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Feasibility of large-scale calorimetric efficiency measurement for wind turbine generator drivetrains

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Abstract. In the course of the global energy turnaround, the importance of wind energy is increasing continuously. For making wind energy more competitive with fossil energy, reducing the costs is an important measure. One way to reach this goal is to improve the efficiency. As the major potentials have already been exploited, improvements in the efficiency are made in small steps. One of the main preconditions for enabling these development activities is the sufficiently accurate measurement of the efficiency. This paper presents a method for measuring the efficiency of geared wind turbine generator drivetrains with errors below 0.5 % by directly quantifying the power losses. The presented method is novel for wind turbines in the multi-MW-class.

1. Introduction
Throughout the past decades, wind energy has gained considerable importance by significantly contributing to the global generation of sustainable energy. For the purpose of characterising and improving the properties of wind turbine generators (WTG), nacelle test facilities have been established across the world. In the end of 2014, the Center for Wind Power Drives (CWD) at the RWTH Aachen University set up its 4 MW WTG test bench – see Figure 1. It is designed to conduct experiments concerning not only single components of a wind turbine, but rather the entire system consisting of mechanical drivetrain, generator, converter, and electrical grid. Up to this point, investigations concerning the mounting concept of WTGs and the local loads in the gearbox [1] have been carried out as well as experiments focussing on the converter system and the connection of a WTG to the electrical grid [2].

According to [3], 13.3 % of the total amount of energy produced in Germany in 2015 was generated by WTGs. This amount will be growing over the next years, as the installed wind power capacity is still increasing. Regarding cost, wind energy is still in competition with fossil energy sources. Consequently, cost pressure is high. As shown in a study on the LCOE (Levelized cost of electricity) of renewable energy technologies [4], the cost of wind energy is in a range comparable to the cost of energy produced by state-of-the-art hard coal plants only at very good onshore locations.
The LCOE is the mean value of specific costs over the operating life of a power plant and a comparison criterion for the profitability of different methods of energy production. It is defined as follows [5]

\[ LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1 + i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1 + i)^t}}. \]  

(1)

The numerator of equation 1 contains the investment expenditures \( I_0 \) and the total annual costs \( A_t \). These values are divided by the produced quantity of energy \( M_{t,el} \) in the respective year \( t \). Real interest rate \( i \) and economic operational lifetime \( n \) are also taken into account. The annual energy production \( M_{t,el} \) of WTGs is directly affected by their efficiency \( \eta \), which is – as for any technical system – defined as the quotient of output power \( P_{out} \) and input power \( P_{in} \)

\[ \eta = \frac{P_{out}}{P_{in}}. \]  

(2)

An increase in \( \eta \) proportionally increases \( M_{t,el} \). As can be observed from equation 1, this leads to a decrease in the LCOE and makes wind energy more able to compete economically with fossil energy. Hence, improving the efficiency of WTGs is a superior development goal. One of the main preconditions for enabling these development activities is the sufficiently accurate measurement of the efficiency. The measurement error has to be small enough to make slight improvements in the efficiency reproducibly visible. This paper presents a method for measuring the efficiency of WTG drivetrains with an error significantly below 0.5 %.

2. Methods for measuring the efficiency of technical systems

When looking at equation 2, the obvious method to obtain the efficiency would be to measure \( P_{out} \) as well as \( P_{in} \) and calculate their quotient. In literature, this method is referred to as power difference method [6]. However, at least four physical quantities are to be measured when using this method: Mechanical power \( P_{mech} \) is either determined via angular velocity \( \omega \) and torque \( T \) (rotational) or via force \( F \) and velocity \( v \) (translational). Electrical power \( P_{el} \) can be calculated from current \( I \) and voltage \( U \), hydraulic power by pressure difference \( \Delta p \) and volumetric flow rate \( \dot{V} \).
Another method is the so-called power loss measurement. When making use of the relation $P_{\text{out}} = P_{\text{in}} - P_{\text{loss}}$, equation 2 can be transposed to

$$\eta = \frac{P_{\text{in}} - P_{\text{loss}}}{P_{\text{in}}} = 1 - \frac{P_{\text{loss}}}{P_{\text{in}}} .$$

(3)

As required by the power difference method, at least four quantities have to be measured. Power loss $P_{\text{loss}}$ occurs in the form of heat. Measuring the amount of heat with high accuracy is much easier than measuring electrical or mechanical powers in the multi-MW-range. Hence, the power loss method is the means of choice in the present case.

