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Measurement uncertainty analysis and challenges associated with the instrumentation of rotating electrical machine test benches for electric vehicle powertrain applications

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Summary

Rotating electric machine test benches used for testing electric drive systems in the automotive industry consist of different kinds of sensors and instruments for measuring and analyzing the performance of different components in electric mobility systems. Even if rigorous, tests performed on the test bench may deliver useless results if the measurement instruments are not configured properly. Efficiency measurements of the electric drive system in the test bench with various speed and torque values are a critical part of analyzing the performance and quality accuracy of the power train units of electrical vehicles (EVs). In this paper, different kinds of experiments are performed on the test bench to calculate its efficiency, with a focus on the measurement uncertainty (MU) values at various speeds and torques.

Keywords: AC motor, efficiency, EV (electric vehicle), inverter, motor, power, torque, uncertainty

1 Introduction and Motivation

In EV applications, the production process of the rotating electrical machine and converter starting from designs, calculations, simulations, and prototypes requires that a series of tests be performed on test benches. This process entails enormous challenges regarding the high and low speeds and torques of such machines and converters, as well as the significant power they consume. As found in the automotive industry, test benches for electric drives consist of different kinds of sensors (torque M and speed n) and instruments for measuring and analyzing the performance of converter-fed rotating electrical machines. An essential requirement (and a major challenge) for characterizing the performance of a given electric drive system is that test results from electric mobility systems that have different instrumentation settings must be understandable and interpretable. Even if rigorous, tests performed on a test bench may deliver useless results if the measurement instruments are not configured properly. This paper investigates the electrical power losses and efficiency of converter-fed electrical machines on a test-bench with a focus on measurement uncertainty (MU) values. The effects of different settings of the measurement instruments are analyzed and a new technique is proposed for varying measurement speed and torque values to allow better test-bench settings to be achieved for electric vehicle powertrain applications. The results are critical for allowing the performance, quality and accuracy of powertrain units to be evaluated. In addition, different complex experiments concerning M and n are performed on the test bench and evaluated in detail. Such experiments and evaluations are very important for the development process of electrical machines and converters.

2 Experimental Methodology and Procedure for Dynamic Testing of Electrical Machines on Test Benches

Experimental results presented as efficiency maps for inverter-fed electrical machines with a wide range of torques and speeds are an important tool for analyzing the performance of electric vehicles (EVs). Information on the efficiency maps together with additional information on the EV battery allows an accurate driving range to be predicted for electrical vehicles. Measurements with more than the standard measurement points help engineers understand the dynamic behaviors of the system. Different publications and standards have shown the best options and minimum measurement points for measurement. However, measurements performed with between a few and several hundred measurement points may be rendered useless if the measurement devices are not configured properly. Therefore, in this paper, results are presented for a critical set of measurement points for which the settings of the instruments and sensors are varied. Changes made to the settings of the individual components on the test bench while the rotating machines are undergoing testing are very important for the complete vehicle system evaluation during the development process. This paper focuses primarily on the power analyzer and torque sensor used to measure the input and output power of the test bench. Furthermore, power-loss measurements (including efficiency measurements) focusing on measurement uncertainty values at various speeds and torques are presented for the converter-fed electric machine in the test bench by considering all the equipment used for carrying out tests, quality control, and final inspection of the propulsive structure.

2.1 Proposed Six Measurement Points Modified from Those Described in IEC 60034-2-3

Test methods for determining the losses and efficiency of converter-fed electrical machines have been mentioned in two international standards – IEC 60034-2-3 [1] and IEC 61800-9-2 [2] – as presented in Figure 1. These standards have proposed loss and efficiency measurements at eight measurement points by varying both speed and torque. However, the standards contain little or no information on changing the order of applying the torque and speed when testing converter-fed electrical machines. This paper investigates the cause/effect relation of speed/torque variation on power loss and efficiency. The six points in Figure 2 are used to study the power losses of the system associated with different instrument settings. The power loss measurements of electrical machines for different load torques and speeds are also used to determine efficiency using the direct efficiency method. Finally, the uncertainty evaluation of the experiments is used to analyze the results.

