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An effective method of determining the drive-train efficiency of wind turbines with high accuracy

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Abstract. Measurement of efficiency under various load conditions is an important prerequisite for the validation of wind turbine drive train systems. Current measurement methods rely highly on the accuracy of the mechanical torque measurement, which is substantially limited by the high level of torque as well as the available calibration capacity. This paper proposes a new method of test and measurement procedures, aiming to substantially reduce the dependency of the efficiency accuracy on the torque and electrical power measurement. Instead of measuring the efficiency directly, the new method focuses on measuring the loss of power and in this way reduces the uncertainty of the determined efficiency. At rated power, an uncertainty lower than 0.5% is considered as achievable. The efficiency uncertainty is analysed in detail in the paper with considerations of different sources of measurement uncertainties and their contributions. An example of the uncertainty calculation with typical parameters is presented as a demonstration. The study shows that the new method can effectively reduce the effect of the torque (as well as the electrical power) uncertainty on the overall uncertainty of the determined efficiency, and therefore achieve a better accuracy despite of the unfavourable accuracy of the torque and electrical power measurement. Finally, experimental tests have been performed on a scaled dynamometer test bench, where the efficiencies at different operation points are determined with the new method. The efficiency results as well as their uncertainties are presented in the paper.

1. Introduction

Drive train efficiency is a key property of a wind turbine. Since stochastic wind loads and varying environmental conditions are the basic operation conditions for the wind turbine, measuring the efficiency under various load cases and environmental conditions provides manufacturers with an comprehensive evaluation of the turbine’s efficiency property. This knowledge forms the basis of a more targeted further development.

Drive train efficiency is normally determined experimentally on test benches in a laboratory environment, where the drive train is driven up throughout the whole operation range up to rated power. More advanced test benches can apply loads in 6-DOF and emulate different load cases. One example of such test benches is the 10-MW dynamic nacelle test laboratory DyNaLab [1] of Fraunhofer IWES in Germany. For the measurement on the test bench, the input mechanical torque and electrical power output are necessary for the efficiency determination. However, accurate torque measurement is hindered by the multi-MN·m torque level and the limited calibration capacity of the high accuracy calibration machines. The currently largest calibration capacity is 1.1 MN·m, which is owned by the PTB [2]. Additionally, professional torque transducers with high level of torque measurement usually come together with high cost.
One alternative way is to use a partially calibrated part (e.g. the input shaft adapter) for the measurement, instead of a fully calibrated transducer. For doing that, a calibrated torque transducer can be used as reference, to calibrate the shaft adapter between the test bench and the turbine drive train. It is of course also possible to calibrate the shaft adapter directly under a professional calibration machine. The shaft adapter can be calibrated to the capacity of the reference transducer or the calibration machine. The behaviour beyond the calibration range has to be obtained via extrapolation. With professional handling and favourable conditions, the method does deliver a good measurement accuracy [3, 4]. However, the cost and reliability can be big problems especially for the common application in the industry. The calibration has to be carried out to a torque level as high as possible and needs to be repeated regularly. Furthermore, since the shaft adapter is not a designed transducer, the professional instrumentation and compensation procedures are difficult to be guaranteed, for example the compensation against temperature change and creep, the protection against humidity and so on.

Another alternative avoids the need of torque measurement, using two identical drive trains running in a back-to-back setup. One of the drive trains operates in motor mode and the other in generator mode. In this case, the total power loss (of the whole setup) can be measured through the input and output electrical power difference on both sides. This method is also outlined in the IEC 60034 standard [5]. However, there are some limitations with this method. First, due to power losses along the drive train, the turbine in generator mode operates at a lower power level than the turbine in motor mode. The electrical output power can be, depending on the turbine efficiency, over 10 %. This means the electrical machines from both sides have different operation points. Furthermore, there may also be behaviour discrepancies between the two individual drive trains. These facts lead to an increase of uncertainty in the determination of the power loss from each drive train. Second, the assembling and instrumentation of the test have to be designed for every different type of wind turbine and it would be difficult to apply additional loads (e.g. the bending moment) to the turbine drive train in order to study the influences of parasitic loads on the efficiency.