2.1. Propagation of uncertainty

In many cases physical and technical quantities cannot be measured directly, but have to be determined by various single measurements. The resulting measurement error of the sought quantity is crucial for evaluating the quality of the measurement and can e.g. be found by application of the linear calculation of error propagation [7]. For a physical quantity $y$ gained by measuring $n$ independent quantities $x_i$

$$y = f(x_1, x_2, \ldots, x_n) ,$$

(4)

the absolute maximum error $\Delta y$ can be calculated by considering the $n$ individual absolute errors $\Delta x_i$

$$\Delta y = \pm \sum_{i=1}^{n} \left| \frac{\partial f}{\partial x_i} \right| \Delta x_i .$$

(5)

Relating the absolute error to the nominal value of the respected quantity yields the relative error $\Delta x/x$, which allows for comparison of the measurement errors of different physical quantities.

This approach can be used to calculate the theoretically possible accuracies of the different methods for measuring efficiency. Applying the calculation of error propagation to equation 2 leads to

$$\Delta \eta = \pm \left( \frac{1}{P_{\text{in}}} \Delta P_{\text{out}} + \frac{P_{\text{out}}^2}{P_{\text{in}}^2} \Delta P_{\text{in}} \right) \Rightarrow \frac{\Delta \eta}{\eta} = \frac{\Delta P_{\text{out}}}{P_{\text{out}}} + \frac{\Delta P_{\text{in}}}{P_{\text{in}}} .$$

(6)

Herein, $P_{\text{in}}$, $P_{\text{out}}$, and $P_{\text{loss}}$ are considered with respect to their absolute value. When making use of the power difference method, the relative measurement error equals the sum of the relative errors in input power and output power. For the method of power loss measurement (equation 3) we obtain

$$\Delta \eta = \pm \left( \frac{1}{P_{\text{in}}} \Delta P_{\text{loss}} + \frac{P_{\text{loss}}^2}{P_{\text{in}}^2} \Delta P_{\text{in}} \right) \Rightarrow \frac{\Delta \eta}{\eta} = \left( \frac{1}{\eta} - 1 \right) \left( \frac{\Delta P_{\text{loss}}}{P_{\text{loss}}} + \frac{\Delta P_{\text{in}}}{P_{\text{in}}} \right) .$$

(7)

Apparently, the measurement error vanishes for $\eta \rightarrow 1$, as the sum of the relative errors of input power and power loss is scaled with $(1/\eta - 1)$. This is not only a mathematical phenomenon: If the power loss vanishes, the efficiency converges towards 1 and the measurement error of the input or output power does not influence the accuracy of the efficiency values. Figure 2 shows a comparison of the calculated relative measurement errors in the efficiency $\Delta \eta/\eta$ for the two methods described above with the assumption that the relative errors of $P_{\text{in}}$, $P_{\text{loss}}$, and $P_{\text{out}}$ are 2.5% each.

2.2. Applicability of the presented methods on WTG drivetrains

At the National Renewable Energy Laboratory (NREL), the efficiency of a 1.5 MW WTG drivetrain has been measured with various methods [9]. Due to an insufficient sensor setup
the power difference method did not lead to reproducible results. There was a deviation of up to 7% between single measurements, which is by far not good enough for proving slight enhancements of the overall efficiency. With the power loss measurement, the correspondence between predicted and measured efficiency values was improved. The report, however, does not state the actual measurement accuracy.

For machines of the multi-MW-class, the efficiency is usually being measured with the power difference method. Because of the size of suchlike drivetrains, a direct quantification of the power loss is difficult to realize – there are no known cases from literature regarding applications to WTGs in the multi-MW-class. On the other hand, the potential of this method lies in the excellent accuracy especially in the regions of high efficiencies.

