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EFFICIENCY MEASUREMENT WITH A FOCUS ON THE INFLUENCE OF ROTATION AND TEMPERATURE ON TORQUE MEASUREMENTS PERFORMED ON SMALL-SCALE TEST BENCHES

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Abstract:

Torque measurements that account for the influences of temperature and rotation are vital in determining the efficiency of rotating electrical machines on test benches. During experimental efficiency measurements, the influences of temperature and rotational speed generate errors in the torque measurements that could also affect the overall traceable efficiency measurement on test benches. In this paper, experimental efficiency mapping results with a focus on the influence of rotation and temperature on torque measurements are presented.

Keywords: efficiency measurement; rotating electrical machines; torque calibration; torque measurement under rotation

1. INTRODUCTION

An efficiency determination method for electrical machines on test benches is dependent on traceable electrical and mechanical measurements and their respective standards. The electrical transfer standard consists of a number of voltage and current sensors along with a power analyser. Similarly, the mechanical transfer standard consists of a torque and speed transducer for measuring torque and rotational speed. The influence of varying temperature and humidity on torque measurements is generally known and its dependence on different quantities has also been studied. The effect of temperature and humidity on the sensitivity of torque transducers in the static state without rotational effect was presented in [1], [2], [3]. However, to the authors' best knowledge, very few publications are available in the literature that discuss the effect of temperature on torque measurement during continuous operation and its influence on efficiency measurement. In this paper, we will investigate the variation of rotational speed and temperature during continuous operation before machines reach the thermal steady state, as well as the resulting temperature rise and its effect on the efficiency of rotating electrical machines on the test bench. Machine efficiency decreases with increasing temperature due to the rise in resistance that accompanies the rise in the temperature of the machine. This effect will be described theoretically and experimentally in this paper and concluding results will be presented when the machine is running at room temperature (RT). They will then be compared with the results of machines operating at an energy-optimal operating temperature.

2. METHODOLOGY OF EFFICIENCY AND TORQUE MEASUREMENT UNDER ROTATION

The device-specific operating points (combination of torque and rotational speed) in the test bench, which vary for the two torque sensors used here, are an interesting phenomenon. Neither the method for static torque calibration as described in DIN 51309 [4] and EURAMET cg-14 [5] nor the information given in the calibration certificate (CC) can be easily applied during rotational operation. Therefore, a similar procedure (Figure 1) based on the international standard IEC 60034-2-1 [6] and a torque calibration procedure under rotation [7] are used in this paper. The load profile (CM2) for efficiency determination will be used in this paper to demonstrate the relation between the rotational speed and applied torque. This load profile for an input-output method of efficiency determination is still based on six loading points (or eight loading points for motors driven by converters) and was further modified to study the influences of the speed variation at the constant load points. The load profile includes the feature which is optimised from the test sequence used for the torque calibration under static conditions.

The objective of this study is to explore the influences of rotational operation and temperature on torque measurements and hence their effect on the direct efficiency determination (IEC 60034-2-1 [6]) of the four-pole squirrel-cage asynchronous machine (ASM) (Table 1). To further investigate the dependencies, the efficiency determination of the ASM at speeds of 150 min^{-1}, 500 min^{-1}, 1 000 min-1, and 1 500 min-1 under varying torque load conditions is presented.

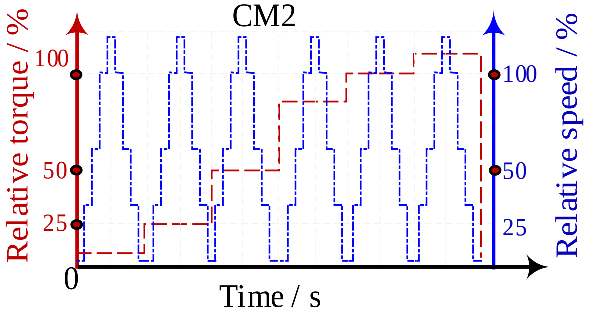


Figure 1: Stepwise changes of the load torque at different rotational speeds for efficiency measurement based on [6], [7], and [8]

In the applied method, the efficiency of the rotating ASM operating in generator mode is determined by directly measuring the electrical power P_{elec} and the output power P_{mech}. The subscript G is used in this paper to denote generator mode operation.

$$\eta_{d\_\mathrm{G}} = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \frac{P_2}{P_1} = \frac{P_{\mathrm{elec.G}}}{P_{\mathrm{mech.G}}} = \frac{\sqrt{3} \cdot U \cdot I \cdot \cos(\varphi)}{2\pi \cdot n \cdot M} \qquad (1)$$

where n is the operating speed in revolutions per minute (min-1), M is the torque in N·m, and the electrical quantities are represented as voltage U, current I, and power factor (p.f.) $\lambda = \cos\,\varphi$.