2. New Method of Efficiency Determination

On a nacelle test bench, the turbine drive train can be run in a number of designed test scenarios, with various load cases, specific control and system configurations and on different operational points. Turbine behaviours in different scenarios can be thoroughly studied through a series of tests.

The uncertainty of the drive train efficiency is a combination of the uncertainties from both mechanical torque and electrical power measurement. The efficiency determination has a very high requirement on the measurement accuracy. An uncertainty of for example 2 % would very likely make the determination meaningless for the designer when the efficiency is about 95 %. For a test bench similar as DyNaLab, the shaft adapters have to be designed capable of withstanding large bending moments (up to 20 MN·m). This makes an accurate torque measurement even more difficult.

The new method presented in this paper aims to solve this problem and determine the efficiency with sufficient accuracy. The method is all based on the currently available torque and power measurement techniques. A preliminary analysis within the scope of this paper shows that at rated power, an uncertainty less than 1 % is expected. With more accurate instruments and detailed analysis of the components, an uncertainty lower than 0.5 % is also considered as achievable.

Instead of relying on the absolute measured torque and power values, the new method focuses on the changes of the measured values. In fact, the percentage of power loss is measured first and the efficiency is calculated as a result. The torque change is measured between two different tests with opposite transmission directions. Since the power loss is much smaller than the transmission
power, the influence of the absolute measurement uncertainties are essentially reduced.

2.1. Test configuration and the major assumption
Two tests with opposite power transmission directions are needed for this method:

- Test A (normal mode). The turbine drive train works in normal generator mode at a certain operating point (speed, power, etc.) where the efficiency needs to be determined. The test bench also runs in the normal mode and drives the turbine drive train. Torque measurement is instrumented on the shaft adapter between the test bench and the drive train; the electrical measurement is carried out between the generator and the power converter. The transmission direction and power losses are shown in the upper part of Figure 1. A warm up running of the whole test setup should be carried out in advance of the test.

- Test B (reversed mode). The turbine drive train works in motor mode and drives the test bench, while the test bench works as a generator. The operating point of the turbine is tuned to be as close to test A as possible, which means the same electrical power, the same rotating speed (but with opposite direction) and similar control parameters. The reason for the opposite rotating direction is to have the same direction of mechanical torque. The bearing and generator temperatures should be monitored and kept to be similar to test A. The mechanical and electrical measurements are carried out at the same positions as in Test A. The transmission direction and power losses in case of test B are shown in the lower part of Figure 1.

![Diagram of drive train power loss in normal and reversed modes](image)

Figure 1. Drive train power loss in normal mode (upper) and reversed mode (lower).
An important foundation of the method is that the relation of drive train losses in test A and test B are known or can be assumed at the price of introducing additional uncertainty. A simple assumption would be that the total power loss is equally shared by the two tests. The major power losses in the turbine drive train are related to the bearings, the generator and the gearbox when available. The bearing friction depends mainly on external loads, rotating speed, temperature and the lubrication condition. For test A and B, all these conditions are the same or similar. The change of rotating direction might have some effect on the lubrication condition, but the overall impact to the friction is very limited. Electrical machines generally have a good consistency of efficiency between generator and motor mode. The power loss within the gearbox comes mainly from the friction of bearings, the meshing of teeth and the viscosity of the lubricant. Because both the rotating direction and the power transmission direction change in test B, the gear teeth still contact on the same side as in test A. However, depending on the individual gearbox structure and lubrication design, there might be some efficiency difference on the gearbox and this needs to be individually considered in the uncertainty calculation.