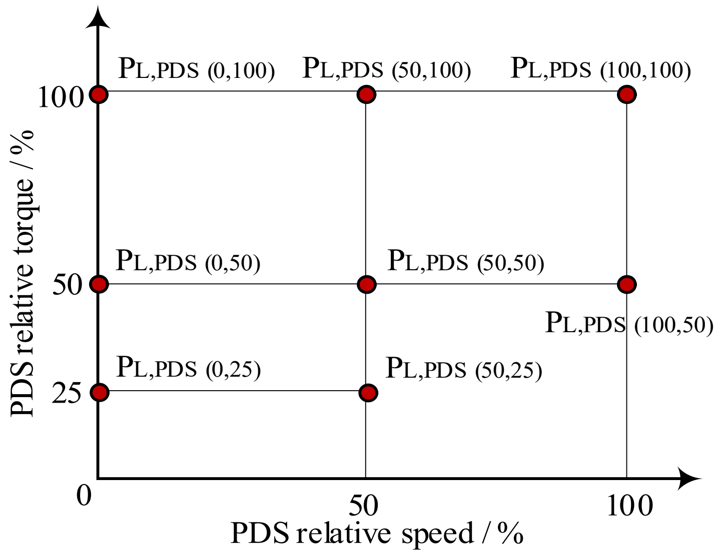


Figure 1: Proposed efficiency measurement as described in IEC 60034-2-3 [1] and IEC 61800-9-2 [2].

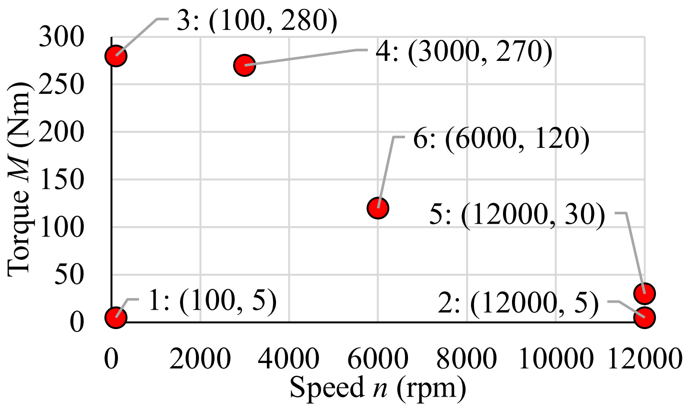
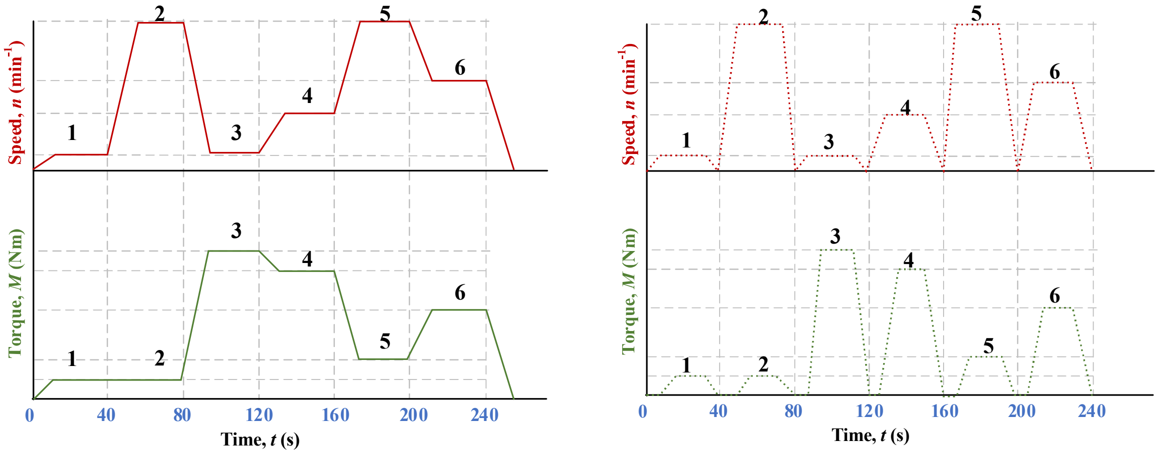


Figure 2: Six measurement points (① to ⑥) for dynamic testing of the rotating inverter-fed electrical machine on the test bench.

2.1.1 Experimental procedures to apply speed and torque on the test bench for the proposed six measurement points

The six measurement points (MPs) for dynamic testing shown in Figure 2 are further described using the ramp diagram shown in Figure 3. This diagram explains how the torque and speed are applied to the test bench in different steps that are described in further detail in Table 1.



(a) Experimental procedure 1.

(b) Experimental procedure 2.