2.1. Specification of Torque Transducers with Rotating Electrical Machine on Small-Scale Test Bench (SSTB)

The rated nameplate parameters of the ASM and the torque sensors used in this paper to analyse efficiency measurement with a focus on the influence of rotation and temperature on torque measurements are shown in Table 1 and Table 2, respectively.

Table 1: Rated datasheet parameters of the ASM

Power / kW	Torque / (N·m)	Speed / min^{-1}	p.f.	η / %	IE class
160	1028	1485	0.82	95.9	IE3

Table 2: Rated datasheet parameters of the T10F and T12HP torque sensors

Sensor type	Rated torque M_{n} /(kN·m)	Max. speed / min^{-1}	Temp. effect /(%/(10 K))	Frequency output / kHz at:		
				0 N·m	$+M_{\mathrm{n}}$	$-M_{\mathrm{n}}$
T10F	3	10 000	± 0.05	10	15	5
T12HP	2	12 000	± 0.005	60	90	30

A photographic representation of the basic experimental setup of the 200 kW small-scale test bench with different measuring instruments, including a test ASM and two series-connected torque transducers (T12 HP and T10F), is shown in Figure 2. The ASM runs continuously until thermal stability (i.e., rate of change of temperature is ≤ 1 K per half hour) is obtained and referred to as heat run in this study. The surface temperature is measured using a temperature recorder (Yokogawa HB 8000). All the electrical quantities (such as voltage U, current I, and power factor $\lambda = \cos\varphi$) are displayed on the power analyser (Yokogawa WT5000) together with the measured electrical power P_{elec}. Similarly, the mechanical quantities such as torque M and speed n are measured using HBK torque sensors (type T12HP and T10F) and used to determine the mechanical power P_{mech}. The power analyser (PA) time interval for the data acquisition of electrical and mechanical quantities was set to 0.5 s with 16 points moving averaging.

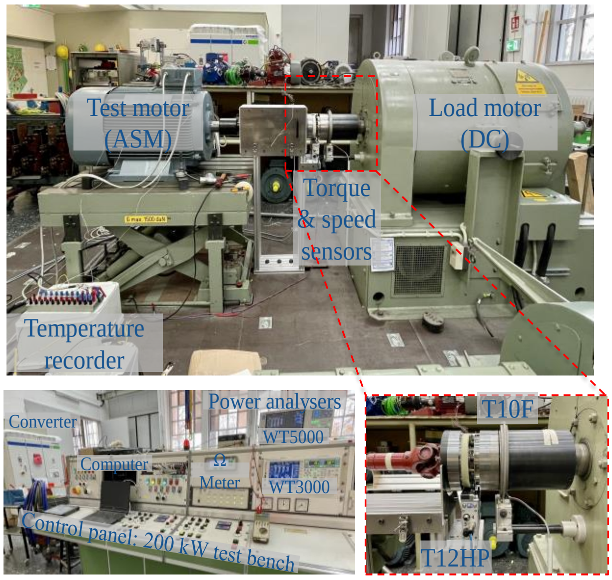


Figure 2: Photographic representation of the small-scale test bench (SSTB) for torque measurements with varying ASM rotation speeds

2.2. Setting in PA with Torque Sensor CC for Torque Measurements under Rotation in SSTB

In this paper, the motor evaluation function available in the PA [9] is used for computing the torque values for the pulse input torque signal from torque transducers using equation (2).

$$M = S\,(A\,X + B) - Null \qquad (2)$$

where S is the scaling factor, A the torque pulse coefficient, X the pulse frequency, B the torque pulse offset and $Null$ the null value.

The torque pulse coefficient and torque pulse offset are determined from the torque signal pulse rating as shown in Figure 3 and the experience of the test bench operator to minimise the torque offset value (zero balancing). The graph shows the relationship between the torque signal pulse input range and the pulse rating configured based on the static calibration certificate (CC). In addition, Figure 4 compares the relative measurement uncertainty with a coverage factor of k = 2 for the T10F and T12HP transducers taken directly from the static CC based on DIN 51309 [4].