3. Execution of the measurement

Due to the advantageous measurement accuracy of the power loss measurement, this method was chosen to quantify the efficiency of the HybridDrive manufactured by Winergy [10]. The HybridDrive is an integrated drivetrain consisting of a two-stage planetary gearbox and a permanent-magnet mid-speed synchronous generator with a rated power of 3 MW. Figure 1 shows the HybridDrive mounted on the CWD test bench.

Figure 3 depicts the schematic of the HybridDrive. It contains an oil and water cooling system to regulate the temperature in the drivetrain. The thermal energy flow of the gearbox oil $\dot{Q}_{\text{Gbx}}$ is transferred to the cooling water through a heat exchanger. In addition, the water circuit takes the thermal discharge of the generator $\dot{Q}_{\text{Gen}}$ and is connected to the in-house water cooling system of the test facility.

As the power loss is normally directly emitted into the environment in the form of heat and the surface of the DUT is not suitable for measuring heat flowing through, an additional system boundary needs to be established. This new boundary has to isolate the DUT from the environment for the purpose of making the heat loss measurable. A housing was built around the DUT. It consisted of a wooden frame which was faced with reflecting foil on the inside and polystyrene blocks on the outside. Figure 4 shows the insulation box containing the HybridDrive on the test bench. Owing to this insulation layer, the major part of the heat is conducted away in the water cooling system. By measuring the volumetric flow rate $\dot{V}$ and the temperature difference between outlet and inlet ($\vartheta_{\text{out}} - \vartheta_{\text{in}}$), the major part of the power loss $P_{\text{conv,water}}$ can
be calculated

\[ P_{\text{conv,water}} = c_p \cdot \varrho \cdot \dot{V} \cdot (\vartheta_{\text{out}} - \vartheta_{\text{in}}) \].

(8)

The heat capacity \( c_p \) and the density \( \varrho \) are material constants of the cooling fluid known from respective charts.

Before meaningful values for the power loss are obtained, the DUT and the insulation box have to reach the stationary temperature characterising the thermal state of the current operating point. Due to its considerable mass, the DUT has a significant thermal inertia. The emitted heat originates from frictional and churning losses as well as losses in the electrical system. Thermal equilibrium the heat loss and the heat conducted away in the cooling system attunes as soon as the temperature within the insulation box does not change anymore. That steady-state temperature depends on the operating point (input power) and the power lead away by the cooling system. As long as the equilibrium has not been reached, the mass of the DUT works as a heat sink and the energy transferred into the cooling system is smaller than the actual power loss – the real efficiency is being overestimated. When going from large to small input powers, the DUT is a heat source, which inverts the described effect.

Nine points from the HybridDrive’s power curve have been chosen for individual efficiency measurements. They are shown in figure 5 and represent the complete power band of the HybridDrive. The points labelled 7, 8, and 9 represent the same power level and differ only in the ratio of torque and rotational speed.

Apart from the quantities required for the calculation of the power loss according to equation 8, temperatures were logged at four more measuring points. The temperatures at three positions inside the insulation box (bottom, center, top) and directly on its outer surface are required do determine the occurrence of an equilibrium and to calculate additional heat fluxes not being gathered by equation 8. Heat spreads by three mechanisms, namely conduction, convection, and radiation. Losses caused by radiation and convection of input shaft and the metal frame carrying the DUT can be determined by the measured temperatures and will be described in the next section.

4. Data analysis

As soon as there is thermal equilibrium in the system, the physical quantities required for the calculation of the efficiency according to equation 3 are recorded as time series and averaged.
Figure 5. Selected operating points on the power curve of the HybridDrive. Power is constant along the gray dashed lines.

over several minutes. The following paragraphs explain the calculation of the HybridDrive’s efficiency and of the maximum measuring error.