2.2. Processing and calculation
The mean values from measurement of both mechanical and electrical powers are used for calculating the efficiency. The power loss diagrams of both tests shown individually in Figure 1 are illustrated together in Figure 2. $\bar{P}_{\text{mech}.A}$, $\bar{P}_{\text{elec}.A}$ denote the mean mechanical and electrical powers in test A, while similarly $\bar{P}_{\text{mech}.B}$, $\bar{P}_{\text{elec}.B}$ describe the mean powers in test B.

\[ \bar{P}_{\text{mech}.A} = \frac{E_{\text{mech}.A}}{t_A} = \frac{\int_0^{\theta_A} T d\theta}{t_A} \quad (1) \]
\[ \bar{P}_{\text{mech}.B} = \frac{E_{\text{mech}.B}}{t_B} = \frac{\int_0^{\theta_B} T d\theta}{t_B} \quad (2) \]

where, $E_{\text{mech}.A}$ and $E_{\text{mech}.B}$ denote the mechanical energy of test A and test B, integrated over $\theta_A$ and $\theta_B$ in the angle domain respectively. $T$ is the mechanical torque, while $t_A$ and $t_B$ stand for the corresponding time periods.

The total power loss of the two tests (in the mean value perspective) can be expressed as Equation (3). It’s composed of the mechanical and electrical power changes between test A and test B. The accuracy of the total power loss is therefore not depended on the absolute uncertainty of every single torque or power measurement, but on the uncertainties of the torque and power differences. This is also the main reason of the uncertainty reduction in this method.
It is actually the power loss that is being measured, rather than the efficiency itself. As it is not possible to control the electrical power in test B to be exactly the same as in test A, the equation still contains electrical power terms.

\[ P_{\text{Loss.total}} = \overline{P}_{\text{mech.A}} - \overline{P}_{\text{mech.B}} + \overline{P}_{\text{elec.B}} - \overline{P}_{\text{elec.A}} \]  

(3)

In order to determine the efficiency of the drive train in each operating mode, the total power loss needs to be divided into components contributed by test A and test B. As a general case, the proportion of power loss in test A out of the whole power loss is defined as \( k_A \), thus \( \overline{P}_{\text{Loss.A}} \) can be expressed as in Equation (4). The efficiency of the drive train in normal operating mode can be then obtained following Equation (5).

\[ \overline{P}_{\text{Loss.A}} = k_A \overline{P}_{\text{Loss.total}} \]  

(4)

\[ \eta = \frac{\overline{P}_{\text{elec.A}}}{\overline{P}_{\text{mech.A}}} = \frac{\overline{P}_{\text{elec.A}}}{\overline{P}_{\text{elec.A}} + \overline{P}_{\text{Loss.A}}} = \frac{\overline{P}_{\text{elec.A}}}{\overline{P}_{\text{elec.A}} + k_A \overline{P}_{\text{Loss.total}}} \]  

(5)

3. Uncertainty consideration

The efficiency of test A as expressed in Equation (5) is determined by the electrical power measurement \( \overline{P}_{\text{elec.A}} \), the total power loss \( \overline{P}_{\text{Loss.total}} \) and the proportion factor \( k_A \). Therefore, the uncertainty of the efficiency is depending on the uncertainties of these three variables.

\( \overline{P}_{\text{Loss.total}} \) is calculated from the mechanical and electrical powers as expressed in Equation (3), where the mechanical powers are in turn functions of torque and angle position and the time stamp of the measurement, as expressed in Equation (1) and (2). Because of the high accuracy of the angle position (from incremental or absolute encoder) and the time stamp, the corresponding uncertainties are considered to be zero. Therefore the uncertainty of \( \overline{P}_{\text{Loss.total}} \) is contributed by torque and electrical power measurement. Taking the measurement errors into consideration, the measured torque and electrical power can be expressed as Equation (6).

\[
\begin{aligned}
\{ & \tilde{T} = aT + b + r(t) \\
& \tilde{P}_{\text{elec}} = cP_{\text{elec}} + d + q(t)
\end{aligned}
\]  

(6)

where, \( \tilde{T} \) and \( \tilde{P}_{\text{elec}} \) are the measured values of torque and electrical power, while \( T \) and \( P_{\text{elec}} \) are the true values. A number of parameters are introduced here to describe the sources of measurement errors:

- \( a \) and \( c \) are the sensitivity errors of corresponding measurements. Sensitivity error is also known as gain error or slope error.
- \( b \) and \( d \) are the offset errors.
- \( r(t) \) and \( q(t) \) represent the summation of miscellaneous errors, including the linearity, the hysteresis and repeatability errors. As a result, they are time dependent.