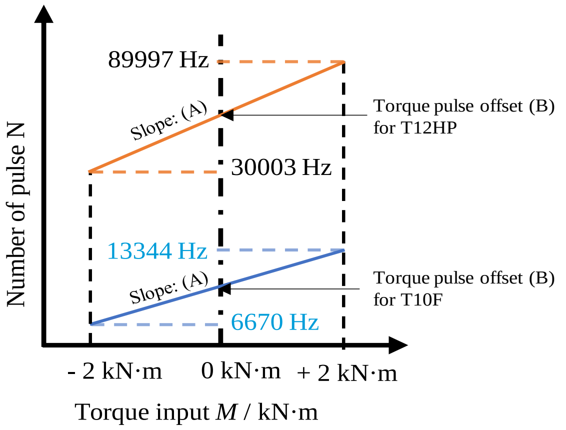


Figure 3: Pulse input range setting in WT5000 for pulse input signals of the T12HP and T10F torque transducers (connected in series)

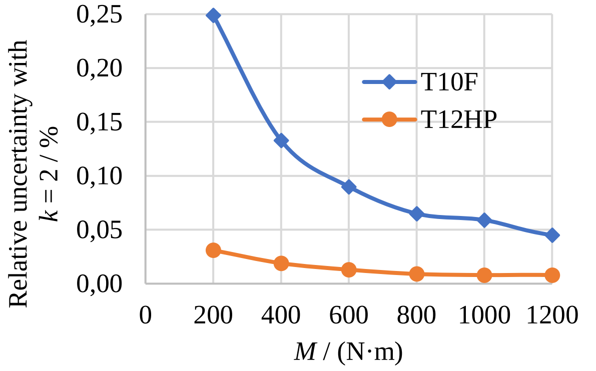


Figure 4: Comparison of expanded relative measurement uncertainty with a coverage factor of k = 2 and linear regression for T10F and T12HP

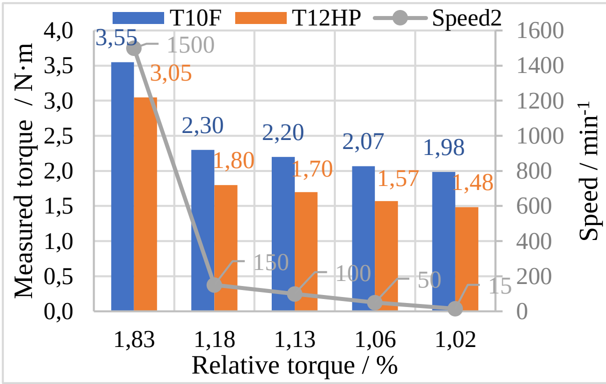
The configuration of the pulse input range and the pulse rating settings of the torque sensors in the WT5000 strongly influences the torque and speed values. Therefore, a zero balancing as described in [10] of the torque transducer and null function as mentioned in the user manual of Yokogawa WT5000 is required as shown in Figure 3 and Table 3.

Table 3: Configuration of pulse input range and pulse rate settings of T12HP and T10F

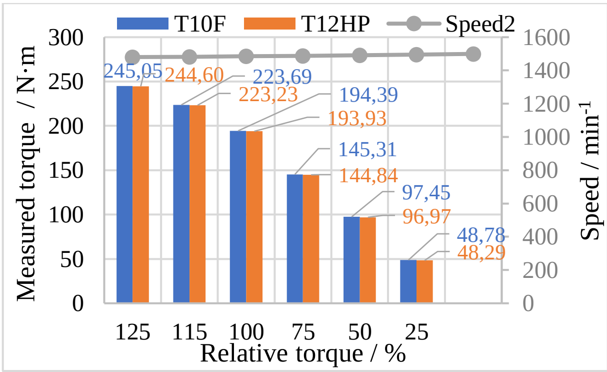
Channel setting (unit)	Torque sensors			
	T10F		T12HP	
	Torque 1	Speed 1	Torque 2	Speed 2
Pulse Range Upper	2 000	1 000	2 000	1 000
Pulse Range Lower	-2 000	0	-2 000	0
Rated Upper / (N·m)	2 000		2 000	
Rated Freq Upper / Hz	13 344		89 997	
Rated Lower / (N·m)	-2 000		-2 000	
Rated Freq Lower / Hz	6 670		30 003	
Number of pulses N		360		600

2.3. Torque Measurement with Varying Speeds

The first step was to test the ASM without load and at varying speeds using the load machine on the SSTB. This served to show the effect of varying speed on the torque measurement by looking at the torque offset values. Similarly, the ASM was loaded with different torques at contact speed (1 500 min^{-1}) to show the torque deviation between the two torque transducers on the SSTB. The measured torque values from the torque transducers at varying speeds are shown in Figure 5a at no load. Figure 5b shows the measured torque values under loaded conditions at constant speed in the SSTB. Although the torque transducers have a nominal value of 2000 N·m, they were loaded only up to around 250 N·m as the aim was just to show the offsets between the torque values.



