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Review of Efficiency Measurement Standards for Wind Turbines in Nacelles Test Benches: Based on Small-Scale Test Bench for Electrical Machine

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***Abstract*— Globally there is a huge demand for clean renewable energy sources to compensate for the energy-related carbon dioxide (CO2) emission. The widespread development of increased energy efficient multi-megawatts wind turbines is playing an important role in overcoming the demand for clean energy. Therefore, the traceable efficiency measurements for wind turbines on test benches or in the fields are very crucial and are of great interest for evaluating the usability of wind energy. However, there are currently no standardized methods available for traceable efficiency determination of wind turbines on test benches during the design phase. In this paper, the review of standards of efficiency measurements for rotating electrical machine on test benches is summarized and an innovative small-scale test bench measurement concept with results similar to nacelle test benches for wind turbines is presented.**

Keywords*— *efficiency, losses, nacelle test bench, rotating electrical machines, small-scale test bench, wind turbine

I. Introduction and Motivation

In the last few years, there has been a growing interest in installing energy-efficient wind turbines to increase renewable energy sources across the world. Since wind energy is one of the most important renewable energy sources for electrical power generation and plays a vital role for Europe to meet the 32 % of final energy consumption from the renewable energy sources by 2030 [1]. Therefore, the accurate efficiency measurement method of wind turbines is crucial and essential for obtaining the precise efficiency map of electrical power generation over its lifetime. It is an important issue for renewable energy sources because even a small amount of measurement deviation of electrical and mechanical parameters of wind turbines may result in an enormous deviation of electrical power generation. Clearly, the efficiency measurement methods for wind turbines are needed to trace the highest possible degree of efficiency of the wind power plants with the lowest possible measurement uncertainty and traceable to national and international standards.

As mentioned in the international standards IEC 61400-12-1 [2], several publications and guidelines (FGW – TG2 [3] and MEASNET Guideline [4]) have appeared in recent years documenting the efficiency determination of a wind turbine based on the power curve method. The major drawback of this approach is that the efficiency of a wind turbine is expressed as electrical power output over wind speed and based on field tests, i.e., on the wind power plant site as shown in Fig. 1. (The wind power plant consists of a rotor blades, a hub, a nacelle housing, a gearbox, an electrical generator, a power converter, and a tower). In addition, the power curve method does not consider the efficiency determination of the nacelle on a nacelle test bench (NTB). Before the nacelle is installed in the field, it must be ensured that the higher reliability of electrical power generation is possible and there should be standardized methods that could be used to test the nacelle prototypes with its efficiency. Based on the project WindEFCY "Traceable mechanical and electrical power measurement for efficiency determination of wind turbines" [5], the purpose of this paper is to focus on standards for efficiency determination of nacelles on NTBs as shown in Fig. 2. In this paper, while we refer to our earlier work [6], [7] and [8], the focus is mainly to find efficiency measurement standards for wind turbines in NTBs based on standards that are available for small-scale test bench for electrical machine.

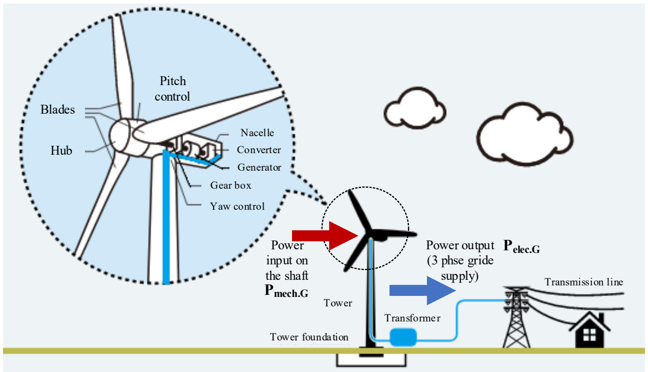

Fig. 1. Graphical representation of wind energy generation including rotor blades, nacelle, generator, tower and gride connection transmission line in the wind power plant based on [9].

The nacelle as shown in Fig. 1 is located behind the rotor and located above the tower consists of a gearbox, an electrical generator and a power converter which is also visual represented in the test set-up of an NTB as shown in Fig. 2 (a) and (b). The overview of the NTB available at Fraunhofer IWES (DyNaLab), Germany is shown in Fig. 2 (a) based on [10] where nacelle is shown as the device under test (DUT).