4.1. Input power
The input power $P_{\text{in}}$ consists of the mechanical power delivered by the test bench and the electrical power supplying the oil pumps

$$P_{\text{in}} = P_{\text{in,mech}} + P_{\text{in,el}}.$$  \hfill (9)

Table 1 gives an overview of the shares of the input power $P_{\text{in}}$.

| Symbol  | Quantity               | Average share | Max. error |
|---------|------------------------|---------------|------------|
| $P_{\text{in,mech}}$ | Mechanical input power | 99.9 %        | ±2.5 %     |
| $P_{\text{in,el}}$  | Oilpump power supply   | 0.1 %         | ±25.0 %    |

Table 1 gives an overview of the shares of the input power. $P_{\text{in,mech}}$ is calculated from input torque and rotational speed. As it is not possible to calibrate torque transducers above 1.1 MNm at present day, the measurement error of the torque cell in use at the CWD has been extrapolated based on values yielded from calibration procedures by the manufacturer. The quoted value for the relative error is ±2.5 %.

The electrical power required to supply the oil pumps is calculated from data given in the specification sheet. Due to uncertainties in the calculation, the relative error is estimated to be ±25 % at the maximum.

4.2. Power loss
The power loss $P_{\text{loss}}$ is composed from various shares as well

$$P_{\text{loss}} = P_{\text{conv,water}} + P_{\text{trans,ins}} + P_{\text{conv,ins}} + P_{\text{rad,shaft}} + P_{\text{conv,shaft}} + P_{\text{rad,frame}}.$$  \hfill (10)
Table 2. Shares of the power loss $P_{\text{loss}}$. The maximum error values are shares of the respective quantities.

| Symbol         | Quantity                                                        | Average share | Max. error |
|----------------|-----------------------------------------------------------------|---------------|------------|
| $P_{\text{conv,water}}$ | Heat lead away in the water cooling system                     | 95.61%        | ±0.9%      |
| $P_{\text{trans,ins}}$   | Heat transmitted through the insulation layer                   | 0.84%         | –          |
| $P_{\text{conv,ins}}$    | Heat flowing through gaps in the insulation layer               | 3.25%         | ±47.0%     |
| $P_{\text{rad,shaft}}$   | Radiation from the input shaft                                  | 0.13%         | ±50.0%     |
| $P_{\text{conv,shaft}}$  | Heat flow from the input shaft due to forced convection         | 0.05%         | ±50.0%     |
| $P_{\text{rad,frame}}$   | Radiation from the main frame                                  | 0.12%         | ±50.0%     |

$P_{\text{conv,water}}$ (equation 8) is the main share of the power loss. Besides, some considerably smaller heat fluxes have to be taken into account. Due to the temperature difference between inner and outer surface of the insulation layer, a certain amount of heat $P_{\text{trans,ins}}$ is transmitted. As the thermal conductivity of the polystyrene ($\lambda = 0.035 \text{ W/mK}$), its thickness $d$, and the surface area $A$ of the box are known, this part of the power loss can easily be calculated

$$P_{\text{trans,ins}} = A \cdot \lambda \cdot \frac{\vartheta_{\text{inside}} - \vartheta_{\text{outside}}}{d}. \quad (11)$$

The convective losses caused by inevitable narrow gaps between the individual polystyrene blocks are much harder to quantify. Measured temperature values show that there is a vertical temperature gradient inside the box, which results in a small pressure difference between inside and outside. In further experiments and analyses designed for that purpose, the volumetric flow rate through different configurations of gaps in a polystyrene wall was assessed for different pressure gradients. The resulting convective heat flux through the insulation layer $P_{\text{conv,ins}}$ was calculated to account for (3.4 ± 1.6)% of the heat flux lead away in the cooling water. $P_{\text{trans,ins}}$ is much smaller than that, therefore its error is assumed to be covered by the error of ±47% in the convective flux.

Additional losses ($P_{\text{rad,shaft}}$, $P_{\text{rad,frame}}$) originate from thermal radiation. Parts of the frame carrying the HybridDrive were not enclosed by the insulation layer, as well as a short section of the input shaft. Thanks to elastomer bushings in the bolt connections, the thermal coupling between the shaft and the flange of the test bench is negligible. This could be verified by means of thermal imaging. With the assumption that the temperature of these parts equals the mean temperature inside the box, the radiated power can be determined using the Stefan-Boltzmann law [11]

$$P_{\text{rad}} = A \cdot \sigma \cdot \varepsilon \cdot (\vartheta_{\text{sf}}^4 - \vartheta_{\infty}^4) \quad (12)$$

with $A$ being the radiating surface area of shaft resp. frame, $\sigma$ the Stefan-Boltzmann-constant, $\varepsilon$ the emissivity of protective varnish, $\vartheta_{\text{sf}}$ the temperature of the surface, and $\vartheta_{\infty}$ the environmental temperature.

