Side-by-Side Testing to Verify Improvements of Power Curves

6th Nordic Wind Power Conference,
4th of November 2014, Stockholm
Förderprojekte in der Windindustrie
Contents

• Description of Method
• Requirements
• Details
• Uncertainties
• Possibilities and limitations
What Does Side-by-Side Testing Mean?

- 2 adjacent turbines (Reference and Test Turbine)
- 2 periods (Training and Testing)
- Reference Turbine remains unchanged
- Power curve of Test Turbine is changed
- Shift of power to power relation is analysed

![Graph showing power comparison between Test and Reference Turbines during Testing and Training Periods]
Principle of Side-by-Side Testing or Relative Power Curve Analysis

Training Period
Before Change of Test Turbine

Evaluate $P_T$ as Function of $P_R$

Assume Power Curve of Test Turbine during Training Period

Testing Period
After Change of Test Turbine

Measurement $P_T$

PT as Function of $v_T$ during Testing Period

$v_T$

Comparison

Measurement $P_R$

$R$: Reference Turbine not changed
$T$: Test Turbine changed

$v_T$
Needed Data

- SCADA-data fully sufficient
- 10-minute resolution
- Data channels for Test Turbine and Reference Turbine

Required:
- active power output
- nacelle (azimuth) position
- status code turbine operational (can be generated via RPM)

Useful additional signals:
- RPM (rotor or generator)
- pitch angle
- air temperature
  (- nacelle anemometer)

- Mean, max, min, standard deviation of each channel preferred
- No wind speed measurement needed!
SCADA Data Needs Detailed Checking

- Double appearance of data
- Synchronisation of data of Test and Reference Turbine
- Plausibility of data
  - plausible range
  - consistency of different data channels of each turbine
  - consistency of same data channels of different turbines
- Consistency of WT settings in Training Period and Testing Period
- Northing, drifting of nacelle position signal
• Reference Turbine:
  Settings unchanged throughout Training Period and Testing Period

• Test Turbine:
  Settings change between Training and Testing Period, but unchanged within each of the two periods
Data Filtering

- Test Turbine and Reference Turbine operational, filtering by status code or e.g. by RPM signal
- Test Turbine and Reference Turbine not curtailed, filtering by status signal
- No blade icing, filtering by temperature
- Test Turbine and Reference Turbine free of wakes is often preferable, but no necessary condition
- In Testing Period: use only wind direction ranges and power ranges also covered by Training Period
Wind Direction Measurement

- Direction measurement needed for:
  - filtering of wake conditions
  - application of directional dependent power-to-power relation
- Realisation via nacelle position signal
Northing of nacelle position signals of both turbines against known breakings

Check of parity of corrected signals

Warning: nacelle position signal can drift!

Peaks appear at 30°, but are expected at 5°.
- Power-to-power relation is dependent on wind direction and wind speed.
- Binning $P_T$ as function of wind direction and $P_R$ in Training Period.
- Use $10^\circ$ wide wind direction bins and 5 power bins from 0kW to rated power.
• 1\textsuperscript{st} step: Chose wind direction bin according to nacelle azimuth position of Test Turbine

• 2\textsuperscript{nd} step: Reproduce power output of Test Turbine for case of non-optimised state by piecewise linear fit of correction matrix elements in the relevant direction bin according to measured power at Reference Turbine:

\[
P_{T,\text{simulated}} = \frac{P_{T,j,i} - P_{T,j,i-1}}{P_{R,j,i} - P_{R,j,i-1}} \left( P_{R,\text{measured}} - P_{R,j,i-1} \right) + P_{T,j,i-1}
\]

• 3\textsuperscript{rd} step: calculate wind speed at Test Turbine by piecewise linear fit of power curve assumed for Training Period according to \( P_{T,\text{simulated}} \) as gained from step 2:

\[
V_T = \frac{V_i - V_{i-1}}{P_{\text{non-opt},i} - P_{\text{non-opt},i-1}} \left( P_{T,\text{simulated}} - P_{\text{non-opt},i-1} \right) + V_{i-1}
\]
Result: Power Curve Raw Data

- $v_T$ from 3rd step combined with measured power output of Test Turbine in Testing Period gives power curve raw data in Testing Period (blue crosses)
- Method can also be applied in Training Period (red triangles)
• Use method in Training Period and compare result with assumed PC for Training Period
• Often unwanted trend due to binning effects
Solution to Overcome Binning Effects