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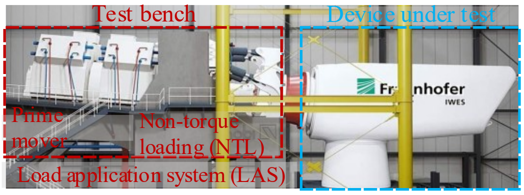
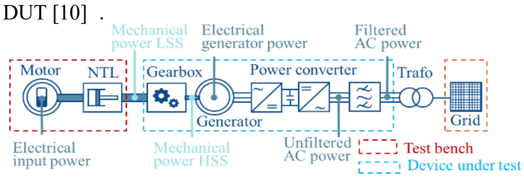


(a) Illustration of an NTB showing the load application system (LAS), consisting of a prime mover and a non-torque loading (NTL), and the DUT [10] .



(b) Schematic diagram of the set-up of an NTB including a nacelle as a DUT based on [11].

Fig. 2. Overview of the NTB (DyNaLab) at Fraunhofer IWES, Germany with schematic diagram.

II. Review of the Standards for a Traceable Efficiency Determination of Wind Turbines

The standards for a traceable efficiency determination of wind turbines can be classified as: (1) the methods based on field tests (wind power plants) and (2) the methods based on tests in test benches for nacelle drive trains. The tests in NTBs are based on rotating electrical machines standards which are further discussed below.

A. Standards for an Efficiency Determination of Wind Turbines in the Field (Power Curve Determination)

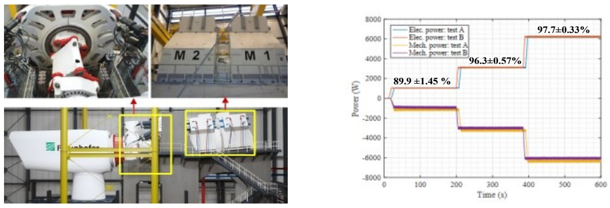
An international standard IEC 61400-12-1 [2] and several guidelines (FGW – TG2 [3] and MEASNET Guideline [4]) deal with the power curve method for an efficiency determination of wind turbines in the field. It is a procedure for measuring the power output characterization of a single wind turbine. It is a direct method where the simultaneous measurement of the averaged values of the wind speed and power output at the test site are plotted. It is an approach for the estimation of the annual power production of the wind turbine in the field.

B. Standards for a Traceable Efficiency Determination of a Nacelle based on Rotating Electrical Machines Standards

The drive train of a nacelle is a crucial component in harvesting electrical energy from wind energy using wind speed striking on the rotor blades. The efficiency determination method for nacelle drive trains on an NTB is an important issue for experimentally testing prototypes of wind turbines before they are installed in the field. It helps in the design process of wind turbine prototypes and verifies the design as well as the calculated electrical output power with the experimental measurement values. In the last few years, there has been a growing interest in standards for a traceable efficiency determination of nacelle drive trains on NTBs. However, a standardized efficiency determination method for nacelle drive trains on NTBs is not yet available. In this section, two efficiency determination methods for nacelle drive trains on NTBs based on rotating electrical machines standards that are used by different research institutes are explained:

1. ***Alternative back-to-back method for nacelle test benches***
2. ***Calorimetric method for nacelle test benches***

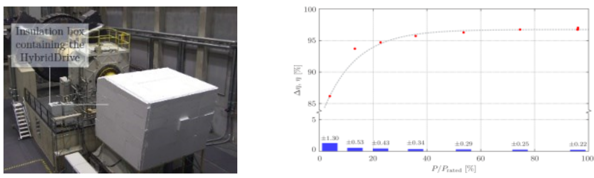
In recent publications [12] and [13], the most interesting approach of efficiency determination of a nacelle on an NTB known as "**alternative back-to-back measurement method**" as shown in Fig. 3 has been proposed. The issue of an effective method of determining the drive-train efficiency of wind turbines with a high accuracy has been proposed based on standard IEC 60034-2-1 [14]. In the standard IEC 60034-2-1 [14], it is known as the back-to-back method. This method requires two identical machines being mechanically coupled together and forming as a generator–motor set, which may not readily be available. Therefore, with some modification to the test procedure, the alternative back-to-back measurement methods with the result as shown in Fig. 3 (b) is presented in [12] and [13].



(a) (b)

Fig. 3. The 10 MW NTB ''DyNaLab'' at Fraunhofer IWES in Bremerhaven (a), with the result of the efficiency determination of rotating electrical machines on a scaled test bench (b) based on [12] and [13].

Similarly, in publication [15] it was shown (Fig. 4) that an efficiency determination of a nacelle drive train on an NTB can be performed using the large-scale **calorimetric efficiency measurement method** based on the rotating electrical machines calorimetric method standard IEC 60034-2-2 [16]. The calorimetric method for rotating electrical machines has also been presented in [17], [18], [19] and is capable of achieving quite low levels of uncertainty [20] compared to typical input-output power measurements, i.e., the direct efficiency method. However, the measurement uncertainty (MU) levels of efficiency determination of machines are higher compared to loss segregation methods, i.e., the indirect efficiency method. The main disadvantage of performing the calorimetric method for an efficiency determination on an NTB is that the thermal equilibrium of the nacelle drive train needs to be reached at all temperature measurement points. In addition, due to the larger size of the NTB, it is hard and time-consuming to perform the tests at all operating points as shown in Fig. 4 (b).



