An energy efficiency measurement test bench for gearboxes

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Abstract

Over the last decade, forced regulations and a growing social awareness with respect to energy efficiency have resulted in a renewed interest in the research for high efficient electrical machines. When an electrical motor is coupled to a machine, in many cases a gear or belt is used. Research shows a lack of information on energy efficiency of these components. In comparison to electrical motors and drives, there is very few regulation and if efficiency values can be found in catalogues, there’s no regulated test procedure available to validate the data. As a result, the reliability of these efficiency values is low and comparison between manufacturers and technologies is impossible.

Regulation on energy efficiency on the other hand evolves to a total system approach such as the new European fan directive 327/2011. Information on the efficiency of mechanical transmission components such as gearboxes and belt drives will be required to invest on which drive train part it is most recommended to invest in order to optimize the overall system efficiency.

Due to the lack of reliable information on energy efficiency of these components, the need for a test bench emerged. This paper discusses the test bench build for testing gearboxes up to 15kW in their entire working area. In the first part of the paper the technical set-up and influence factors on measurements are discussed. Secondly a test procedure will be proposed to ensure reliable and reproducible results. Finally the first results obtained by this procedure are presented and discussed.

Technical description and construction test bench

The purpose of the test bench is to measure gearbox efficiency at different loads and speeds within the allowed working area of the gearbox. Industrial gearboxes come in various types and power ranges. With the gearbox test bench it is possible to test a large scope of these types for a power range until 15kW.

Test benches for tests on gear sets are fairly common. In such cases it is just one gear wheel pair that is being tested (Figure 1). Wear, load capacity, oil level, seal friction and efficiency are subjects which can be tested with these test rigs.

![Figure 1: FZG back-to-back test rig with add-ons for efficiency tests [1]](image-url)
An industrial gearbox however usually contains more than one gear wheel pair. As can be seen in figure 2, the typical gearbox losses are located at some specific locations.

The gears are fixed in their right position by means of bearings, which have friction losses. While transmitting power, losses occur in the gear pairs as gear losses. The lubrication oil is transported via the gears which result in churning losses. To prevent the oil from leaking out of the gearbox, seals are implemented and they also result in some friction losses. To measure the efficiency of a complete gearbox a few different principles can be applied.

**Back-to-back mechanical**

An equal setup as in figure 1 could be used to test a complete gearbox. To do so two identical gearboxes with same ratio should be connected to each other at the input axes and respectively at output axes as shown in figure 3.

To load the transmissions a preload has to be set at ‘X’ and by applying a speed, different work points can be reached. The efficiency is determined by measuring the mechanical power from the motor which is equal to the losses from the two gearboxes together. This method could work for gearboxes with parallel axes but in many cases it's not possible to connect in- and output axes to each other. The rotation of both gearboxes is also opposite. Losses of gearboxes can be rotation dependent and gear boxes of the worm wheel type can sometimes only be run in one rotation sense. As a result, the back-to-back mechanical setup is not universally applicable.

**Calorimetric method**

This is a test method in which the losses in a machine are deduced from the heat produced by them. With the right equipment this would be possible to do and it can result in a very high accuracy, but reminding that the purpose is to test at a large set of different loads and speeds, the measuring time would be very large because at every working point the whole test set up has to be thermally stabilized which would take too much time.
Back to back electrical

Another way to measure the efficiency of a gearbox is to drive it with an electrical motor on one side and load the gearbox with a motor on the other side (figure 4). The drive motor sets the speed, the load motor sets the torque and works as a generator. The generated energy can be used for the drive motor or can be send back into the grid. In this case two torque and speed measurements are necessary to determine the efficiency.

![Figure 4: Back-to-back electrical](image)

Usually a gearbox reduces the speed and enlarges the input torque. This means the load motor has to be able to deliver a large torque, which generally means a motor with higher power range. To solve this problem a second gearbox can be implemented to reduce the torque so the load and drive motor can be equally sized. This is shown in figure 5.

![Figure 5: Back-to-back electrical with reducer](image)

This test method is used for the test bench discussed in the paper. The method allows a large range in types and power for gearboxes to be tested. Also it will be possible to measure the efficiency at different speed and load points in a flexible way. The accuracy of the efficiency determination depends on the speed and mainly on the torque measurement, so selection of these sensors will be important.