(a) Offset torque at varying rotational speeds (15 min^{-1} to 1 500 min^{-1}) at cold ASM for T10F and T12HP with out any load applied



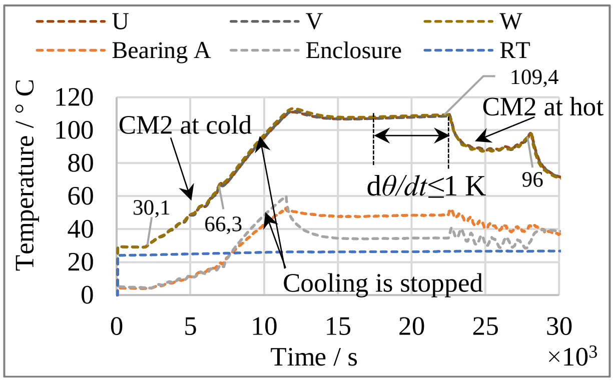
(b) Deviations of torque at a constant rotational speed of 1 500 min^{-1} for T10F and T12HP with different relative torques

Figure 5: Deviations of the torque transducers at varying rotational speeds from 15 min^{-1} to 1 500 min^{-1}

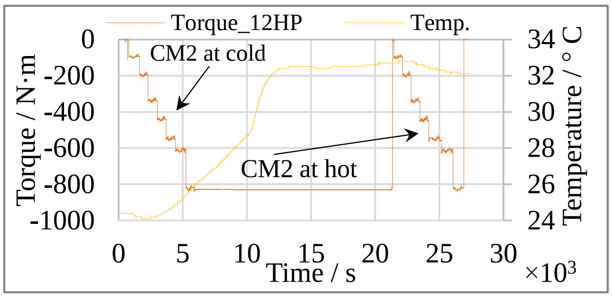
The zero torque drift values from the torque transducers as a function of speed are shown in Figure 5a. This zero torque drift value adjustment was done separately for each transducer. However, its effect on the torque sensitivities and characterisation with respect to temperature is not discussed in this paper.

2.4. Thermal Quantities for Direct Efficiency Determination in Generator Mode on the SSTB

The temperature rise curves measured at different points in the test ASM are shown in Figure 6a. The ASM was initially operated at RT and continuously run in generator mode until steady-state values (thermal stability) at the winding temperature of the DUT were reached as presented. The load profile (CM2) was measured first in the DUT when in a cold state and again after the steady state was achieved. The two states are denoted as “CM2 at cold” and “CM2 at hot,” respectively, in Figure 6a. Similarly, for a visual representation of the influence of temperature on torque measurement, consider Figure 6b, which plots torque values on the CM2 profile against temperature at the cold and hot states using the inbuilt sensors (torque and temperature) of the T12HP torque transducers. The torque transducers are constructed with spring elements combined with strain gages and compensation elements as well as adaptation accessories to minimise the effects of temperature variation on the output signal [11]. However, the temperature curve indicates that there is a variation of around 1 °C to 2 °C when the CM2 profile is applied.



(a) Measured temperature for stator winding (U, V, W), enclosure and bearing of ASM compared to RT



(b) Measured temperature and torque values from T12HP

Figure 6: (a) The measured temperature curve until steady-state values are reached, with CM2 profile for ASM; (b) HBK T12HP torque and temperature measured in CM2 profile from cold to hot state in generator operation

