque deviation does not directly contribute to the uncertainty budget of efficiency determination. This is because the variations of mechanical and electrical power of electrical machines are correlated with each other. The influence of the torque deviation on the efficiency determination is to be investigated in future work.

#### 5. SUMMARY

The torque measurement chain that uses a power analyser on electric motor test benches is different from the measurement chain used during its static calibration. If the power analyser uses a short

averaging time, the torque transducer shows significantly less accuracy than the accuracy stated in its calibration certificate. The averaging time of the power analyser should be prolonged and adequately adjusted to show the same response from the lowpass filter used during the static calibration.

On the test bench for electrical machines, both torque measurement chains are incapable of reducing the ripples down to a negligible scale. The remaining torque deviation due to instability should be considered as an additional uncertainty contribution to the torque measurement on test benches. This contribution is not negligible, particularly under severe torque ripples.

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