Actual test bench

sizing

A lot of industrial gearboxes are used for conveyors and other applications in the lower power range. Therefore a 15kW, 4 pole induction motor was selected at drive and load side. 4-pole because in gearbox catalogs a speed of 1400rpm is very common. Usually double speed is also allowed for gearboxes and with the 4 pole drive motor this can easily be reached with the help of a frequency converter. To ensure that the chassis doesn’t become too complex and heavy and therefore expensive, a maximum permissible torque of 1000Nm is chosen. To be able to load the gearbox at 1000Nm a torque reducer with a ratio of 10:1 is selected. Taking into account these parameters the range of gearboxes that can be tested is defined and presented in table 1.
Table 1: Measuring range test bench (limiting values in red)

<table>
<thead>
<tr>
<th>Input Power</th>
<th>Input Torque</th>
<th>Input speed</th>
<th>Max. ratio gearbox</th>
<th>Output torque gearbox</th>
<th>Output speed gearbox</th>
<th>Load torque</th>
<th>Load speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max P</td>
<td>15 kW</td>
<td>100 Nm</td>
<td>1460 rpm</td>
<td>10</td>
<td>1000 Nm</td>
<td>140 rpm</td>
<td>100 Nm</td>
</tr>
<tr>
<td></td>
<td>15 kW</td>
<td>50 Nm</td>
<td>2920 rpm</td>
<td>10</td>
<td>500 Nm</td>
<td>292 rpm</td>
<td>50 Nm</td>
</tr>
<tr>
<td>Min P</td>
<td>0.12 kW</td>
<td>0.78 Nm</td>
<td>1460 rpm</td>
<td>1282</td>
<td>1000 Nm</td>
<td>1,14 rpm</td>
<td>0.78 Nm</td>
</tr>
<tr>
<td></td>
<td>0.12 kW</td>
<td>0.39 Nm</td>
<td>2920 rpm</td>
<td>2564</td>
<td>1000 Nm</td>
<td>1,14 rpm</td>
<td>0.39 Nm</td>
</tr>
</tbody>
</table>

The nominal torque of a 15kW, 4 pole induction motor is about 100Nm. Given the maximum torque for the test bench of 1000Nm the ratio of a 15 kW gearbox cannot be higher than 10. When the input speed doubles the limiting factor is no longer the torque but the speed of the load motor.

**Measurement principle**

The aim is to conduct steady state measurements, i.e. constant speed and constant load torque. The loading of the gearbox is realized by means of the reducer gearbox via an induction machine with regenerative VSD in field oriented torque control mode and speed feedback. The drive side VSD, also with speed feedback, drives the gearbox at desired speed. By connecting both VSD’s via DC-bus the energy flows from generator to drive side and only the losses of the system have to be added to the grid.

The direct method is used to determine the overall efficiency. It requires accurate measurement of the mechanical in- and output power. The torque is measured by means of dedicated ‘dual range’ torque sensors with an accuracy of 0.1% full scale. At input side the torque range is 10Nm/100Nm and at output 100Nm/1000Nm. The speed is measured using an incremental encoder of 1204 pulses/rev. at input side and at output side a 360 pulses/rev. encoder embedded in the torque sensor. The ambient and gearbox temperature are measured and logged with calibrated thermocouples type K. Also the temperatures of the torque sensors are logged. The impact of temperature is explained further on in this paper.
The control of the test bench is done with an embedded dSPACE 1103 acquisition board in combination with Matlab Simulink and dSPACE ControlDesk. With this system the desired torque and speed set points are regulated and all the measurement data is synchronized captured and logged.

**Mechanical design**

Industrial gearboxes come in many sizes and types. In contradiction to electrical motors there is no standardization in terms of shaft height, shaft diameter, foot connection, etc… . Consequently the design of the test bench has to be very flexible in order to test all types of gearboxes. As can be seen in figure 7 the height of the drive motor, load motor and test gearbox can be adjusted independently. The base plate of the gearbox under test is adjustable so all the different dimensions for fixation can be handled. In figure 7 the setup is made for an angled gearbox but the drive motor can rotate 90° so a straight gearbox can be tested too.

![Figure 7: Mechanical design gearbox test bench](image)

**Measurement accuracy**

**Test bench accuracy**

The efficiency is determined by direct measurement of the mechanical in- and output power and can be calculated as follows:

\[
\eta_{\text{gearbox}} = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{M_{\text{out}} \times \omega_{\text{out}}}{M_{\text{in}} \times \omega_{\text{in}}}
\]  

(1)

- \(\eta_{\text{gearbox}}\): gearbox efficiency [\%]
- \(P_{\text{out}}\): output power [W]
- \(P_{\text{in}}\): input power [W]
- \(M_{\text{out}}\): output torque [Nm]
- \(M_{\text{in}}\): input torque [NM]
- \(\omega_{\text{out}}\): output speed [rpm]
- \(\omega_{\text{in}}\): input speed [rpm]
- \(i\): ratio [/]