The sensitivity and offset errors defined above are considered to be constant. Additional sensitivity change and offset drift due to environment change (temperature, humidity, etc.) are accounted in the miscellaneous items \( r(t) \) and \( q(t) \).

The mean value of the calculated mechanical powers in the two tests, namely \( \overline{P}_{\text{mech.A}} \) and \( \overline{P}_{\text{mech.B}} \), can be expressed as in Equation (7). Similarly, the mean value of measured electrical
power $\bar{P}_{\text{elec}.A}$ and $\bar{P}_{\text{elec}.B}$ are expressed in Equation (8).

$$\begin{align*}
\bar{P}_{\text{mech}.A} &= \int_0^{\bar{\omega}_A} \left( aT + b + r(t) \right) d\theta \bigg/ t_A = a\bar{P}_{\text{mech}.A} + b\bar{\omega}_A + R_A \\
\bar{P}_{\text{mech}.B} &= \int_0^{\bar{\omega}_B} \left( aT + b + r(t) \right) d\theta \bigg/ t_B = a\bar{P}_{\text{mech}.B} + b\bar{\omega}_B + R_B
\end{align*}$$

(7)

where, $\bar{P}_{\text{mech}.A}$ and $\bar{P}_{\text{mech}.B}$ are the true mean values of the mechanical power. $\bar{\omega}_A$ and $\bar{\omega}_A$ are the mean speed of test A and test B, while $R_A$ and $R_B$ are the power errors caused by $r(t)$ in the two tests.

$$\begin{align*}
\bar{P}_{\text{elec}.A} &= \int_0^{t_A} (cP_{\text{elec}} + d + q(t)) dt \bigg/ t_A = c\bar{P}_{\text{elec}.A} + d + Q_A \\
\bar{P}_{\text{elec}.B} &= \int_0^{t_B} (cP_{\text{elec}} + d + q(t)) dt \bigg/ t_B = c\bar{P}_{\text{elec}.B} + d + Q_B
\end{align*}$$

(8)

where, $\bar{P}_{\text{elec}.A}$ and $\bar{P}_{\text{elec}.B}$ are the true mean values of the electrical power. $Q_A$ and $Q_B$ represent the power errors caused by $q(t)$ in the two tests.

The measured total power loss $\bar{P}_{\text{Loss.total}}$ can be expressed therefore as in Equation (9), which shows that the sensitivity errors $a$ and $c$ apply only on the restrained mechanical and electrical power differences. The offset error of the mechanical measurement is multiplied by the small speed difference, while the offset error of the electrical measurement is balanced out. The miscellaneous errors, on the contrary, can barely be reduced and as a result apply important influences on the uncertainty of $\bar{P}_{\text{Loss.total}}$.

$$\begin{align*}
\bar{P}_{\text{Loss.total}} &= a \left( \bar{P}_{\text{mech}.A} - \bar{P}_{\text{mech}.B} \right) + b \left( \bar{\omega}_A - \bar{\omega}_B \right) + R_A - R_B \\
&\quad + c \left( \bar{P}_{\text{elec}.A} - \bar{P}_{\text{elec}.B} \right) + Q_A - Q_B
\end{align*}$$

(9)

To derive the power loss of each test from $\bar{P}_{\text{Loss.total}}$, a proportion factor $k_A$ is introduced in Section 2.2. The value of $k_A$ should be around 0.5, which means test A and B have the same amount of power loss. In the calculation, a concrete $k_A$ value has to be assumed and the error of this assumption, namely the difference between the assumed value $k_A$ and the real proportion, can be defined as $k_A'$. Correspondingly, the assumed power loss in test A, considering the error of the assumption, can be expressed as in Equation (10). In further calculations of this paper, $k_A$ is assumed to be 0.5.

$$\bar{P}_{\text{Loss.A}} = (k_A + k_A')\bar{P}_{\text{Loss.total}}$$

(10)

where, $k_A$ is the assumed proportion value and $k_A'$ is the error of assumption.