Figure 3: Experimental procedures to apply speed and torque to the inverter-fed rotating electrical machine on the test bench

As a known fact, the transient behaviors of the torque and the speed may negatively influence the reading on the measurement instruments and could occur some problems in the measurements results. Therefore, in experimental procedure 1, the torque and speed are applied at the same instant in time, as shown in Figure 3 (a). This is in contrast to experimental procedure 2, wherein the speed is initially applied to the desired value and the torque is then applied after the steady-state value of the speed is reached as shown in Figure 3 (b). Finally, the quantities are measured and the speed and torque are again set to zero and prepared for the next measurement point (MP).

Table 1: Experimental procedures to apply torque and speed operating conditions

Experimental procedures	Description of operating conditions of torque and speed during the experiment
1	During the test, the torque is applied in parallel with the rotational speed
2	After the speed has been applied, the torque is applied and maintained. After the measurement, the torque is set to 0 Nm and the speed is lowered to 0 rpm.

2.1.2 Experimental setup for power loss measurements of rotating electrical machines and specification of instruments

The schematic block diagram of the basic test setup with different measurement instruments including a test rotating electrical machine is shown in Figure 4. The loading machine (DC machine) is capable of testing rotating electrical machines with a nominal rated load as well as various load conditions at various speeds. In this paper, the power-loss measurement of the test bench (inverter and test machine) is presented for various speed and load conditions. The entire loss measurement process for the test bench including the thermal stability measurement is monitored and controlled by a real-time control test system. During the test, the surface temperature of the device under test (DUT, i.e., the blue dotted box) is continuously measured. The DUT is continuously run until thermal stability is achieved. Thermal stability is achieved in the test machine (DUT) once the rate of temperature change is ≤ 1 K per half hour at the hottest point. The surface temperature is measured using a temperature sensor. All AC electrical quantities (such as voltage U, current I, and power factor $\lambda = \cos \varphi$) and DC electrical quantities (voltage U_{DC}, current I_{DC},), as well as the measured electrical AC power P_{elec} and DC power P_{DC} are displayed by the power analyzer (Yokogawa WT 1800). Similarly, the mechanical quantities such as torque M and speed n are measured using a torque sensor (HBM T12) and angular speed sensors (AK ERM 220). These quantities are used for the measurement of the mechanical output power P_{mech}.

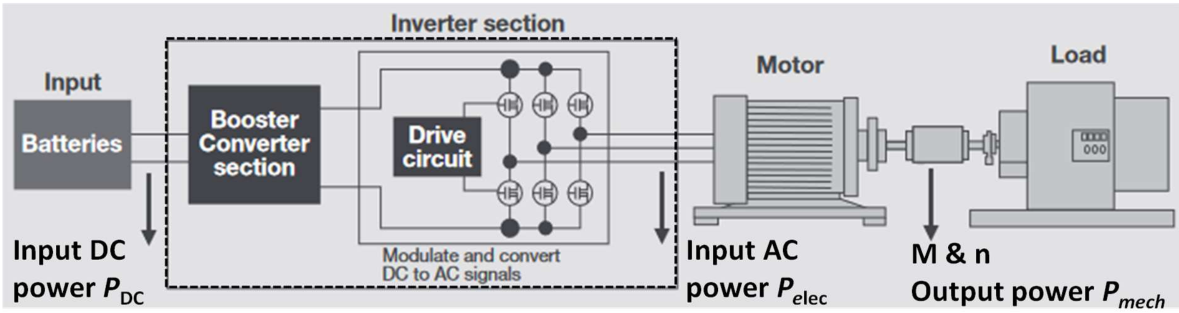


Figure 4: Graphical representation of total system input/output power dissipation for efficiency measurement of the inverter-fed electrical machine in the test bench based on [3] for hybrid electric vehicles (HEVs), electric vehicles (EVs), and plug-in hybrid electric vehicles (PHEVs).

Similarly, the electrical instrument and sensors used in this paper to measure electrical and mechanical quantities are summarized in Table 2 with their rating values and manufacturers. The setup used in the instrument and sensors plays a very important role in the power loss measurement results and MU values.

Table 2: Instrument and sensors used for measurements on the 200-kW test bench.

Instrument and sensors	Name	Rating	Manufacture
Power measurement	WT1800	1.5 - 1 kV; 100 µ A to 55 A	Yokogawa
Torque measuring flange	HBM T12	1000 Nm	HBM i.e., HBK
Current transducer	ITN 1000-S	1000 A	LEM
Speed sensor (Modular encoders)	AK ERM 220	18000 rpm	Heidenhain

2.1.3 Instrument measurement settings

To understand the variables which have the greatest influence on power losses and efficiency during the operation of the test bench for the six measurement points, different instrument settings are configured for the power analyzer (WT 1800) and torque sensors (T12) as shown in Table 3.