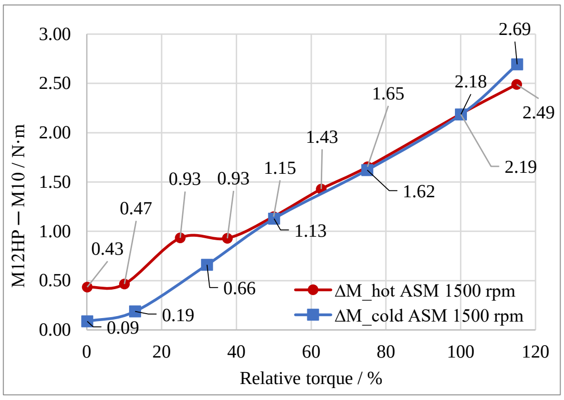
3. RESULTS OF TORQUE MEASUREMENT UNDER ROTATION FOR EFFICIENCY DETERMINATION

3.1. Dynamic Torque Measurement Results for Varying Rotational Speeds and Influences on Direct Efficiency Determination

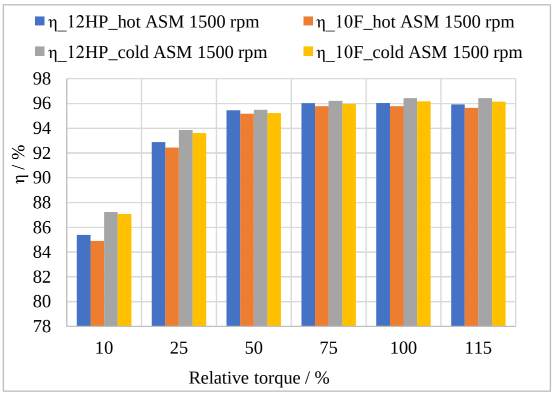
Besides rotational speed, the influence of the temperature on precision torque measurement is one of the important measurement constraints affecting efficiency determination on SSTBs. Keeping this in mind, the torque measured on the proposed small-scale test bench was used to investigate the impact of temperature and speed on sensors during load operation and on efficiency determination in the CM2 profile (cf. Figure 1). The influence of the adapter between T10F and T12HP can be directly seen from the comparisons of the T10F transducer’s static calibration (Figure 4). When the additional length of the adapter and length of the T12HP are connected in series and calibrated, the deviation is larger than when only the T10F is calibrated.

The effect of rotating speeds and the heating of ASM and transducers on the readings of the torque values and the direct efficiency determination is presented in Figure 7. In the first measurement round, ASM with the reference torque transducers connected in series was rotated at 1 500 min^{-1}. Initially, the measurement was done with varying load (relative torque) when the ASM was in a cold state. The torque values are different for each load step as defined in IEC 60034-2-1 [6] for generator mode Similarly, the ASM was run till it reached the steady state condition and again the measurement was done with varying load, and it is mentioned as the hot state measurement of torque and efficiency as shown in Figure 7a and Figure 7b. Finally, at 500 min^{-1} the final measurement was done with varying load cycles during cold and hot states and proceeded as in the previous round as shown in Figure 7c and Figure 7d.

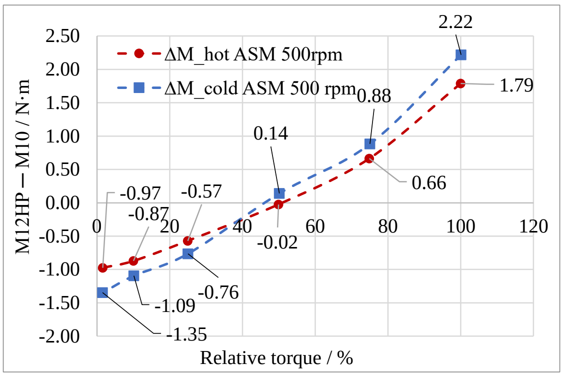
The direct efficiency determination method in generator mode is depicted in Figure 7b and Figure 7d at 1 500 min^{-1} and 500 min^{-1} respectively. In this measurement scenario, the efficiency is taken as a reference for the two operating speeds to study the influences of speeds on the torque measurement. As can be seen in Figure 7a and Figure 7c the effect of temperature on the readings of the torque transducers was proportional to the increase in load torque in the machines at both speeds (1 500 min^{-1} and 500 min^{-1}). The total efficiency of electrical machines is directly influenced by the temperature distribution during the operations as shown in Figure 7b and Figure 7d. With the increased operation time of the electrical machines with full load operation, the temperatures of the housing, stator core, winding copper core increases non-



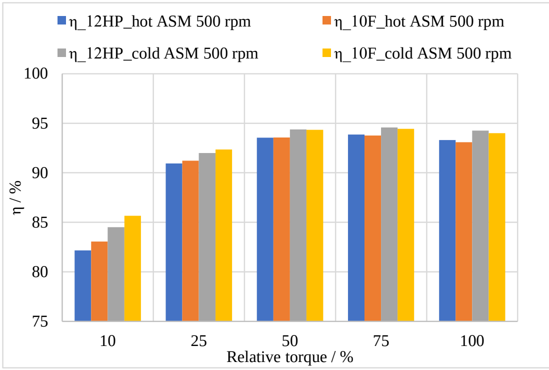
(a) Torque deviations at a rotational speed of 1 500 min^{-1}



(b) Efficiency deviations at a rotational speed of 1 500 min^{-1}



(c) Torque deviations at a rotational speed of 500 min^{-1}



(d) Efficiency deviations at a rotational speed of 500 min^{-1}

Figure 7: Experimental investigation of rotating torque transducers showing the influence of temperature and its impact on efficiency η determination

linearly as shown in Figure 6a. The effect of temperature directly influences the losses, which are the main factors affecting the total efficiency of the machines and the system too including the torque transducers. Therefore, the direct efficiency determination of the machines is higher in the cold state compared to the hot state at both speeds.