The uncertainty of the efficiency is determined by the uncertainty of power loss as well as the uncertainty of the electrical power measurement together, as shown in Equation (5). In order to demonstrate the uncertainty calculation, an example is given here, where typical parameters of the wind turbine and conservative measurement uncertainties are adopted. Details of the parameters are listed in Table 1. The standard uncertainty of each error source is calculated based on uniform distribution within the error range. Uncertainty calculations in the paper are carried out in accordance with the GUM guide line [6].

For the uncertainty calculation of $\bar{P}_{\text{Loss.total}}$, all components in Equation (9) are listed and analysed in Table 2. For the purpose of demonstration, an efficiency of 95% is assumed. The corresponding power loss can be determined in Equation (11). As mentioned in Section 2.1,
Table 1. Adopted parameters and corresponding standard uncertainty calculation

| Adopted parameters                      | Value       | Standard uncertainty |
|-----------------------------------------|-------------|----------------------|
| Rated power                             | 5 MW        | -                    |
| Rated rotor speed                       | 9.5 rpm     | -                    |
| Rated torque                            | ∼5000 kN·m | -                    |
| Efficiency (rated power)                | ∼95 %       | -                    |
| Sensitivity error of torque measurement a (of reading) | ±5 %        | ua = 2.89 %          |
| Offset error of torque measurement b    | ±50 kN·m    | ub = 28.87 kN·m      |
| Miscellaneous errors of torque measurement r | ±15 kN·m   | ur = 8.66 kN·m      |
| Sensitivity error of electrical power c (of reading) | ±2.0 %     | uc = 1.15 %          |
| Offset error of electrical power d      | ∼0          | ud = 0               |
| Miscellaneous errors of electrical power q | ±10 kW     | uq = 5.78 kW        |
| Error of power loss distribution assumption k′A | ±5 %        | ukA = 2.89 %        |

The electrical power of the turbine in test B is kept as close as possible to the power in test A. But since the powers cannot be controlled to be exactly the same, a 0.5 % difference of electrical power (25 kW) is adopted. As a result, Equation (11) can be split into the electrical and mechanical parts, expressed in Equation (12). The difference of mean rotating speed in the two tests can be easily measured and calculated. Here, a difference of 1 % is considered to be conservative, as expressed in Equation (13).

\[
\bar{P}_{Loss, total} = \bar{P}_{mech, A} - \bar{P}_{mech, B} + \bar{P}_{elec, B} - \bar{P}_{elec, A} \approx 2 \times 5000 \times 5 \% = 500 \text{ kW} \quad (11)
\]
\[
\begin{cases}
\bar{P}_{mech, A} - \bar{P}_{mech, B} = 475 \text{ kW} \\
\bar{P}_{elec, B} - \bar{P}_{elec, A} = 25 \text{ kW}
\end{cases} \quad (12)
\]
\[
\bar{\omega}_A - \bar{\omega}_B = 0.011 \text{ rad/s} \quad (13)
\]

Table 2. Standard uncertainty of the measured total power loss

| Uncertainty components | Calculation of uncertainty | Standard uncertainty/kW |
|------------------------|----------------------------|-------------------------|
| a (\bar{P}_{mech, A} - \bar{P}_{mech, B}) | 475ua | 13.73 |
| c (\bar{P}_{elec, A} - \bar{P}_{elec, B}) | 25uc | 0.29 |
| b (\bar{\omega}_A - \bar{\omega}_B) | 0.011ub | 0.32 |
| RA | ur\bar{\omega}_A | 9.07 |
| RB | ur\bar{\omega}_B | 9.07 |
| QA | uq | 5.78 |
| QB | uq | 5.78 |

Resultant \( u_{Loss, total} = 20.50 \text{ kW} \)

The results in Table 2 show that, the uncertainty components caused by the sensitivity and offset errors are dramatically reduced and as a result, the other sources of error (referred as “miscellaneous errors” in Table 1) become very important. In fact, the most important benefit of the presented solution is to sharply reduce the influence of the sensitivity and offset errors
of the measurement. This has a great meaning especially for the torque measurement without professional calibration. For the other errors in the measurement however, this method has limited improvement.