Table 3: Experimental configuration for power loss measurements with different levels of rotational speed n (rpm) and output torque M (Nm) in different instrumental setups.

Setting	Description
I	Old measurement with fixed range (1kV/1kA) and line filter (1 kHz) / HBM T12 (10 Hz)
II	Old auto range setting instead of fixed range in power analyzer WT 1800 with reduced HBM resolution error
III	New measurement fixed range HBM 1kV and 1kA
IV	New measurement auto WT 1800 and HBM T12

2.2 Theoretical Background and Overview of Power Loss Measurements on Test Bench

Mechanical power measurements are based on speed and torque measurements. The mechanical power P_{mech} of the rotating electrical machines is measured by multiplying the transient torque $M(t)$ by the transient rotational speed $n(t)$ and averaging the product over a time interval T (in seconds). AC power P_{elec} is measured by multiplying the instantaneous voltage by the instantaneous current then accumulating and integrating the voltage over a specific period. DC power measurement is relatively simple, using the equation watts = volts x amps.

Table 4: Measuring equipment and different power measurements with equations used for total system power dissipation measurements

Measuring equipment	Quantities measured	Equation used	No.
Power analyzer, torque measuring flange, speed sensor (modular encoders), current transducer	Mechanical power measurement	$P_{mech} = \frac{1}{T\int_0^T M \cdot \omega dt}$	(1)
	AC power measurement	$P_{elec} = \frac{1}{T\int_0^T U \cdot I \cdot cos\,\varphi \cdot dt}$	(2)
	DC power measurement	$P_{DC} = U_{DC} \cdot I_{DC}$	(3)
Result	Power loss	$P_{loss} = P_{DC} - P_{mech}$	(4)

2.3 Power Loss Measurements from the Aspect of Measurement Uncertainty

This section presents methods of determining the measurement uncertainty for power loss measurements using the GUM (Guide to the Expression of Uncertainty in Measurement [4]). GUM Workbench, a software program from Metrodata GmbH, is used in this paper to evaluate measurement uncertainties. This software is based on ISO GUM and implements a systematic method of analyzing an uncertainty problem for single and multiple results. Evaluation of the MU is an important task for test bench operators to determine appropriate and correct accuracy measures for power loss measurements and their deviation quantities. This is useful for obtaining a precise efficiency map for the electrical machine. The GUM measurement model is presented in Figure 5 in a block diagram. The power loss measurements (including uncertainties) of the electrical machine are calculated in GUM Workbench using model equations taken from IEC 60034-2-1 and different input quantities from the tests and calibration certificates of the instruments used.

GUM Workbench is used to calculate the loss measurement uncertainties. This calculation depends on the sensitivity coefficients c and the standard measurement uncertainty u of each input variable x, as shown in formula (5)

$$u\,(y) = \sqrt{\sum_{i=1}^{N}\left(c_i * u(x_i)\right)^2} \tag{5}$$

In addition to the standard uncertainty, the probability density function must be specified. In the context of this work, only the normal and rectangular distributions are used. The standard uncertainty of most input variables is given as the normal distribution, whereas the rectangular distribution is assumed if the probability density distribution is unknown. In the rectangular distribution, a value with equal probability lies in the interval [x-a; x+a], which is why it is also called the uniform distribution. The normal distribution, on the other hand, has an expected value to which the greatest probability is assigned; around this value, the probability decreases with increasing distance. The normal distribution is also called the Gaussian distribution and is symmetrical to the expected value.

To accurately calculate the measurement uncertainty in GUM Workbench as shown in Figure 5, the detailed model equations from the measurement based on IEC 60034-2-1 and the uncertainty of each quantity measured (electrical and mechanical quantities) must be specified, since each measuring instrument gives the measured value with an uncertainty. For Type B, the measurement uncertainty is based on values from previous measurements, values specified by the manufacturer or values from calibration certificates. The result is presented in the GUM as the expanded measurement uncertainty. The interval covers a range of 95.45% with a coverage factor of $k = 2$.

When determining the standard uncertainties of the input variables from the calibration certificates, it is of great importance to determine a realistic value. When calibrating a measuring instrument, the uncertainty of each quantity is not given for each possible value. Therefore, one often uses interpolation to determine the uncertainties of the values that lie between the measured values. However, these values can only be used if there is a trend in the interpolation curve. For example, interpolation can be used when increased voltage results in increased measurement uncertainty (i.e., greater voltage is accompanied by greater measurement uncertainty of the voltage). However, if this relationship fluctuates, it is difficult to determine or justify a suitable uncertainty value. In this case, if the value lies between two measured points with a known measurement uncertainty, the worse of the two points is always used.