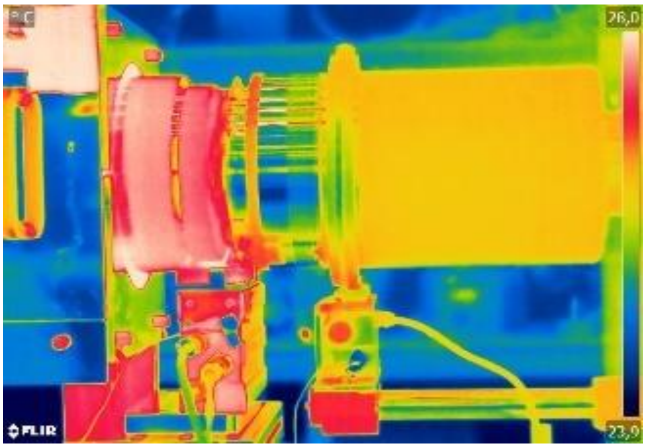
3.2. Temperature Effect on Exact Torque Measurement and Influence on Efficiency Determination

It was possible to further explore the influence on efficiency determination by examining thermal images and their relation to the measured values from the torque transducers. The thermal images of the torque transducers were captured initially with the ASM in a cold state after loading as shown in Figure 8a and then again when ASM had achieved the steady state and the loading profile was completed as shown in Figure 8b. Supplementing the thermal images, we further explored the possibility of measuring temperature variation by means of additional thermoelements during continuous transducer operation, as shown in Figure 8c. The temperature rise curves measured using thermoelements at points shown in Figure 8c in the test T10F and T12HP torque transducers are shown in Figure 8d.

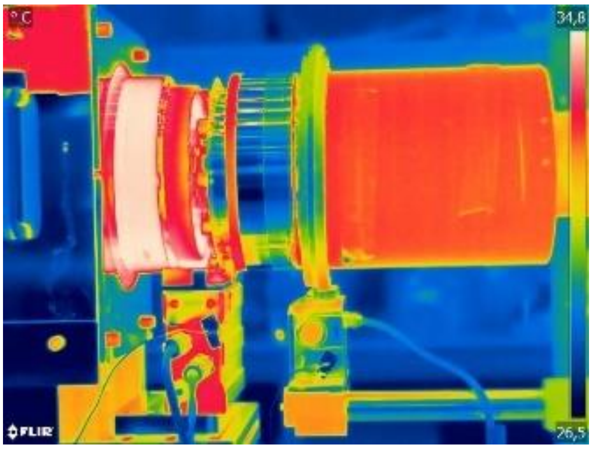
The temperature distribution of the torque transducer can be seen in the thermal images of the test ASM in a cold vs. hot state. The fluctuation is less than 8 °C, as is evidenced by the thermal images and by the temperatures measured by the thermoelements. This means that the strain gauge in the torque transducers should be able to compensate for increased temperature during prolonged operation and decrease torque measurement uncertainty. In our future research, we intend to concentrate on torque measurement while factoring temperature (and also humidity) into the uncertainty calculation. The effect of temperature on torque transducers HBK T12HP can also be seen in Figure 6b above, which shows how temperature variation influences measured torque after around nine hours of operation. The thermal images are only able to show the tentative temperature difference in the torque transducers measured before and after the ASM reached the steady state.

The efficiency of a rotating electrical machine varies with the measured torque and the rotor speed. To achieve measurement traceability and repeatability on test benches, it is desirable to conduct efficiency measurement with a focus on the torque measurements while taking account of the influences of temperature and rotational speed.

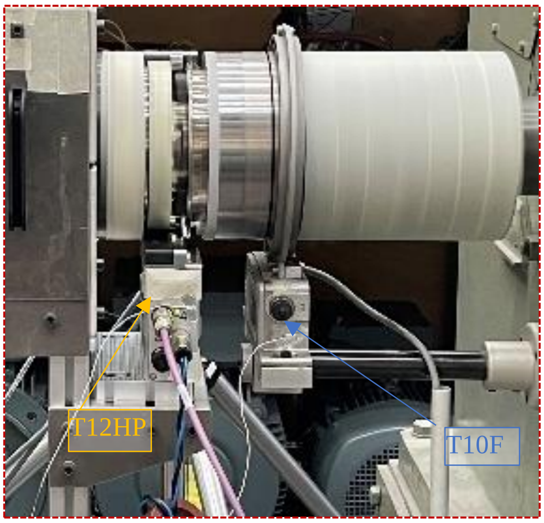
Theoretically, it is assumed that the temperature effect is compensated by the torque transducers and that machine efficiency can be measured at any speed and temperature desired. But in practice the torque-speed curve of the load driven by the machines under test also needs to be considered along with the influences of temperature. The differences in efficiency of a rotating electrical machine are reflected in the significant differences in the same load profile measured in two different states as can be seen in Figure 9a and Figure 9b.



