The intelligent gearbox – more performance and predictable maintenance

Dietmar Tilch, ZF Industrieantriebe Witten GmbH

MDA Forum, Hannover Fair 2017
Wind Power Technology In ZF Group

Mobility across the board

ZF organization is divided into 7 major divisions:

<table>
<thead>
<tr>
<th>Car Powertrain Technology</th>
<th>Car Chassis Technology</th>
<th>Commercial Vehicle Technology</th>
<th>Industrial Technology</th>
<th>E-Mobility</th>
<th>ZF Aftermarket</th>
<th>Active &amp; Passive Safety Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Off-Highway Systems</td>
<td></td>
<td></td>
<td>Wind Power Technology</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Test Systems</td>
<td></td>
<td></td>
<td>Industrial Drives</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Special Driveline Technology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Marine Propulsion Systems</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Aviation Technology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wind Power Technology</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Industrial Drives</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ZF Puts Wind Energy In Motion

Joining forces for the new generation of wind energy

In the gearbox industry since 1979
Manufacturing capacity on annual basis ~ 18,000 MW
Worldwide manufacturing & service coverage Balanced global
Manufacturing depth and processes All critical processes in-house
Global installed base > 100,000 MW whereof 3 MW segment > 15,000 MW
Product portfolio – on- and offshore 0.8 MW - 8.0 MW
Full Service Offering Dedicated service centers in all major wind market
> 100 GW
ZF gearbox capacity installed

> 55,000
Gearboxes

Single point of contact for ~25%* of worldwide installed wind capacity

*) ~400GW of geared wind turbines installed (end 2016, cumulative); thereof >100GW installed by ZF Wind Power
The Wind Power Gearbox as an Intelligent Mechanical System

**Essential operation parameters**
- Speed
- Torque
- Temperatures
- Lubrication status

**Multiple Sensor Network**
- Dynamic Load Monitor
- Vibration
- Oil parameters
- Cameras
- etc.

**On-site data evaluation** and communication to
- turbine controller (real time)
- Cloud: predictive maintenance

Cloud services provide data overview, history and trends as well as:
- Automated detection of abnormalities
- Remaining lifetime calculations
- Remote monitoring information
Dynamic Load Monitoring
Torque Measurement Principle

Determination of position 1 down to a few µm

Determination of position 2 down to a few µm

Possible measurement positions inside a gearbox

Contactless robust inductive sensor
Potential For Energy Yield Increase
Based on individual wind turbine drive train load measurement

With individual drive train load measurement

Higher energy yield without risk
Optimal Drive Train Load Reduction Based On Closed Loop Control

Gearbox as an ideal drive train load measurement position

**Without damping**

- Turbine control
- RPM
- Torque measurement
- Closed loop damping based on torque measurement

**Current state of the art damping** (based on generator signals)

- Damping based on generator signals
- RPM
- Torque measurement
- Stress
- Dynamic torque load
- Average torque load

**Closed loop damping based on torque measurement**

- Torque control
- RPM
- Torque measurement
- Damping in complete frequency range
- Safety margins reduces feasible power
- Potential for torque/power increase
- Dynamic torque load
- Average torque load
- Overload

- Stress
- Dynamic torque load
- Average torque load

- No damping
- Damping
- Risk for excitation
Optimal Drive Train Load Reduction Based On Closed Loop Control

Multi-Body-Simulation of a typical multi megawatt wind turbine

Without damping

- Current state of the art damping
- Closed loop damping

**Current state of the art**

- Torque amplitude
- Frequency [Hz]

**Closed loop damping**

- Torque amplitude
- Frequency [Hz]

Reduction of torque amplitudes caused by wind turbulences (especially storms)

Excitation with current state of the art damping could result in higher torque amplitudes due to open loop control

Reduction of further oscillation with closed loop damping

- better rotor aerodynamics
- higher energy yield
The Wind Power Gearbox As An Intelligent Mechanical System

Cloud services provide data overview, history and trends as well as:
- Automated detection of abnormalities
- Remaining lifetime calculations
- Remote monitoring information