Because of the mechanical design of the gears the speed ratio can be considered as constant [2]. If the ratio is brought into the calculation, formula (1) evolves to:

\[
i = \frac{\omega_{\text{in}}}{\omega_{\text{out}}}
\]

\[
\eta_{\text{gearbox}} = \frac{M_{\text{out}}}{M_{\text{in}} \times i}
\]

(2)
In this way the fault on the speed measurement doesn’t affect the efficiency value if the exact ratio can be determined. The accuracy of the efficiency determination is then solely depending on the torque measurement at in- and output. The two selected torque sensors are equipped with strain gauges and have a contactless signal transmission from rotor to stator. The sensors have a dual torque range to benefit the accuracy at low torque measurement points. The torque sensor specs are listed in table 2.

<table>
<thead>
<tr>
<th>Table 2: Specifications torque sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input torque ( M_{\text{in}} )</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Accuracy</td>
</tr>
<tr>
<td>Speed measurement</td>
</tr>
<tr>
<td>Output</td>
</tr>
</tbody>
</table>

The relative fault (RF) on the efficiency can be calculated by summing up the relative faults on the torque measurements (formula 3).

\[
\eta = \frac{M_{\text{out}}}{M_{\text{in}}}, \quad \text{RF}_{\text{tot}}(\eta) = \text{RF}(M_{\text{in}}) + \text{RF}(M_{\text{out}}) = \frac{AF(M_{\text{in}})}{|M_{\text{in}}|} + \frac{AF(M_{\text{out}})}{|M_{\text{out}}|} \quad (3)
\]

The fault on the torque consists of three different parts. The torque signal itself has a fault of 0,1% full scale. The analog voltage output signal which represents the torque is captured via an analog digital converter of the dSPACE acquisition board. Due to the 16 bits resolution of the AD converter over a bandwidth of 20V (±10V) this absolute fault (AF) is:

\[
AF_{\text{resolution}} = \frac{20V}{2^{16}} = 0,3mV \quad (4)
\]

The fault given by the manufacturer on the AD conversion is 0,25%. This fault together with faults due to the cables and signal isolation are compensated by calibrating the acquisition system. A constant voltage is put on the system input and precisely measured with a voltage meter with an accuracy of 0,1%. The measured calibration values are compared and used to correct the output signal. Because of this calibration the fault is reduced from 0,25% to 0,1%.

The fault calculation can be illustrated by following example. Measured input torque is 95Nm and output torque is 920Nm for a gearbox with ratio 10.

**Fault input torque sensor:**
Range 100Nm; 0,1% full scale
\[ AF_{M_{\text{in}}} = 100Nm \times \frac{0,1}{100} = \pm 0,1Nm \]

**Fault A/D converter input signal:**
Range 10V; 0,1% full scale
\[ AF_{AD_{\text{in}}} = 10 \cdot \frac{0,1}{100} = \pm 0,01V = \pm 10mV \]
\[ 100Nm = 10V \]
\[ AF_{AD_{\text{in}}} = \pm 0,10Nm \]

**Fault resolution converter input signal:** 100Nm = 10V;
\[ AF_{R_{\text{out}}} = 0,0003V \times 10Nm/V = 0,003Nm \]

**Fault output torque sensor:** Range 1000Nm; 0,1% full scale
\[ AF_{M_{out}} = 1000 Nm \times \frac{0.1}{100} = \pm 1 Nm \]

**Fault A/D converter input signal:**
Range tot 10V; 0,25% full scale
\[ AF_{AD_{out}} = 10 \times \frac{0.1}{100} = \pm 0.01V = \pm 10mV \]
\[ 1000 Nm \times 10V \]
\[ AF_{AD_{out}} = \pm 1 Nm \]

**Fault resolution converter output signal:**
\[ 1000 Nm \times 10V; \]
\[ AF_{R_{out}} = 0,0003V \times 100 Nm/V = 0.03 Nm \]

**Fault on efficiency:**
\[ RF(tot) = \frac{AF(M_{in}) + AF(AD_{in}) + AF(R_{in})}{|M_{in}|} + \frac{AF(M_{out}) + AF(AD_{out}) + AF(R_{out})}{|M_{out}|} \]
\[ = \frac{0.1 + 0.1 + 0.003}{95} + \frac{1 + 1 + 0.03}{920} = 0.00434 \]
\[ \eta = \frac{M_{out}}{i \times M_{in}} = \frac{920 Nm}{95 Nm \times 10} = 0.968 \]
\[ AF(tot) = |\eta| \cdot RF(tot) = 0.968 \times 0.00434 = 0.00420 \]
\[ \eta = 96.8 \% \pm 0.4\% \]

An absolute error of ±0,4% is reached with a measurement point close to full range of the sensors. If the torque sensors only would have a single range and a point at low load would be taken, the fault will be much larger. This is shown in table 3 were an example is given for two different load points.