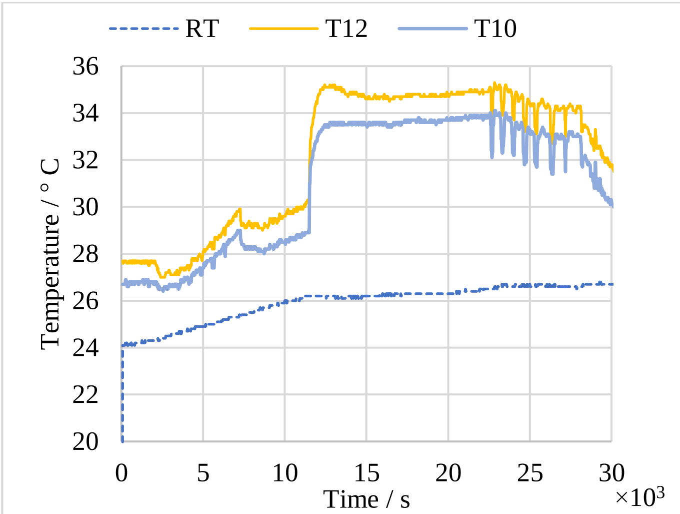
(a) Cold torque transducers HBK T12HP and HBK T10F



(b) Hot torque transducers HBK T12HP and HBK T10F

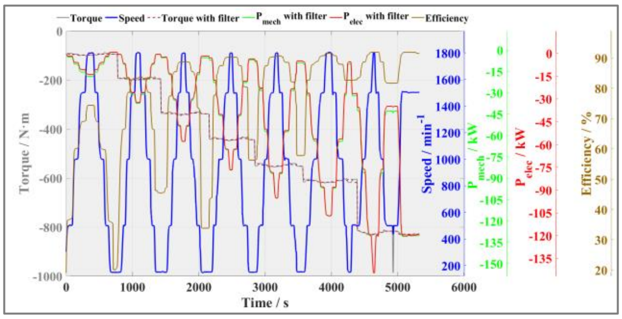


(c) Photographic representation of transducers

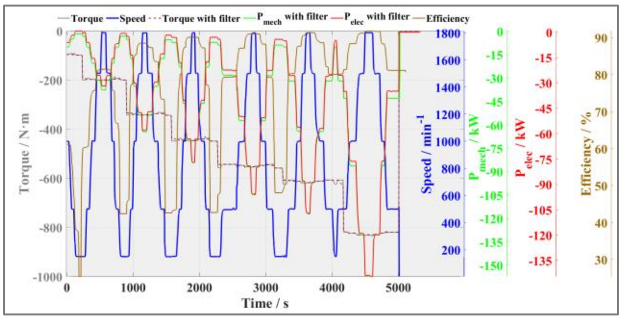


(d) Additional thermoelement measurement at transducers

Figure 8: (a) Temperature distribution of torque transducers HBK T12HP and HBK T10F on 200 kW small-scale test bench in cold state; (b) after steady-state operation, i.e. 9 hours operation time; (c) photographic representation of transducers with additional thermoelements; (d) continuously measured temperature using additional thermoelement at T12HP and T10F



(a) CM2 cold generator

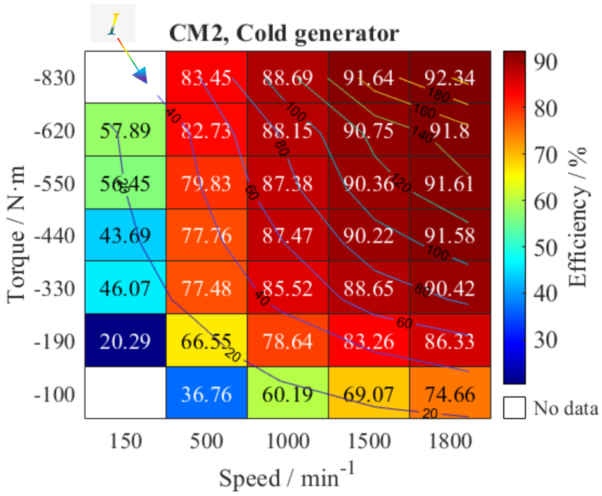


(b) CM2 hot generator

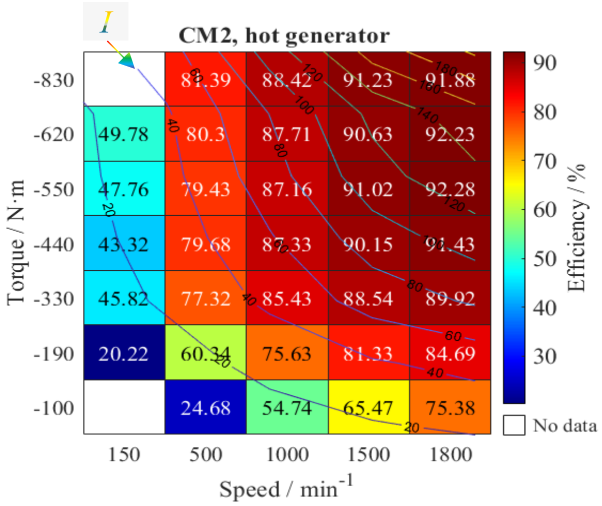
Figure 9: The measured electrical and mechanical power used to determine machine efficiency in the (a) cold and (b) hot states on the CM2 profile