OEM and operator benefits:
-> ZF enables the reduction of the Cost of Energy sustainably by:
- Minimizing Operational Expenditures
  - reduced stress and wear
  - demand-oriented maintenance
  - extended oil life cycles
- Optimizing the turbine performance
Contribution of Intelligent Performance Management to reducing the Cost of Energy

LCOE Drivers

- AEP
  - Reliable & efficient operation
  - Performance increase
- CAPEX
  - Lifetime extension
  - Value engineering
- OPEX
  - Maintenance optimization
  - Increase availability

Cloud-based Performance Management, Park Overview

Drive Train Performance Status
- Y115 (7)
- Y115 (9)
- Y115 (8)
- Y115 (10)

Gearbox Load Status
- Y115 (7)
- Y115 (9)
- Y115 (8)
- Y115 (10)

Farm Statistics
- Drive Train Dynamics
- Full Load Hours
- Load Status
  - Y115 (7)
  - Y115 (9)
  - Y115 (8)
  - Y115 (10)

Lubrication Monitoring
- Y115 (7)
- Y115 (9)
- Y115 (8)
- Y115 (10)

Vibration Monitoring
- Y115 (7)
- Y115 (9)
- Y115 (8)
- Y115 (10)
Drive Train Dynamics Dashboard

Drive Train Characteristics

Drive Train Dynamics

Performance Potentials

HSS Speed, Torque and Power Analysis

Drive Train Dynamics

<table>
<thead>
<tr>
<th>Power Group (kW)</th>
<th>Operating Hours [h]</th>
<th>Dynamic Factor [%]</th>
<th>Highest Dynamic FFT Amplitude [N.m]</th>
<th>Lowest Dynamic FFT Amplitude [N.m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 200</td>
<td>19</td>
<td>41</td>
<td>57</td>
<td>5</td>
</tr>
<tr>
<td>201 - 400</td>
<td>264</td>
<td>39</td>
<td>53</td>
<td>5</td>
</tr>
<tr>
<td>401 - 600</td>
<td>378</td>
<td>38</td>
<td>59</td>
<td>5</td>
</tr>
<tr>
<td>601 - 800</td>
<td>256</td>
<td>43</td>
<td>54</td>
<td>5</td>
</tr>
<tr>
<td>801 - 1000</td>
<td>191</td>
<td>48</td>
<td>65</td>
<td>5</td>
</tr>
<tr>
<td>1001 - 1200</td>
<td>152</td>
<td>53</td>
<td>59</td>
<td>6</td>
</tr>
<tr>
<td>1201 - 1400</td>
<td>122</td>
<td>58</td>
<td>87</td>
<td>6</td>
</tr>
<tr>
<td>1401 - 1600</td>
<td>111</td>
<td>62</td>
<td>73</td>
<td>6</td>
</tr>
<tr>
<td>1601 - 1800</td>
<td>112</td>
<td>67</td>
<td>57</td>
<td>7</td>
</tr>
<tr>
<td>1801 - 2000</td>
<td>196</td>
<td>71</td>
<td>69</td>
<td>8</td>
</tr>
<tr>
<td>2001 - 2200</td>
<td>467</td>
<td>69</td>
<td>67</td>
<td>8</td>
</tr>
<tr>
<td>2201 - 2400</td>
<td>0</td>
<td>0</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Torque Frequency Analysis