(a) (b)

Fig. 4. DUT covered by a thermal insulation box in the NTB at the Center for Wind Power Drives (CWD) at RWTH Aachen University (a) and the efficiency measurement results using the calorimetric method (b). [15]

III. Review of Standards for the Efficiency Determination of Rotating Electrical Machines

International standards regarding the efficiency measurement of rotating electrical machines in the EU, USA, Canada, Japan and Russia have been analyzed and presented in paper [21]. The different national and international standards bodies concerning the losses efficiency measurement of electrical machines are summarized in Table I below.

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TABLE I. NATIONAL AND INTERNATIONAL STANDARDS REGARDING EFFICIENCY DETERMINATION OF ROTATING ELECTRICAL MACHINES

National and International Standards	Testing for Losses and Efficiency Measurement Method	Standards Apply for
IEC 60034-2-1 [14]	2-1-1A: Direct measurement: Input-output 2-1-1B: Summation of losses: Residual losses 2-1-1C: Summation of losses: Assigned value 2-1-1D: Dual-supply-back to-Back 2-1-1E: Single-supply-back to-back …	All 1 phase machines All 3 phase machines≤2MW All 3 phase machines>2MW
IEC 60034-2-2 [16]	7.1: Calibrated machine 7.2: Retardation 7.3: Calorimetric	Special and large electrical machines
IEC 60034-2-3 [22]	2-3-A: Summation of losses with test converter supply 2-3-B: Summation of losses with specific converter supply 2-3-C: Input-output method 2-3-D: Calorimetric method	Converter-fed AC induction motors (ASM)
IEEE 112 [23]	6.3 Test method A–Input-Output 6.4 Test method B–Input-Output with loss segregation 6.5 Test method B1–Input-Output with loss segregation and assumed temp. 6.6 Test Method C–Duplicate machines …	Polyphase Induction Motors and Generators
USA: DOE 10 CFR Part 431 [24] and NEMA: MG 1 [25]	Part 12 – Test and performance of AC motors: 12.58, 12.78: Efficiency Part 21– Large machines – Synchronous motors: 21.14: Efficiency	Motors and Generator
Canada: C390-10 [26]	A very similar procedure to the IEEE112-B Standard.	Three-phase induction motors
Note: Similar regulations in many other countries, e.g., UK (British Standards (BS) BS-269), South America (COPANT), Japanese Electrotechnical Commission (JEC 37), South Korea, China, Australia (AS), New Zealand (NZS), etc. are available for different test methods for the determination of the electrical machine efficiency.		

IV. THEORETICAL BACKGROUND AND OVERVIEW OF EFFICIENCY DETERMINATION METHODS OF ROTATING ELECTRICAL MACHINES USED IN THIS PAPER

The standard for determining the losses and the efficiency of rotating electrical machines from tests are based on IEC 60034-2-1 [14], IEC 60034-2-2 [16] and IEC 60034-2-3 [22]. In this paper, we explore the possibility of an efficiency determination method on a small-scale test bench that could be easily transferred to NTBs. Therefore, the objective of this section is to explore the direct and indirect efficiency determination method and the alternative back-to-back efficiency determination method that improves existing methods with new suggestions. The rotating electrical machine efficiency determination method as mentioned in this section with measurement uncertainty (MU) calculation based on calibration certificates of the measurement instruments and the sensors was experimentally measured and presented in [6], [7], [8], and [13].

A. *Direct and Indirect Efficiency Determination Method of Rotating Electrical Machines Based on IEC 60034-2-1*

The experimental procedure for direct efficiency $\eta_{\mathrm{d,Motor}}$ determination of rotating electrical machines on test benches is carried out by measuring the input power P_1 and output power P_2 on a test machine (DUT) as in (1). Whereas, in the indirect efficiency $\eta_{\mathrm{i,Motor}}$ determination method as in (3) the actual power losses P_{loss} occurring in a test machine as in (2) are determined as shown in Fig. 5. The total dissipated mechanical output power P_2 is calculated as the difference of the sum of the separately determined losses from the consumed input electrical power P_1 based on IEC 60034-2-1 [14], which is summarized in Table(II).

$$\eta_{d,Motor} = \frac{P_2}{P_1} = \frac{2\pi \cdot M \cdot n}{\sqrt{3} \cdot U \cdot I \cdot cos\varphi} \quad (1)$$

$$P_{loss} = P_s + P_{fe} + P_r + P_{fw} + P_{LL} \quad (2)$$

$$\eta_{\mathrm{i,Motor}} = \frac{P_2}{P_1} = \frac{P_1 - P_s - P_{fe} - P_r - P_{fw} - P_{LL}}{P_1} \quad (3)$$