3.3. Exploring the Efficiency of Electrical Machines with Focus on Torque Measurements on an SSTB

For a visual representation of the influence of temperature on the efficiency measurement of an ASM, the reader is referred to the maps in Figure 10a and Figure 10b. The efficiency maps of a test electrical machine (ASM) were plotted for efficiency determination using data from the direct measurement of electrical and mechanical power at various rotor speeds and electromagnetic torques and with the machine at different temperatures. The results are shown in Figure 10. As can be seen from these two efficiency maps for the proposed load profile, the effect of rising temperature after the thermal steady state is reached in the test ASM is visible in the total efficiency of the machines at every load step.



(a) Efficiency map with contour lines of the total stator current using cold torque transducer HBK T12HP



(b) Efficiency map with contour lines of the total stator current using hot torque transducer HBK T12HP

Figure 10: Efficiency maps of electrical machines at RT including the effects of temperature rise when the machine is in a cold state (a) and hot state (b)

As shown in Figure 6 above, the temperature of the test ASM rose by around 40 °C on the SSTB during continuous operation before reaching a steady state. It was found that the temperature difference is around 35 °C for cold and 10 °C for hot profile measurements. The overall measurement results show that the net result is a change in efficiency distribution due to temperature rise. After accounting for the effect of temperature increase, we can observe a reduction in the total efficiency of the test ASM for every step of average torque values for the same range of stator current values. The results help us to better evaluate the suitability of the efficiency determination method for rotating electrical machines during continuous operation in any sort of application. It enables users to get an accurate picture of the efficiency of the machines they are planning to use in the application of interest.

The two efficiency maps in Figure 10 also include horizontal contour lines that depict total stator current to show the correlation of torque and current. A reasonable agreement of the hot and cold state current values needed for generating the desired torque is revealed, and the decrease in total machine efficiency is evidenced by the reduction, after factoring in the effect of temperature rise, in the average ASM torque values for the same range of stator current values. Even though the total stator current, torque values, and efficiency of the machines are plotted in the cold and hot states, it is still difficult to exactly determine the influence of temperature on the torque transducers and their compensating function. In our future research, we therefore intend to concentrate only on the torque transducers to investigate the influence of temperature on torque measurements and on the compensating capabilities of the transducers.

A lower temperature in the rotor and stator of the test ASM results in lower rotor and winding losses and hence exerts a positive effect on efficiency, but at the same time fails to reflect real-world operations. To avoid these misleading effects, the ASM usually needs to be ramped up to a thermal steady state before applying the load profile for the efficiency determination test. The findings suggest that this approach of thermal steady state could also be useful for accurately characterising rotating electrical machines at varying speeds.

4. SUMMARY AND CONCLUSION

The purpose of this paper was to examine the traceability of efficiency measurements performed via torque measurement under the influences of rotation and temperature in industrial applications. Calibrating torque transducers with torque measured under rotation is very important for the zero balancing of the torque in order to reduce the offset values of torque transducers when operating under rotation.

The primary focus of this paper was to study the dynamic behaviour of torque transducers under the influences of rotational speed and temperature during operation and how this impacts on overall efficiency. Moreover, two torque transducers (T12HP and T10F) with specifications as shown in Table 2 were connected in series to obtain a better understanding of the effects. A comparison between the two torque transducers at dynamic loads and under rotation was achieved by testing the synchronisation of signals with additional transducers.

We investigated how increases in temperature during continuous operation influence the variation of electromagnetic torque and examined the losses of iron and copper at different rotor speeds. Such analyses can be used to more exactly determine the efficiency of rotating electrical machines on an SSTB for a test machine. A comparative study of the temperature rise under continuous operating conditions at constant speed makes it easy to accurately determine the efficiency of the machines and choose a suitable cooling method. Examining the efficiency map of the test machine in the cold state and hot thermal state after accounting for temperature rise allows us to trace efficiency determination and to make a refined judgment on the machine's performance in the context of an intended application.

5. ACKNOWLEDGEMENTS

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