Predicting major interventions in PAWP

June 9th, 2015

Largest uncertainty in O&M cost is caused by exchange of major components (Ecolys, 2014)

Motivation

A2Sea Sea-Installer jack-up vessel
Aim

Determine the medium- to long-term financial risk of major component failure in Prinses Amalia wind park

Structure

1. Introduction
2. Failure modes and root causes
3. Long-term failure predictions
4. Short-term failure predictability
5. Maintenance optimization
6. Conclusions and recommendations
Introduction

Definition: Exchanging a main component in an offshore wind turbine, which requires a jack-up vessel.
Princess Amalia Wind Farm (PAWP)

IJmuiden, North Sea

Prinses Amalia windpark (PAWP)

60x V80 2MW Mk IV
Commissioned in 2008
3500 full load hrs

Good availability (96-98%)
• 16 GBX exchanges
• 5 main shaft exchanges
• 4 other exchanges

Similar sites:
Horns Rev (Vattenfall, 2012): 80x V80
Scroby Sands (EON, 2004): 30x V80
North Hoyle (RWE, 2003): 30x V80

Component characteristics

Introduction

Main bearing lay-out
Main shaft and gearbox assembly

Generator-side

High Speed stage
Planetary stage
Intermediare stage

Gearbox lay-out
What is a main component failure?
Introduction

“A component is no longer able to fulfill its function”
- Gear failure
- Bearing failure
- Shaft failure
- Electrical system failure
- Etc.

Borescope inspections on exchanged gearboxes

Failure modes and root causes

Introduction
- Failure modes and root causes
- Long-term predictability
- Short-term predictability
- Supporting numerical optimization
- Conclusions and recommendations
Failure modes

• Bearing failures
  • Spalling
  • Axial hairline cracks on inner ring

Location in wind farm
Failure modes and root causes

* Wind data from nearby Meestmast Noordwijk, 30km south of PAWP [Barth, 2008]
**Wind regime – Average wind speed**

Failure modes and root causes

Loads in drivetrain are introduced by wind:
- Are WTGs on locations with higher wind speed failing?

![Graph showing average wind speed over time](image)

* Based on PAWP 10min SCADA data from 2009 - 2014

**Wind regime – Turbulence intensity**

Failure modes and root causes

Turbulence intensity calculated according to:

\[ l = \frac{\sigma_u}{u} \]

- Are wind turbine which endure higher turbulence failing?

![Graph showing turbulence intensity over time](image)

* Based on PAWP 10min SCADA data from 2013 - 2014
**No. of (emergency) stops**

Failure modes and root causes

* Based on PAWP SCADA data from 2007 - 2015

---

**Suspected root causes**

Failure modes and root causes

**Root causes**

- Failures are load related, thus introduced by wind, braking, yawing, etc.
- It can be the case each failure has different root cause (high wind speeds, bad manufacturing, bad maintenance..)
- Debris from other parts of gearbox
- White-etching cracks (WECs)

---

**Hypothesis** | **Crack origin** | **Failure mechanism** | **Root cause**
---|---|---|---
NSK | Subsurface | Hydrogen enhanced localized plasticity (HELP) | Hydrogen embrittlement, due to lubricant decomposition
SKF | Surface | Brittle fracture followed by crack propagation due to corrosion fatigue cracking | Tensile stress, due to high surface traction
Hansen | Subsurface | Adiabatic shear bands | Elastic stress waves, due to impact on surface asperities
Schaeffler | Subsurface | Severe plastic deformation | Complex interaction between lubricant, surfaces, materials, and loads
How many failures should be expected?

Component exchanges at Scroby Sands wind farm (30x V80)
Great Yarmouth, North Sea

How to model failure rates?

Long-term failure rate predictions

Reliability modelling is performed according to Power Law Process (PLP), which follows Weibull distribution

- $\beta$ = shape parameter
- $\eta$ = scale parameter
How reliable are PAWP gearboxes?
Long-term failure rate predictions

Time-to-failure modelled on age, high correlation with:
- Production (capacity factor)
- Running hours (availability)
- Generator hours

Results:
- MTTF: 9.6 years
  - 80% confidence between 8.0 and 11.5 years
- $\beta = 2.68$

Benchmark:
- Offshore V80 wind farm: MTTF = 3.9 yrs
- Onshore population (3000 WTG):
  - MTTF = 11 years
  - Significant differences between wind farms and gearbox types

Expected gearbox exchanges in PAWP
Long-term failure rate predictions

83 exchanges expected (no reliability increase)
- 80% confidence bounds between 77 and 90.
75 exchanges expected (20% reliability increase)
Component exchanges at Scroby Sands wind farm (30x V80)
Great Yarmouth, North Sea

How far ahead can we predict failures?