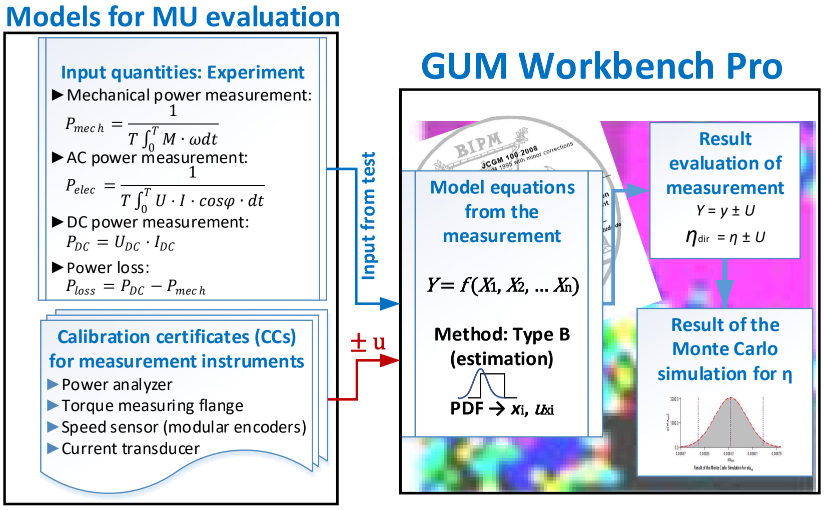


Figure 5: Block diagram of the GUM [4] measurement model based on the calibrated certificate for measurement instruments for MU for power loss measurements.

3 Comparing the Results of Power Loss Measurements Including Uncertainties Performed on the Test Bench for Rotating Electrical Machines

The power loss measurement results including MUs performed on the test bench for the converter-fed rotating electrical machine are presented in Table 5 and Table 6. The test results shown in Table 5 were performed and compared using settings III (i.e., fixed range) and IV (i.e., auto range). Detailed information on the settings of the instruments used for the measurements is described in Table 2. The results are presented with expanded measurement uncertainties (with k = 2, i.e., 95% interval) related to the power loss measurements.

Table 5: Comparisons of the power loss measurements of the converter with MU values for experimental procedures 1 and 2 using settings III and IV.

Measurement points (speed n / Torque M)	Power losses (W) in experimental procedure 1		Power losses (W) in experimental procedure 2	
	Setting III (1)	Setting IV (2)	Setting III (3)	Setting IV (4)
MP 1 (n=100/M=5)	100.5 ± 3.2	100.5 ± 0.2	137.8 ± 3.2	137.8 ± 0.19
MP 2 (n=12000/M=5)	437.3 ± 5.6	437.3 ± 4.5	427.4 ± 5.6	427.4 ± 4.5
MP 3 (n=100/M=280)	3113.3 ± 8.5	3113.3 ± 6.9	6101.3 ± 7.3	6101.3 ± 5.9
MP 4 (n=3000/M=270)	3253 ± 38	3253 ± 35	3233 ± 42	3233 ± 40
MP 5 (n=6000/M=120)	1200 ± 27	1200 ± 24	1181 ± 27	1181 ± 25
MP 6 (n=12000/M=30)	579 ± 13	579 ± 11	576 ± 13	576 ± 11

Similarly, the comparisons of the power loss measurement results with MU values for experimental procedures 1 and 2 using the different instrument settings are shown in Table 6. After performing the tests, the results are compared between setting I (standard fixed range), setting II (old auto range), setting III (fix range), and setting IV (auto range WT 1800 and HBM T12).

Table 6: Comparisons of the power losses of the converter with MU values for experimental procedures 1 and 2 using settings I to IV.