<table>
<thead>
<tr>
<th></th>
<th>Single range sensors</th>
<th>Dual range sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M\textsubscript{in} = 8Nm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>M\textsubscript{out} = 76Nm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total RF</td>
<td>5,2086%</td>
<td>0,5209%</td>
</tr>
<tr>
<td>Total AF</td>
<td>95% ±4,9%</td>
<td>95% ±0,5%</td>
</tr>
</tbody>
</table>

| **M\textsubscript{in} = 12Nm** |                      |                    |
| **M\textsubscript{out} = 115Nm** |                      | **Worst case**     |
| Total RF               | 3,5\%                | 3,5\%              |
| Total AF               | 95,8 ±3,3\%         | 95,8 ±3,3\%       |

If the measured torques lie just beneath the first torque range the fault gets high when only one range would be available. With the dual range sensor this is avoided. When a point just above the first range (10Nm resp. 100Nm) is taken, the fault will be at its highest. In table 3 one can see in worst case the absolute error on the test bench is about 3,3%.

**Temperature dependency measurements**

An important parameter which influences the efficiency measurements is the temperature. Figure 8 shows a graph where an efficiency measurement is performed at different ambient temperatures on a reference gearbox.
The gearbox is loaded with a constant nominal torque and runs at nominal speed. The tests show a significant efficiency difference when the ambient temperature varies. A temperature rise of 10°C results in an efficiency rise of ±2%. The causes of the temperature dependency can be found partly in the temperature sensitivity of the torque sensor. To counteract these effects a thermal model was made up for the torque sensor. By measuring the temperature of the sensors at every measuring point, the model can be used to compensate this error. Other causes are the gearbox depended parameters such as oil temperature, mounting position, oil level and mechanical properties. The oil temperature influences the viscosity of the oil which influences o.a. the friction losses and thus the efficiency of the gearbox [3]. To make sure the test bench gives reproducible measurements it is important to stabilize the ambient temperature. Therefore the complete test setup was placed in a temperature controlled room.

Measurement procedure (Flowchart) gearbox efficiency tests

In order to guarantee reproducibility and obtain accurate measurements, a measurement protocol has been setup. The gearbox under test first is fixed on the test bench and the gearbox in- and output shaft are precisely aligned with respectively the shaft of the drive and load motor. The oil level has to be checked with the prescribed level in accordance with is installation position.

Running-in test

Before starting the actual efficiency measurements, the gearbox is subjected to a running-in test. In the first operating hours a gearbox doesn’t work at its nominal efficiency. First the gears will run in and in this way ‘polish themselves’. In the most gearbox catalogs this running-in is also stated and a running-in period of 24 to 48 hours is mentioned before nominal values are reached. To start up the running-in test the gearbox is driven and loaded at rated values for a minimum of 48 hours. After this period the measurement values, especially efficiency and gearbox temperature, are checked until they stabilize.

Start-up test

This second test is carried out to confirm the gearbox has run in and reproducible measurements can be obtained. After cooling down from the running-in test until ambient temperature it is started up again at nominal load and speed. If the same gearbox temperature and efficiency are being reached the next step in the procedure can be taken. Otherwise, the start-up test is performed again from ambient temperature until reproducible results are obtained. Usually this start-up test takes about 1 to 2 hours depending on the size of the gearbox. The stabilized gearbox temperature will be used as reference temperature for the next experiments.
ISO efficiency map measurement

Before starting the tests a measuring grid has to be defined. Using the catalog data the maximum speed and corresponding maximum load are specified. The determination of the minimum number of measurement points required to obtain an accurate ISO efficiency map for a gearbox is important. With the experience gathered out of a previous project [4] concerning ISO efficiency maps of VSD’s and electrical motors a measuring grid (figure 8) of 16 different torque values and 19 speed measurement points is defined.

As can be seen from figure 9, the measurement points are not evenly distributed over the entire operating area of the gearbox. A higher concentration is required in the regions near zero torque and zero speed because it is expected that the efficiency in those regions varies more.