Introduction

Failure modes and root causes
Long-term predictability
Short-term predictability
Gearbox exchange optimization

Conclusions and recommendations

Available data in PAWP

Short-term failure indicators

Gearbox
- SCADA:
  - Temperatures
  - SCADA alarm and status (available/down)
- Condition monitoring system (CMS): vibration
- Oil samples
- Visual inspection
Does temperature give an indication?
Short-term failure indicators

Feng et al. observed temperature increase due to failures:

\[ \Delta T = T_{\text{oil}} - T_{\text{nacelle}} \]

- Effect not observed in PAWP. Also investigated:

\[ \Delta T = T_{\text{oil}} - T_{\text{ambient}} \]

\[ T_{\text{oil,absolute}} \]

Conclusion: temperature vs. power level no good indicator for developing failures

How accurate is CMS?
Short-term failure indicators

Detectability of gearbox failures:
- Planetary stage are hard to detect
  - 3 months average prior to exchange
  - 2 months STD
- HSS and IMS failure are easier to detect (higher rotational speed)
  - Avg.: 11 months
Gearbox exchange optimization

Introduction
Failure modes and root causes
Long term predictability
Short term predictability
Gearbox exchange optimization
Conclusions and recommendations

What is the cost of different strategies?
Maintenance optimization

Comparison of batch and single exchange
- Cost per exchange: -51%
- Smaller share of mobilization costs: 10% vs. 26%
- Significant lower production losses for preventive exchange regime: -88%
  Preferred strategy

How to move to predictive campaign-based regime?
- Predict how many failures
- Predict which turbines

North Hoyle wind farm (RWE, 30 x V80)
Prestatyn, Irish Sea
What is the most optimal gearbox exchange strategy?

Maintenance optimization

Reactive strategy
6 weeks after detection of failure

Single annual campaign
July

Two annual campaigns
April & September

Three annual campaigns
March, June, October

Downtime due to different strategies

Maintenance optimization

Strategies results in different risk of lost production,
- Trade-off with mobilization cost
- Lower impact after subsidy expiration in Jan. 2018
PAWP strategy optimization
Maintenance optimization

Cost for each year modelled
Lowest total cost and risk after 2017 achieved by 2 annual campaigns

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive strategy</td>
<td>100%</td>
</tr>
<tr>
<td>1 annual campaign</td>
<td>96.0%</td>
</tr>
<tr>
<td>2 annual campaigns</td>
<td>93.6%</td>
</tr>
<tr>
<td>3 annual campaigns</td>
<td>92.4%</td>
</tr>
<tr>
<td>Optimal</td>
<td>79.3%</td>
</tr>
</tbody>
</table>

Year 10

PAWP sensitivity analysis
Maintenance optimization

Use optimal strategy (-21%)
- Schedule vessel for fixed periods
- Use synergies with other activities

Double detectability of failures (-19%)
- Educate on CMS
- Test different CMS systems
- Integrate data from all systems to acquire holistic view of main components

Reduce mobilization costs (-11%)
- Use synergies with nearby parks (OWEZ, LUD, Belgian WF)
- Use jack-ups located in nearby ports
- Draw up frameworks agreements with marine contractors (A2Sea, DBB)
Outlook – 350 MW wind farm
Maintenance optimization

Same optimization performed on future 350MW wind farm:

Conclusions and discussions
Conclusions
Major interventions in PAWP

1. Failure modes
   - Consistent failure modes, root-cause could not be determined

2. Long term predictions
   - 83 gearbox exchanges expected (no rel. increase) or 75 (20% increase)
   - Expected annual failure rate: 3 to 9

3. Short term failure indicators
   - CMS most suitable, avg. detectability: 3 months

4. Maintenance optimization
   - 21% cost reduction can be achieved with optimal strategy compared to reactive, or 8 Million euro
   - After 2018: Single or two campaigns preferred
**Recommendations**

- Increase reliability of gearboxes by research on WEC
- Focus on increasing predictability of failures for single campaign strategy
- Reduce cost of jack-up vessel
- Contact between industry and operators

**Questions?**
Workability at PAWP
Maintenance optimization

Gearbox exchange takes 1 day, main bearing exchange takes 2 days
- Need to take weather days into account
- Assumed:
  - summer: 25% delay
  - Spring/autumn: 50%
  - Winter: 100%

Most critical: jacking limits

<table>
<thead>
<tr>
<th></th>
<th>DBB Wind</th>
<th>DBB Wind Pioneer</th>
<th>DDB Wind Server</th>
<th>A2Sea Sealack</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$ [m]</td>
<td>1.25</td>
<td>2.5</td>
<td>3</td>
<td>1.5m</td>
</tr>
<tr>
<td>$V_W$ [m/s]</td>
<td>10</td>
<td>14</td>
<td>25.2</td>
<td></td>
</tr>
<tr>
<td>Current [kts]</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Simulation approach
Maintenance optimization

Monte-Carlo simulations are performed to model uncertainty in:
1. Time-to-failure
2. Weibull parameters
3. Detectibility