Measurement points (speed *n* / Torque *M*)	**Power losses (W) in experimental procedure 1**				**Power losses (W) in experimental procedure 2**			
	Setting I (5)	Setting II (6)	Setting III (7)	Setting IV (8)	Setting I (9)	Setting II (10)	Setting III (11)	Setting IV (12)
MP 1 (*n* =100/*M* =5)	3.4 ± 3.2	3.44 ± 0.19	100.5 ± 3.2	100.5 ± 0.2	8.3 ± 3.2	8.26 ± 0.19	137.8 ± 3.2	137.8 ± 0.19
MP 2 (*n* =12000/*M* =5)	119.5 ± 5.7	119.5 ± 4.6	437.3 ± 5.6	437.3 ± 4.5	214.1 ± 5.6	214.1 ± 4.5	427.4 ± 5.6	427.4 ± 4.5
MP 3 (*n* =100/*M* =280)	2439 ± 8.6	2438.7 ± 7	3113.3 ± 8.5	3113.3 ± 6.9	2542 ± 8.6	2542.5 ± 7	6101.3 ± 7.3	6101.3 ± 5.9
MP 4 (*n* =3000/*M* =270)	3285 ± 38	3285 ± 36	3253 ± 38	3253 ± 35	2990 ± 37	2990 ± 35	3233 ± 42	3233 ± 40
MP 5 (*n* =6000/M=120)	634 ± 27	634 ± 25	1200 ± 27	1200 ± 24	614 ± 26	614 ± 24	1181 ± 27	1181 ± 25
MP 6 (*n* =12000/*M* =30)	277 ± 13	277 ± 11	579 ± 13	579 ± 11	116 ± 13	116 ± 11	576 ± 13	576 ± 11

4 Conclusions

A novel set of six measurement points (MPs) are particularly useful for measurement uncertainty analysis and for meeting the challenges associated with the instrumentation of the rotating electrical machine test bench for electric vehicle powertrain applications. This paper has presented factors influencing measurement uncertainty as determined based on instrument settings and experimental procedures. A comparison was made of the effects of different settings of the power analyzer and the torque sensor on the output quantities including the measurement uncertainty of the rotating electrical machine concerning six measurement points. A large measurement range covered torques and speeds at start-up and for hill climbing, highway driving, overtaking and two other scenarios. In addition, the best method (setting) for achieving accurate and traceable measurements on the test bench was offered and suggested. The following conclusions are summarized on the basis of the measurement results:

- Due to a new measurement setting wherein the power factor is no longer rounded to two decimal places, the rounding error no longer affects the MU.
- The new measurement procedure yields only very small changes in the MU values. As before, the setting of the auto range for the MP 1/2/3 yields a better measurement uncertainty than a setting using fixed ranges for current and voltage. This is because the small amount of current (I_{DC}) is measured with the MP 1/MP 2/MP 3 in the high fixed range.
- The new measurement setting brings a significant change in the power loss. Here, the losses are usually much greater than with the previous procedure.

- The power factor listed in the calibration certificate has a constant expanded MU of 0.0001 (values are not in the scope of accreditation). Compared to the old measurement procedure, the MU of the new procedure is thus significantly higher for MP 1/2/3 and lower for MP 5 (similar MU for MP 4 and MP 6). Thus, this contributes significantly to a high MU for the first three measurements and to a lower MU for MP 5.

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Authors

Dr.-Ing. Nijan Yogal was born in Dhulikhel, Nepal, in 1985. He completed his M.Sc. in Electrical Power Engineering at the Technical University of Darmstadt, Germany in 2012. He complicated his PhD at the Technical University of Braunschweig, Germany in 2019. His PhD thesis was on the analysis of a permanent magnet synchronous machine with regard to explosion protection capability. He worked at Bombardier Transportation in Mannheim, Germany while doing his master's thesis, where he was employed in the field of power electronics, focusing on new semiconductor devices such as SiC MOSFET and PinFin IGBT module Si-SiC IGBT for motor converters for locomotive applications. His special fields of interest are power electronics, electrical machines and electrical drives. Since 2013, he has been carrying out research on energy-efficient rotating electrical machines (ASMs, PMSMs and SynRM) with a focus on explosion protection.

Dr.-Ing. Christian Lehrmann was born in Wolfenbüttel, Germany, in 1972. He received his Dipl.-Ing. in Electrical Engineering from the Technical University of Braunschweig in 1999. In 1999, he also joined Working Group 3.72 (then called Explosion-proof Electrical Drive Systems) at the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, as a research assistant and completed his PhD in 2006. His thesis was on type-approval procedures for explosion-protected converter-fed squirrel-cage rotors with the "increased safety" protection type. He has worked as the Assistant Head of the Explosion-protected Electrical Drive Systems Working Group since 2006, where he researches electric motors and electric drives in the "high safety" field of explosion protection. Dr. Lehrmann is a member of the working group on drive technology at the VIK (German Federation of Industrial Energy Consumers) as well as IEC TC 31 Working Group 27 focusing on electric machines (motors and generators).

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