Speed Frequency Analysis

Torque Order Analysis

Speed Order Analysis

© ZF Friedrichshafen AG
Critical Drive Train Dynamics

Drive Train Characteristics

Drive Train Dynamics

Performance Potentials

HSS Speed, Torque and Power Analysis

Drive Train Dynamics

<table>
<thead>
<tr>
<th>Power Group (kW)</th>
<th>Operating Hours [h]</th>
<th>Dynamic Factor [%]</th>
<th>Highest Dynamic FRT Amplitude [kHz]</th>
<th>Lowest Dynamic FRT Amplitude [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 200</td>
<td>19</td>
<td>56</td>
<td>70</td>
<td>8</td>
</tr>
<tr>
<td>0 - 400</td>
<td>279</td>
<td>57</td>
<td>72</td>
<td>7</td>
</tr>
<tr>
<td>0 - 600</td>
<td>307</td>
<td>64</td>
<td>79</td>
<td>8</td>
</tr>
<tr>
<td>0 - 800</td>
<td>153</td>
<td>81</td>
<td>95</td>
<td>10</td>
</tr>
<tr>
<td>0 - 1000</td>
<td>87</td>
<td>96</td>
<td>81</td>
<td>11</td>
</tr>
<tr>
<td>1001 - 1200</td>
<td>59</td>
<td>109</td>
<td>55</td>
<td>13</td>
</tr>
<tr>
<td>1201 - 1400</td>
<td>57</td>
<td>118</td>
<td>96</td>
<td>15</td>
</tr>
<tr>
<td>1401 - 1600</td>
<td>80</td>
<td>117</td>
<td>92</td>
<td>11</td>
</tr>
<tr>
<td>1601 - 1800</td>
<td>141</td>
<td>114</td>
<td>94</td>
<td>12</td>
</tr>
<tr>
<td>1801 - 2000</td>
<td>205</td>
<td>119</td>
<td>105</td>
<td>14</td>
</tr>
<tr>
<td>2001 - 2400</td>
<td>467</td>
<td>110</td>
<td>100</td>
<td>13</td>
</tr>
<tr>
<td>2401 - 2400</td>
<td>0</td>
<td>0</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Torque Frequency Analysis

Speed Frequency Analysis

Torque Order Analysis

Speed Order Analysis

© ZF Friedrichshafen AG
Load based Lifetime Calculation

**Gearbox Configuration**

- Gearbox Overview
- Full Load Hours
- Consumed Lifecycle of Bearings

**Details**

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Stage</th>
<th>Consumed Lifetime</th>
<th>Gear Comp.</th>
<th>Stage</th>
<th>Failure Mechanism</th>
<th>Consumed Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBS_R5</td>
<td>2</td>
<td>3.1%</td>
<td>r_sun</td>
<td>1</td>
<td>Gear Root Breakage</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>LBS_G5</td>
<td>2</td>
<td>3.1%</td>
<td>r_sun</td>
<td>1</td>
<td>Surface Durability T=0</td>
<td>2.8%</td>
</tr>
<tr>
<td>HBS_R5</td>
<td>3</td>
<td>3.0%</td>
<td>r_sun</td>
<td>1</td>
<td>Surface Durability T=0</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>HBS_G5</td>
<td>3</td>
<td>3.1%</td>
<td>r_planet</td>
<td>1</td>
<td>Gear Root Breakage</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>LBS_R5</td>
<td>3</td>
<td>3.1%</td>
<td>r_planet</td>
<td>1</td>
<td>Surface Durability T=0</td>
<td>2.6%</td>
</tr>
<tr>
<td>HBS_R5</td>
<td>3</td>
<td>&lt; 0.1%</td>
<td>r_planet</td>
<td>1</td>
<td>Surface Durability T=0</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>HBS_G5</td>
<td>3</td>
<td>3.0%</td>
<td>r_ringwheel</td>
<td>1</td>
<td>Gear Root Breakage</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Planet_Lowspeed</td>
<td>3</td>
<td>3.1%</td>
<td>r_ringwheel</td>
<td>1</td>
<td>Surface Durability T=0</td>
<td>&lt; 0.1%</td>
</tr>
</tbody>
</table>

**Consumed Lifecycle of Bearings**

- HBS_R5
- LBS_G5
- LBS_R5
- HBS_G5
- Planet_Lowspeed

**Consumed Lifecycle of Gears**

- HBS-gear: Surface Durability T=0
- LBS-gear: Surface Durability T=0
- Planet-gear: Surface Durability T=0
The Intelligent Gearbox

Making wind power the leading renewable energy source

Intelligently designed  plus
Intelligently operated and maintained
Thank you

Meet you on our booth

Hall 25, A12