- Rearrange assumed PC to identical bins as reproduced power curve by directly binning $P_{T,\text{simulated}}$ versus $v_T$ (black circles)
- Note: PC reproduced is binning $P_{T,\text{measured}}$ versus $v_T$ (blue crosses)
• Calculate \( v \) from power measured at Test Turbine and evaluated power curve: \( v(P_T) \)
• Calculate ratio of \( v(P_T) \) and \( v \) evaluated from power measured at Reference Turbine \( v(P_R) \) (for position at Test Turbine)
• Bin average ratio as function of wind direction
• Take out sectors where critical limit exceeded
Self-Consistency Test after Sector Reduction

- Difference of result for Testing Period and Training Period is measure of change of power-to-power relation
• Don’t use $P_R$ on x-axis! (too many assumptions)
• Use $P_{T,simulated}$: power simulated for Test Turbine for non-optimised case on basis of measured power of Reference Turbine and power-to-power matrix
Result: Improvement of Power Curve

- Testing Period
- PC assumed for Training Period, rearranged
- Improvement [%]

Diagram showing the relationship between P/P-rated and v/v-rated with improvement [%] on the y-axis and v/v-rated [-] on the x-axis. The graph includes data points and error bars, indicating a clear trend of improvement with increasing v/v-rated values.
### Result: Improvement of AEP

<table>
<thead>
<tr>
<th>v-average [m/s]</th>
<th>AEP measured [MWh]</th>
<th>uncertainty AEP [%]</th>
<th>AEP extrapolated [MWh]</th>
<th>AEP assumed PV before change [MWh]</th>
<th>improvement of AEP [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>1333</td>
<td>11</td>
<td>1333</td>
<td>1271</td>
<td>4.9</td>
</tr>
<tr>
<td>4.5</td>
<td>1952</td>
<td>12</td>
<td>1952</td>
<td>1867</td>
<td>4.6</td>
</tr>
<tr>
<td>5.0</td>
<td>2665</td>
<td>13</td>
<td>2667</td>
<td>2557</td>
<td>4.3</td>
</tr>
<tr>
<td>5.5</td>
<td>3436</td>
<td>15</td>
<td>3446</td>
<td>3315</td>
<td>3.9</td>
</tr>
<tr>
<td>6.0</td>
<td>4227</td>
<td>17</td>
<td>4260</td>
<td>4113</td>
<td>3.6</td>
</tr>
<tr>
<td>6.5</td>
<td>4998</td>
<td>19</td>
<td>5081</td>
<td>4923</td>
<td>3.2</td>
</tr>
<tr>
<td>7.0</td>
<td>5715</td>
<td>21</td>
<td>5889</td>
<td>5725</td>
<td>2.9</td>
</tr>
<tr>
<td>7.5</td>
<td>6354</td>
<td>22</td>
<td>6667</td>
<td>6503</td>
<td>2.5</td>
</tr>
<tr>
<td>8.0</td>
<td>6897</td>
<td>23</td>
<td>7405</td>
<td>7243</td>
<td>2.2</td>
</tr>
<tr>
<td>8.5</td>
<td>7339</td>
<td>24</td>
<td>8093</td>
<td>7936</td>
<td>2.0</td>
</tr>
<tr>
<td>9.0</td>
<td>7680</td>
<td>24</td>
<td>8724</td>
<td>8575</td>
<td>1.7</td>
</tr>
<tr>
<td>9.5</td>
<td>7926</td>
<td>24</td>
<td>9296</td>
<td>9155</td>
<td>1.5</td>
</tr>
<tr>
<td>10.0</td>
<td>8086</td>
<td>24</td>
<td>9804</td>
<td>9672</td>
<td>1.4</td>
</tr>
<tr>
<td>10.5</td>
<td>8170</td>
<td>24</td>
<td>10246</td>
<td>10124</td>
<td>1.2</td>
</tr>
<tr>
<td>11.0</td>
<td>8190</td>
<td>24</td>
<td>10623</td>
<td>10511</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Relevant Uncertainties:

- A1: statistical uncertainty of PC in Testing Period
- A2: statistical uncertainty of power-to-power relation
- B1: power curve reproduction capability (how well can the power curve assumed for the Training Period be reproduced with the method?)
- B2: possible shift of power-to-power relation with time

Irrelevant Uncertainties:

- Uncertainty of power measurements: evaluation process designed such that uncertainty almost entirely cancels out!
- Uncertainty due to influence of air density, turbulence intensity, wind shear, wind veer on power curve: change of influence between Training Period and Testing Period is nearly the same at Test Turbine and Reference Turbine and cancels out (big advantage over methods based on wind measurements!)
Assessment of Uncertainties

• A1: statistical uncertainty of PC in Testing Period
  - by variation of power values in wind speed bin as in IEC 61400-12-1
• A2: statistical uncertainty of power-to-power relation
  - equals statistical uncertainty of power curve reproduced for Training Period (scaled by change of power curve)
• B1: power curve reproduction capability
  - by deviations of assumed and reproduced power curve in Testing Period as gained from Power Curve Self-Consistency Test (reduced by statistical unc.)
• B2: possible shift of power-to-power relation with time
  - split Testing Period in two sub periods, or
  - evaluate change of sector self-consistency test from Training to Testing Period, or
  - assess how power relation of two unchanged Reference Turbines varies from Training to Testing Period
• Typical standard uncertainty in single bins: 1% to 2% of $P$
• Typical standard uncertainty in AEP: 0.2% to 1%
• Uncertainty in AEP much lower than in $P$ because dominating statistical uncertainties $A1$ and $A2$ are uncorrelated across wind speed bins
Minimisation of Uncertainties by Weighting Results of Different Tests

- L power curve tests:
  - same Test Turbine, different Reference Turbines
  - same Test Turbine, different direction sectors
  - different Test Turbines

- Weighting of L power curves in wind speed bin i:
  \[ P_i = \sum_{m=1}^{L} t_{i,m} \cdot P_{i,m} \quad v_i = \sum_{m=1}^{L} t_{i,m} \cdot v_{i,m} \quad \sum_{m=1}^{L} t_{i,m} = 1 \]

- Uncertainty component j in wind speed bin i of weighted power curve:
  \[ u_{i,j} = \sqrt{\sum_{m=1}^{L} \sum_{l=1}^{L} t_{i,m} u_{i,j,m} t_{i,m} u_{i,j,l} \rho_{i,j,m,l}} \]

- Selection of weighting factors \( t_{i,m} \) such that total uncertainty of weighted power curve in bin i is minimised:
  \[ u_{i,\text{total}} = \sqrt{\sum_{j=1}^{M} u_{i,j}^2} = \text{Min} \]
Strong uncertainty reduction possible by weighting due to high content of statistical uncertainties (often highly uncorrelated across tests)
Requirements on Test Site

- Good correlation of wind conditions at Test Turbine and Reference Turbine
  - distance up to 10D
  - maximum distance dependent on terrain complexity (lower distance in complex terrain)
  - sufficient correlation reflected by acceptable statistical uncertainty (A1 and A2)

- Applicability in complex terrain possible only by use of directional dependent power-to-power relation (otherwise only small direction sector applicable in complex terrain)

- Applicability in wakes possible only by use of directional dependent power-to-power relation
Advantages Side-by-Side Testing

• Cheap: only SCADA-data needed, no additional measurements
• No relevant sensor uncertainties
• Large wind direction sector applicable, shorter measurement period
• No air density normalisation needed (self normalising to reference air density of power curve assumed for Training Period)
• Results hardly influenced by turbulence intensity, wind shear or wind veer as Test Turbine influenced in the same way as Reference Turbine
• Hardly influenced by site effects and effects of vertical flow inclination due to directional dependent power-to-power relation
• Often strong uncertainty reduction possible by weighting results gained with different Reference Turbines
Disadvantages Side-by-Side Testing

- No information on wind speed above rated power of Reference Turbine: often not applicable for tracking change of power curve by increase of rated power
- Application requires presence of Reference Turbine
- Loss of wind data correlation at larger distances of Test Turbine and Reference Turbine
Conclusions

- Side-by-side testing is inexpensive and accurate
- Ideal for tracking changes of power curves
- Ideal for investigating success of optimisation measures
- Fully repeatable method with complete description of uncertainties has been developed
Thank you
Contact: a.albers@windguard.de