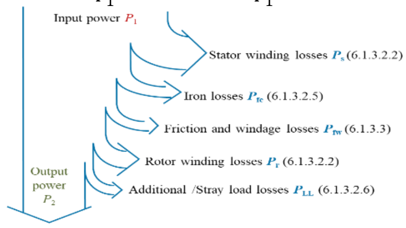

Fig. 5. Diagram describing the efficiency determination method of rotating electrical machines based on the indirect (summation of losses) method with reference chapters (clause) from IEC 60034-2-1 [14].

TABLE II. SUMMARY OF TYPES OF MEASUREMENTS AND THE QUANTITIES TO BE MEASURED FOR INDIRECT EFFICIENCY DETERMINATION OF ASYNCHRONOUS MACHINES (SQUIRREL-CAGE) WITH REFERENCE CHAPTERS (CLAUSE) FROM IEC 60034-2-1 [14]

Efficiency Determination Type of measurement method 2-1-1B, (6.1.3.2)			
Test type (Clause)	***(1) Rated load test (6.1.3.2.1)***	***(2) Load curve test (6.1.3.2.3)***	***(3) No-load test (6.1.3.2.4)***
When	In the beginning, coupled with rated load	After the test with rated load	In the beginning or at the end
Additional note	Operation until thermal steady-state ($d\theta/dt \leq 1$ K)	Before this test, the machine must be run in a thermal steady state	Resistance measurement before and after test
Points to be measured	At the rated torque	125%, 115%, 100%, 75%, 50%, 25% of the rated torque	110%, 100%, 95%, 90% 60%, 50%, 40%, 30% of the rated voltage
Results	Thermal steady-state ($d\theta/dt \leq 1$ K per 30 min.) Winding resistance at rated load	6.1.3.2.2 Stator P_s and rotor P_r winding losses, 6.1.3.3 Friction and windage losses P_{fw} 6.1.3.2.6 Additional-load losses P_{LL}	6.1.3.2.5 Friction and windage losses at no-load P_{fw0} 6.1.3.2.5 Iron losses P_{fe}
	P_{loss} an d $\eta_{\mathrm{i,Motor}}$		

B. *Alternative Back-to-Back Efficiency Determination Method for Rotating Electrical Machines*

A rotating electrical machine was tested using the alternative back-to-back method, with the machine working in motor mode and generator mode separately as shown in Fig. 6. The electrical power was kept close to each other between the two working modes as shown in Fig. 6 (b) and as in (4). All the operating points (loading points) needed to be measured considering the electrical power difference $P_{\mathrm{elec.diff}} \cong 0$ % of rated power. All the operating points should almost met twice in both operation modes.

$$P_{\mathrm{elec.diff}} = (P_{\mathrm{elec.M}} - P_{\mathrm{elec.G}}) \cong 0 \text{ W} \quad (4)$$

The overall power loss in the two modes can be expressed as in (5).

$$P_{\mathrm{loss.total}} = (P_{\mathrm{mech.G}} - P_{\mathrm{mech.M}}) + (P_{\mathrm{elec.M}} - P_{\mathrm{elec.G}}) \quad (5)$$

The motor mode efficiency can be determined as in (6)

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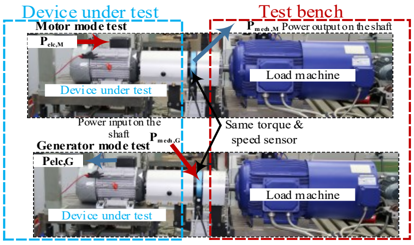
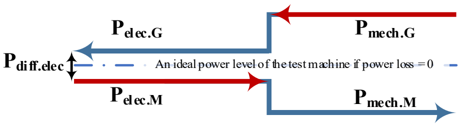
$$\eta_M = 1 - \frac{k_{\mathrm{M}} \cdot P_{\mathrm{loss.total}}}{P_{\mathrm{elec.M}}} \quad (6)$$

where,

- $P_{\mathrm{loss.total}}$ is the total power loss.
- $P_{\mathrm{elec.M}}$, $P_{\mathrm{elec.G}}$ is the electrical input and output power in motor and generator mode respectively.
- $P_{\mathrm{mech.M}}$, $P_{\mathrm{mech.G}}$is the mechanical output and input power in motor and generator mode respectively.
- k_{M} is the portion of the power loss in motor mode out of the total power loss $P_{\mathrm{loss.total}}$.
- If no further information is available, k_{M} can be simply chosen as 50 %. But in case detailed power losses are available from the indirect method of efficiency determination, this factor can be chosen accordingly. In this way the uncertainty of the adopted k_{M} can also be achieved.