The standard uncertainty of the mean measured electrical power in test A is calculated in Equation (14).

$$u_{elec,A} = \sqrt{(5000 \times 1.15 \%)^2 + 10^2} = 58.37 \text{ kW}$$  \hspace{1cm} (14)\]

The efficiency calculation Equation (5) can be expressed as a function of $\bar{P}_{elec.A}$, $\bar{P}_{elec.A}$ in Equation (15). With the uncertainties of all the three variables already known, the uncertainty of the efficiency can be determined in Table 3 as $U = 0.66 \%$, with the level of confidence at about 95 % (coverage factor of 2). It is worth pointing out that, the variables $\bar{P}_{elec.A}$ and $\bar{P}_{Loss.total}$ are not independent and according to the GUM guideline, the cross term between these two variables needs to be considered. However, because the covariance of them are equivalent to the covariance between $\bar{P}_{elec.A}$ and $\bar{P}_{elec,B} - \bar{P}_{elec,A}$, the contribution of the cross term to the overall uncertainty is very small or even negative. Therefore, for simplicity and conservative reasons, the variables in Table 3 are considered to be independent from each other.

| Variable     | Standard uncertainty | Partial derivative | Uncertainty contribution |
|--------------|----------------------|--------------------|-------------------------|
| $\bar{P}_{elec.A}$ | 58.37                | 9.07E-06           | 0.053 %                 |
| $\bar{P}_{Loss.total}$ | 20.50                | 9.07E-05           | 0.158 %                 |
| $k_A$        | 2.89 %               | 0.0907             | 0.263 %                 |

Resultant standard uncertainty $u = 0.33 \%$

Expanded uncertainty $U = 0.66 \%$, with coverage factor 2.

Table 3 shows that the largest contribution of the efficiency uncertainty comes from the $k_A$ factor, which denotes the proportion of the power loss of test A in the total power loss. This is also the reason why the electrical power, instead of the mechanical torque of test B, is kept as close as possible to test A. Because in this way the electrical machine of the turbine will have the most similar power loss. In this paper, the error range of $k_A$ are conservatively assumed as ±5 %. In case of $k_A = 0.5$ (the losses of test A and B are the same), this assumption implies a difference of roughly ±10 % between the power losses. In case of better knowledge of the turbine and therefore a smaller uncertainty of $k_A$, better accuracy of the efficiency calculation can be achieved. Thanks to the new test solution presented in this paper, the uncertainty of the total power loss only plays a secondary role in the overall efficiency uncertainty in this case.

4. Test on a scaled test bench
As an example of the proposed test and measurement method, experimental tests are performed on a 50 kW laboratory dynamometer test bench described in [7]. Figure 3 shows a picture as well as the schematic diagram of the test bench. Three electrical machines are available in the drive train, denoted as machine 1, 2 and 3 in the figure. Machine 1 and 2 emulate the tandem drive motors of a turbine test bench and operate always in the same mode (either motor or
Machine 3 emulates the turbine drive train under test, and works as a counter part of the other two machines. A mechanical torque measurement is located between machine 2 and 3. Electrical power measurement on machine 3 is used for the efficiency calculation.

Figure 3. The 50kW small dynamometer test bench used in the tests

Two tests are carried out for measuring the efficiency of machine 3. In accordance with the test process in Section 2.2, machine 3 runs during test A in generator mode, and afterwards during test B in motor mode. In each test, three different load levels (level I, II and III) are reached and stayed on for about 3 minutes each. The load steps are shown in Table 4. On each load level, the demanded torque of machine 3 is set to be the same between the two tests. The rotating speed is controlled constant through out the tests, while the drive train rotates in opposite directions between test A and B. The opposite rotating speed ensures that the direction of mechanical torque stays the same and therefore the torque signal experiences a small change.