Another mechanism that has to be considered is forced convection at the input shaft caused by the rotation. The shaft is rotating in resting air, thus it can be modelled as an even plate under a parallel flow. The heat flux transferred from the shaft into the environment $P_{\text{conv,shaft}}$ is calculated according to equation 13

$$P_{\text{conv,shaft}} = A \cdot \overline{\alpha} \cdot (\vartheta_{\text{sf}} - \vartheta_{\infty}) \quad (13)$$

The average heat transfer coefficient $\overline{\alpha}$ has to be calculated from the average Nusselt number $\overline{\text{Nu}}_L$ in advance

$$\overline{\alpha} = \overline{\text{Nu}}_L \cdot \frac{\lambda_{\text{air}}}{L} \quad (14)$$
with the thermal conductivity of the surrounding air $\lambda_{\text{air}}$, and the characteristic length $L$, in the present case the circumference of the shaft. The Nusselt number is yielded by thermal laws based on the dimensionless quantities $\text{Re}$ (Reynolds number) and $\text{Pr}$ (Prandtl number). Due to the varying rotational velocities of the input shaft, a distinction between laminar boundary layer flow and turbulent flow is necessary. Gnielinski [12] gives a model for laminar flow

$$\overline{\text{Nu}}_L = 0.664 \cdot \text{Re}_L^{\frac{1}{4}} \cdot \text{Pr}^{\frac{1}{3}}.$$  

(15)

If the Reynolds number at the surface of the shaft exceeds $2 \cdot 10^5$, another law for turbulent flow is applied [13]

$$\overline{\text{Nu}}_L \approx 0.036 \cdot \text{Pr}^{0.43} \cdot \left(\text{Re}_L^{0.8} - 9400\right).$$  

(16)

As there was no observable air movement at the parts of the frame protruding from the insulation, convectional heat transfer at that part of the DUT is neglected. The calculations of $P_{\text{rad,shaft}}$, $P_{\text{rad,frame}}$, and $P_{\text{conv,shaft}}$ cannot be validated, thus the relative error is assumed to be rather high in the range of about $\pm 50\%$.

As can be seen from the data displayed in tables 1 and 2, the very high errors occur only in the shares of small magnitude. Related to the quantities required for determining the efficiency, the maximum measurement errors are in the order of 2.5\% for the input power and 4.9\% for the power loss.

### 4.3. Efficiency

The efficiency is determined according to equation 3 with values from equations 9 and 10. Again, a calculation of error propagation as introduced in section 2.1 is performed. Figure 6 shows the resulting efficiency values. The vertical bars at each individual measuring point indicate the maximum error of the efficiency $\Delta \eta$, which decreases from $\pm 1.30\%$ at $\eta = 86.18\%$ to $\pm 0.22\%$ at $\eta = 97.02\%$. The phenomenon described by equation 7 becomes obvious: As the efficiency improves with rising power, the measurement error declines.

![Figure 6](image-url)

**Figure 6.** Measured efficiency over power with fitted curve. The vertical bars indicate the maximum error.
5. Conclusion
With the presented method, the feasibility of calorimetric efficiency measurement for WTG drivetrains in the multi-MW-class has been proven. Especially at overall efficiencies near 100%, the accuracy is good enough to validate even very small improvements. The required time for measurement campaigns as described is rather high due to the fact that a constant thermal state can only be reached after a couple of hours. However, investigations for further refinement of the measurement setup and accuracy are currently in progress. Increasing the effort to seal the insulation and to control convective fluxes through inevitable gaps of the insulation layer are promising ways to reduce the error. One of the research projects currently in progress at the CWD is dedicated to develop methods for calibrating torque transducers in the MNm range [14]. The results of this project enable accurate measurement of high mechanical power especially in the low rpm range, which is also a prerequisite for accurate efficiency measurement.

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