(a) Photographic representation of a small-scale test bench for rotating electrical machines using the alternative back-to-back efficiency determination method showing the power flow in motor and generator mode.



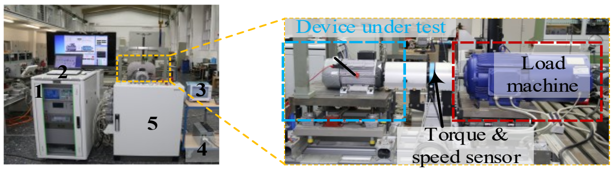
(b) Electrical and mechanical power levels of a rotating electrical machine in motor and generator mode test.

Fig. 6. Experimental setup for the alternative back-to-back efficiency determination method for rotating electrical machines based on [12] and [13] with layout of the power flow representation on the small-scale test bench.

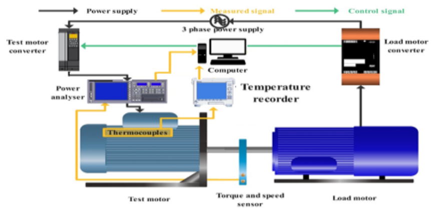
V. Experimental Methodology and Procedure for the Efficiency Determination of Rotating Electrical Machines on a Small-Scale Test Bench

A. *Experimental Setup for the Efficiency Determination of Rotating Electrical Machines and Specification of Electrical Machine*

The photographic representation and the schematic block diagram of the basic test setup with different measurement instruments including a test rotating electrical machines are shown in Fig. 7 (a) and (b) respectively. respectively. In addition, an induction machine operates as the load motor. The loading induction machine is capable of testing rotating electrical machines with nominal rated load and overload conditions with varying speeds. In this paper, the efficiency determination of a rotating electrical machines (asynchronous machine (AM) and permanent magnet synchronous motor (PMSM)) is presented only for a rated speed of 1500 rpm and at varying load conditions. The whole process of the efficiency determination of the rotating electrical machines (AM and PMSM) with thermal stability measurement is monitored and controlled by a real-time control test system programmed in LabVIEW. During the test, the surface temperature of the DUT is continuously measured. The DUT is continuously run until a thermal stability is obtained. The thermal stability of the test machine (DUT) is achieved once the rate of change of temperature is ≤ 1 K per half hour at the hottest point. The surface temperature is measured using the Yokogawa temperature measurement device (MV2000). All the electrical quantities (such as voltage *U*, current *I* and power factor λ = cos φ) are displayed on the power analyzer (Yokogawa WT 3000) and read in the LabVIEW software on the computer with the measured electrical power P_{elc}. Similarly, the mechanical quantities such as torque *M* and speed *n* are measured using the torque sensor (Kistler type 4504B) and are used for the measurement of the mechanical power P_{mech}. This small-scale test bench (Fig. 7 (a) and (b)) for electrical machine measurements is similar to NTBs as for a wind turbine as shown in Fig. 2 (a) and (b).



(a) Photographic representation of the small-scale test bench for rotating electrical machines. 1) Power analyzer WT 3000, 2) Computer with LabVIEW, 3) Temperature recorder, 4) Test motor converter and 5) Load motor converter.



(b) Schematic representation of the small-scale test bench for rotating electrical machines.

Fig. 7. Experimental setup for the efficiency measurement of rotating electrical machines with measurement equipment layout on the small-scale test bench.

Table III below shows the summary of different types of electrical machines with IE classes that are used in this paper to measure the efficiency based on the review of standards for efficiency determination of rotating electric machines. The 4 poles permanent magnet synchronous machine (PMSM) and asynchronous machine (ASM) i.e., Squirrel-cage ASM is used as the test machine (DUT) at 50 Hz operating frequency and rated speed of 1500 rpm with varying load conditions.

TABLE III. Summary of Different Types of a 4 Poles PMSM and an ASM with their Nameplate Values at 50 Hz Operating Frequency.

Machine Type	**Rated Nameplate Values**					
	Power (kW)	***Torque (Nm)***	***Speed (rpm)***	***p.f***	***η (%)***	***IE class***
ASM	4.0	26.5	1440	0.82	88.6	IE3
PMSM	7.5	47.8	1500	0.99	91.8	IE4

B. *Results and MU Analysis Of Direct and Indirect Efficiency Determination of Rotating Electrical Machines (ASM and PMSM) fed with Inverter Supply*

The test results with a MU analysis of the direct and the

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indirect efficiency determination of an ASM and a PMSM fed with inverter supply after reviewing the national and international standards are presented in Fig. 8 and Fig. 9. It can be clearly seen in Fig. 8 and Fig. 9 that the PMSM has a higher efficiency in partial load conditions compared to the AM. Therefore, these result comparisons show the reason why there is a necessity of conducting at least 6 operating point measurements as mentioned in IEC 60034-2-1 [14] and IEC 60034-2-3 [22]. The results of the indirect method show that there is a relatively small MU compared to the direct method for both ASM and PMSM. The relatively large MU result of the direct method is mainly due to the higher MU values of the mechanical power measurement as mentioned in [6] and [7].