The measurements start directly after the start-up test when the gearbox runs at operating temperature. During the measurements at different torques and speeds, a temperature window of 3°C is allowed. After measuring all the points the measurement data is organized in matrices which can be handled in Matlab to construct ISO efficiency maps.

First test results

The first measurements with the test bench have been done for a comparison of a worm gearbox and a bevel gearbox. Both types are right angle transmissions which have a similar scope. The specifications of the gearboxes are presented in table 4.

<table>
<thead>
<tr>
<th>Table 4: Specifications worm and bevel gearbox</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Worm gearbox</strong></td>
</tr>
<tr>
<td>( \omega_{\text{in}} ) (rpm)</td>
</tr>
<tr>
<td>( i )</td>
</tr>
<tr>
<td>( \omega_{\text{out}} ) (rpm)</td>
</tr>
<tr>
<td>( M_{\text{out}} ) (Nm)</td>
</tr>
<tr>
<td>( P ) (kW)</td>
</tr>
<tr>
<td>( \eta_{\text{catalog}} ) (%)</td>
</tr>
<tr>
<td><strong>Gear stages</strong></td>
</tr>
<tr>
<td><strong>Oil viscosity (mm²/s)</strong></td>
</tr>
<tr>
<td><strong>Ambient temperature (°C)</strong></td>
</tr>
</tbody>
</table>
The worm gear unit reached a stable efficiency of ±74% at nominal load after about 70 hours. This means a 12% higher efficiency compared to the catalog value. After about 90 hours the bevel gear reached a stable efficiency of ±84% resulting in a 11% lower efficiency than specified in the catalog. These differences show that catalog efficiency doesn’t give a good view on the performance of the gearbox. A reason could be, in comparison to electric motors, that there is no standardized test procedure by which the efficiency of gear units can be determined. Each manufacturer probably has its own methods and therefore catalog efficiencies of different manufactures are not comparable.

Next the measurements for the ISO efficiency map where carried out and the results are shown in figure 10 and 11. For the worm gearbox, at rated speed and torque the efficiency is maximum. The efficiency decreases both with decreasing speed as torque.

![Figure 10: ISO efficiency map worm gearbox](image1)

![Figure 11: ISO efficiency map bevel gearbox](image2)

For the bevel gearbox, the highest efficiency is achieved at low speed and rated torque. It is also noticeable that a speed variation has a much smaller effect on the efficiency compared to a torque variation. Only when the speed falls below 60% of the nominal speed, with torque kept constant, it has a positive impact on the efficiency. A torque reduction always leads to a lower efficiency.

In order to easily compare the two measurements with each other, a difference contour map is generated and presented in figure 12. At rated speed and load the efficiency of the bevel gear unit is about 10% higher compared to the worm gearbox. When the speed decreases and torque remains stable, this efficiency gain increases up to 38%. For low torque, the efficiency gain is lower.
Figure 12: Difference contour map: bevel versus worm gearbox

Conclusions

This paper discusses the methods, design and measurement principles of a test bench to measure the efficiency of a large range of types of gearboxes. Also typical influences on gearbox efficiency measurements are discussed. A flowchart to perform the measurements is designed to ensure reproducible and trustworthy measurements. At last the first measurements on a worm- and bevel gearbox are presented and shortly discussed.

The accuracy of the efficiency measurement mainly dependents on the torque sensors. Therefore two dual range sensors were selected with a high accuracy. Temperature has a large impact on the determination of the efficiency. When the ambient temperature varies, it affects the torque sensors and the gearbox temperature thus the gearbox oil temperature, and so also the efficiency varies. Not only oil temperature but also oil level and mounting position, which also influences the oil immersion depth of the gears, influences the gearbox efficiency. All these influence factors show the need for some standardization in the field of efficiency testing for gearboxes.

With the first measurements a large difference is noticed between measured efficiencies and catalogue values. Here it would also be helpful to have standardization. Manufacturers now determine the efficiency in different ways, with different ambient temperatures, based on theoretical calculations, etc. As a result, the catalogue values can not be compared.

The ISO efficiency maps of the worm and bevel gear also show that the maximum efficiency is not reached at the same working point. If the gearbox runs at a lower torque the efficiency drops. Especially with worm gears this is also the case when speed drops. At this time such information isn’t available for customers and machine builders causing them to make a selection for a particular machine which is not optimal in terms of energy efficiency.

Further research is still needed and is being done at the moment to enlarge the scope of measurements for different types, ratios and powers. This will help to inform gearbox users on how to select the best gear for their application.

Usage of a more efficient gearbox requires less power from the electric motor to produce the same output torque. Downsizing the motor rating can add to system efficiency and cost.
References