Table 4. Test process of the normal and reversed modes

| Test          | Load step | Speed/rpm | Demanded torque of machine 3 /N·m | Mode of machine 3 |
|---------------|-----------|-----------|-----------------------------------|------------------|
| A (Normal mode) | StepA.I   | 200       | -50                               | generator        |
|               | StepA.II  | 200       | -150                              | generator        |
|               | StepA.III | 200       | -300                              | generator        |
| B (Reversed mode) | StepB.I   | -200      | -50                               | motor            |
|               | StepB.II  | -200      | -150                              | motor            |
|               | StepB.III | -200      | -300                              | motor            |

Measured results of both electrical and mechanical powers from the two tests are shown in Figure 4. The mechanical power is calculated as the measured mechanical torque multiplied by the rotational speed, while the electrical power is given by the measurement in the electrical converter. Corresponding uncertainties are considered according to the sensor data sheets and assumptions. Both the torque and the electrical power measurement here have a large uncertainty of over 3%. The efficiency determined by the conventional method (with output power divided by input power) makes no sense, as it may even give an efficiency over 100%. However, because most of the uncertainty is contributed by the sensitivity and offset errors of the measurement, the new method can give a much smaller uncertainty and therefore also meaningful efficiency values, as shown in Table 5.

It can be observed from Figure 4 that the electrical power remains roughly the same in both modes, while the mechanical power experiences a clear amplitude change. Here the mechanical power change is a result of the power loss of machine 3 in the two tests. Assuming that the
Figure 4. Results of the mechanical and electrical power in both test modes. Electrical powers are displayed as positive and mechanical powers displayed as negative.

losses in the two tests are identical, the efficiency at each load level can be calculated in Table 5. As mentioned above in the paper, how to divide the total power loss into each individual test can be decided according to analysis and experience. A proper uncertainty has to be considered according to the corresponding assumption.

Table 5. Efficiency calculation of machine 3

| Quantity                        | Unit | Level I   | Level II  | Level III  |
|---------------------------------|------|-----------|-----------|------------|
| Mechanical power difference, $\bar{P}_{\text{mech}, A} - \bar{P}_{\text{mech}, B}$ | W    | 232.30    | 241.45    | 291.01     |
| Electrical power difference, $\bar{P}_{\text{elec}, A} - \bar{P}_{\text{elec}, B}$ | W    | 0.03      | -0.10     | -0.33      |
| Total power loss, $\bar{P}_{\text{Loss, total}}$ | W    | 232.27    | 241.55    | 291.34     |
| Power loss in test A, $\bar{P}_{\text{Loss, A}}$ | W    | 116.14    | 120.78    | 145.67     |
| Electrical power of machine 3, $\bar{P}_{\text{elec}, A}$ | W    | 1035.5    | 3108.1    | 6217.2     |
| Efficiency $\eta$              | -    | 89.9 %    | 96.3 %    | 97.7 %     |
| Uncertainty $U$, with coverage factor 2 | -    | 1.45 %    | 0.57 %    | 0.33 %     |

An important feature of the proposed solution can be recognised in Table 5, that the efficiency uncertainty decreases very evidently while the efficiency goes higher. This comes mainly from the uncertainty consideration of the $k_A$ factor and makes sense because higher accuracy is more important for the high efficiencies.

5. Conclusion

A new test and measurement method has been proposed for efficiency determination of the wind turbine drive trains without the requirement on the high accurate torque and electrical power measurements. The uncertainty of the determined efficiency at rated power is expected be lower than 1 %, while further reduction to below 0.5 % is also considered as possible. The method determines the power losses in the tests that based on the changes of the
torque and electrical power measurements, and therefore dramatically reduces the importance of their accuracy. Detailed test and calculation procedures are presented in the paper for the efficiency determination. Uncertainty analysis shows that the influence caused by the sensitivity and offset errors of the measurements can be dramatically reduced. An example with typical and conservative parameters are presented in the paper, demonstrating the uncertainty consideration. The method is tried out on a scaled test bench with the tests run in three different power levels. Efficiency of the studied machine is determined on each of the levels, while the corresponding efficiency is also given. Overall, the proposed method provides a way of efficiency determination for wind turbine drive trains. The method is expected to sharply reduce the uncertainty of the determined efficiency compared to the conventional method, while still based on the conventional measurement techniques that are commonly used in the industry.

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