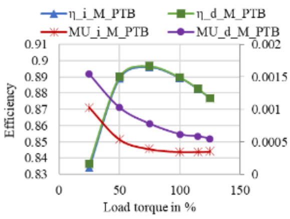

Fig. 8. The measured efficiency of an ASM using direct and indirect methods.

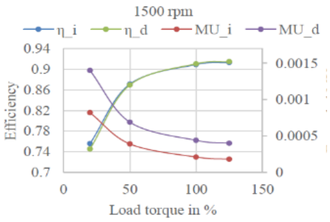

Fig. 9. The measured efficiency with MU of PMSM using direct and indirect methods [6] and [7].

The low MU of the indirect method is the result of determining the losses separately using calculation methods from the measured electrical power measurement at different load conditions and minimizing the higher MU values from the mechanical power measurement. It is obvious that for achieving relatively lower MU values in the efficiency determination of the machines using the indirect method, one needs to invest a lot of time for doing the measurements for the segregation of loss at different load conditions.

VI. Results Comparison of Direct Efficiency Determination Method with Alternative Back-to-Back Efficiency Determination Method for Rotating Electrical Machines (ASM)

Generally, the efficiency determination of nacelle drive trains on NTBs has been conducted using the mechanical and electrical power measurement, i.e., the direct method during the design process of a wind turbine. This method is highly dependent on the reliability and accuracy of the mechanical power measurement. Therefore, in this section, we started by investigating the efficiency determination by comparing the direct method with an improvised alternative back-to-back method for NTBs. These experiments were carried out to find out the test to be performed in order to determine the traceable efficiency of any nacelle drive train with lower uncertainty.

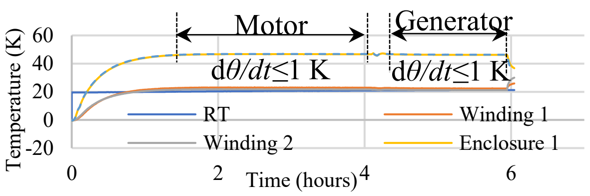

Fig. 10. The surface over-temperature w.r.t. room temperature (RT) of the ASM at the rated speed of 1500 rpm during motor and generator mode test.

The measurements were carried out at room temperature and the test machine (DUT) was run until the thermal stability ($d\theta/dt \leq 1$ K per 30 mins) is achieved in both motor and generator mode operation as shown in Fig. 10. The five operating points were measured once thermal stability were reached in motor mode as well as in generator mood. The proportion factor $k_M = 0.5$ can be assumed for all loads for efficiency determination as in (6). However, a relatively large discrepancy can be found in the results in comparison to the efficiencies determined by the direct method. Since the assumption of $k_M = 0.5$ is chosen here only for simplicity and not based on careful analysis or test results, the efficiency results from the direct method should be taken as reference in the motor ($\eta_{d\_M\_PTB}$) and generator ($\eta_{d\_G\_PTB}$) mode. Using the measurement from the direct method, the k_M factors on different load points can be calculated and presented in Table IV with efficiency values determined using an alternative back-to-back method.

TABLE IV. Comparison of the Calculated Efficiency Results Using The Direct Method And Alternative Back-To-Back Efficiency Determination Method Of Squirrel-Cage ASM At Rated Speed At 5 Operating Points

Mode	Motor Mode Test				Generator Mode Test		
	k_M	$\eta_{d\_M\_PTB}$ (%)	η_{M_IWES} (%)	$\Delta\eta_M$ (%)	$\eta_{d\_G\_PTB}$ (%)	η_{G_IWES} (%)	$\Delta\eta_G$ (%)
1	0.462	90.84	90.10	-0.75	90.13	90.76	0.63
2	0.459	91.04	90.24	-0.80	90.38	91.04	0.67
3	0.451	91.05	90.08	-0.97	90.27	91.06	0.79
4	0.448	90.87	89.81	-1.05	90.08	90.93	0.84
5	0.455	90.02	89.02	-0.99	89.35	90.14	0.80

The efficiency in the motor (η_{M_IWES}) and generator (η_{G_IWES}) mode for the alternative back-to-back method is presented in Fig. 11, which is determined as in using the input electrical power in the test machine mode ($P_{elec.M}$), the proportion factor k_M from Table IV and the total power losses, $P_{Loss.total}$.

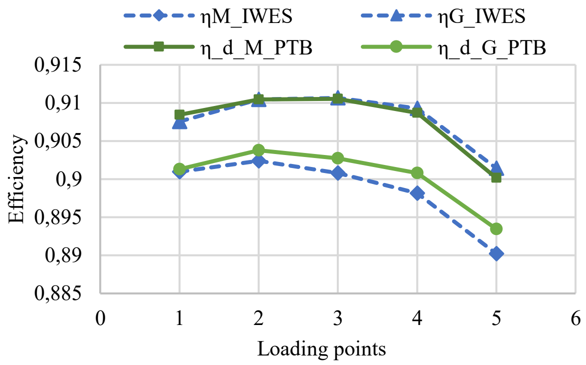

Fig. 11. Comparison of the measured efficiency of ASM using the direct and alternative back-to-back method at rated speed with 5 operating points.

VII. Concluding Remarks and Future Work

This paper has reviewed and summarized efficiency measurement standards for rotating electrical machines on small-scale test benches and its possible application in NTBs for a traceable efficiency determination of nacelles. Summing up the measurement results, it can be concluded that validating the different methods for the DUT is a good idea to conform the traceable efficiency determination with the MU values on NTBs. However, the alternative back-to-back method and the indirect method using loss segregation are difficult to perform on NTBs because these methods consist of time-consuming measurements. The experimental results of these methods on a small-scale test bench seem promising, however, the main limitation to perform these experiments of nacelles on NTBs are the complexity of nacelle drive trains itself and the lack of

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running possibilities and flexibility of NTBs compared to small-scale test benches. It is very cchallenging in determining the k_M factor and its uncertainty too. The results in Fig. 10 shows that the temperature stability needs to be reached which is very time-consuming and two tests need to be done and the DUT needs to be able to run in both modes which could not be possible in the nacelles test bench. It has been demonstrated via the results in Fig. 8, Fig. 9 and

Fig. 11 that there is a relatively larger MU in the direct efficiency determination method, where the input-output power measurement is performed on a test machine (DUT). The findings suggest that the main reason for this is the fallibility of mechanical power measurement resulting from torque and rotational speed measurement transducers. Therefore, no matter if it is a small-scale test bench or an NTB, the mechanical power measurement in test benches needs to be properly calibrated via transfer standards in static as well as in dynamics conditions.

The accuracy of the alternative back-to-back method is highly dependent on the determination of the k_M factor. For applications where high accuracy is required, the k_M factor should be carefully chosen with the assignment of the proper amount of uncertainty. One possible way is to determine the k_M factor through analysis of losses summation with FEM simulation or test methods. Similarly, the accuracy of the direct efficiency measurement method is highly dependent on mechanical (torque and rotational speed sensors) and electrical (instruments and sensors) power measurement. In addition, the direct efficiency measurement method is only recommended for induction machines with a rated power < 1 kW because of the relatively large measurement uncertainty of the mechanical power measurement [6] and [8].

In our future research, we intend to concentrate on higher rating rotating electrical machines (200 kW) on the test bench. Further study of the issue of the MU concerning the transfer standard for electrical power measurement considering electrical quantities measurement sensors and instruments would be of great interest. More tests on different operating points will be needed to determine the efficiency of nacelle drive trains on NTBs to verify whether the transfer standard for mechanical power measurements (torque M and rotational speed n measurements) and electrical power measurements (voltage U, current I and power factor $\lambda = \cos \varphi$ measurements) are transferable and reproducible in all types of test benches.

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References

[1] "Renewable energy | Fact Sheets on the European Union." [Online]. Available: https://www.europarl.europa.eu/factsheets/en/sheet/70/renewable-energy. [Accessed: 20-Aug-2021].

[2] IEC 61400-12-1, *Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*, 2nd ed., vol. 2003. 2017.

[3] "Wind-FGW | technical guidelines (TG 2) – Determination of power curve and standardized energy yields." [Online]. Available: https://wind-fgw.de/shop/technical-guidelines/?lang=en. [Accessed: 16-Aug-2021].

[4] "MEASNET: Power Performance Measurement Procedure," 2009. [Online]. Available: http://www.measnet.com/wp-content/uploads/2011/06/power5.pdf. [Accessed: 16-Aug-2021].

[5] "Traceable mechanical and electrical power measurement for efficiency determination of wind turbines." [Online]. Available: https://www.ptb.de/empir2020/windefcy/home/. [Accessed: 16-Aug-2021].

[6] N. Yogal, C. Lehrmann, and M. Henke, "Determination of the Measurement Uncertainty of Direct and Indirect Efficiency Measurement Methods in Permanent Magnet Synchronous Machines," in *2018 XIII International Conference on Electrical Machines (ICEM)*, 2018, pp. 1149–1156.

[7] N. Yogal, "Analysis of a permanent magnet synchronous machine with regard to explosion protection capability," Dissertation, Technische Universität Braunschweig, Braunschweig, 2019.

[8] C. Lehrmann, U. Dreger, and -Ing Frank Lienesch, "Efficiency determination on (explosion-protected) electric machines-a survey under measurement uncertainty aspects," 2015.

[9] "Wind power generation using wind energy : Systems & Solutions : Renewable Energy | TOSHIBA ENERGY SYSTEMS & SOLUTIONS CORPORATION." [Online]. Available: https://www.toshiba-energy.com/en/renewable-energy/product/wind-power.htm. [Accessed: 05-Aug-2021].

[10] "DyNaLab Test Laboratory." [Online]. Available: https://www.idom.com/en/project/dynalab-test-laboratory/. [Accessed: 05-Aug-2021].

[11] T. Duda, G. Jacobs, and D. Bosse, "Investigation of dynamic drivetrain behaviour of a wind turbine during a power converter fault," *J. Phys. Conf. Ser.*, vol. 1037, p. 52031, 2018.

[12] H. Zhang, J. Wenske, A. Reuter, and M. Neshati, "Proposals for a practical calibration method for mechanical torque measurement on the wind turbine drive train under test on a test bench," *Wind Energy*, vol. 23, no. 4, pp. 1048–1062, 2020.

[13] H. Zhang and M. Neshati, "An effective method of determining the drive-train effciency of wind turbines with high accuracy," *J. Phys. Conf. Ser.*, vol. 1037, p. 52013, 2018.

[14] IEC 60034-2-1, *Rotating electrical machines - Part 2-1: Standards methods for determining losses and efficiency from tests (excluding machines for traction vehicles),* 2nd ed. 2014.

[15] M. Pagitsch *et al.*, "Feasibility of large-scale calorimetric efficiency measurement for wind turbine generator drivetrains," *J. Phys. Conf. Ser.*, vol. 753, p. 72011, 2016.

[16] IEC 60034-2-2, *Rotating electrical machines - Part 2-2: Specific methods for determining separate losses of large machines from tests - Supplement to IEC 60034-2-1*, 1st ed. 2010.

[17] D. X. Llano, X. Wang, J. Wang, and R. McMahon, "Design of a calorimeter for modern power electronics and electrical machines," *10th Int. Conf. Power Electron. Mach. Drives (PEMD 2020)*, pp. 1054–1059, 2021.

[18] R. Article, D. G. Nair, A. Arkkio, and A. Haavisto, "Power loss segregation in electrical machines through calorimetry and inverse thermal modelling; Power loss segregation in electrical machines through calorimetry and inverse thermal modelling," *IET Electr. Power Appl*, vol. 14, no. 7, pp. 1127–1133, 2020.

[19] H. Kärkkäinen and M. Niemelä, "Induction Motor Efficiency Verification Using a Balance-Type Calorimeter Equipped with a Mass Flow Meter Vehicle energy efficiency View project ENTALT View project," 2018.

[20] L. Aarniovuori, J. Kolehmainen, A. Kosonen, M. Niemelä, and J. Pyrhönen, "Uncertainty in motor efficiency measurements," *2014 International Conference on Electrical Machines (ICEM)*. pp. 323–329, 2014.

[21] B. Tsybikov, E. Beyerleyn, and P. Tyuteva, "Comparison of energy efficiency determination methods for the induction motors," *MATEC Web Conf.*, vol. 91, p. 1034, Jan. 2017.

[22] IEC TS 60034-2-3, *Rotating electrical machines - Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors*, 1st ed. 2013.

[23] "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators," *IEEE Std 112-2004 (Revision of IEEE Std 112-1996)*. pp. 0_1-79, 2004.

[24] USA DEPARTMENT OF ENERGY (DOE) 10 CFR Part 431, "Energy Conservation Program: Energy Conservation Standards for

This is an author-created, un-copyedited version of a Conference contribution published in 2021 24th International Conference on Electrical Machines and Systems (ICEMS), 2021, 10.23919/ICEMS52562.2021.9634389 . The present version is available for open access, DOI: 10.7795/EMPIR.19ENG08.CA.20230831B.

Commercial and Industrial Electric Motors," 2014.

[25] National Electrical Manufacturers Association (NEMA), *NEMA MG-1: Motor and Generators*. 2014.

[26] Canadian Standards Association (CSA) C390-10, *Test methods , marking requirements , and energy efficiency levels for three-phase induction motors*, 3rd ed., no. JANUARY. 2020.

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