Investigation of wide band Fiber Bragg grating accelerometer use for rotating AC machinery condition monitoring

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Outline

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3. FBG wide band vibration monitoring system
4. Generator test rig
5. Bearing fault specific vibration frequencies
6. Measured Vibration spectra under bearing fault conditions
7. Generator electrical fault specific vibration frequencies
8. Measured Vibration spectrum for stator short-circuit and open circuit fault
9. Conclusions
Motivation

• Vibration analysis frequently used to detect mechanical and electrical faults in rotating machines

• Wind generators larger than 2MW show combined bearing and stator winding failures of more than 73%

• **Cost effective and robust** wide bandwidth vibrations required to replace currently used costly piezoelectric (PE) accelerometers
Fibre optics Vibration sensing

- Immune to EMI and high voltages
- Longer life
- Proven for monitoring low frequency end winding vibration in large generators
- Direct electrical output
- Distributed vibration sensing using Long Gauge technology
- Single sensor measures both temperature and vibration
# Large wind turbines failure statistics

![Graph showing failure statistics for drive train, structural, and electrical components of large wind turbines.](image)

<table>
<thead>
<tr>
<th>Component Type</th>
<th>Drive Train</th>
<th>Structural</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>2.6 days</td>
<td>1.8 days</td>
<td>3.1 days</td>
</tr>
</tbody>
</table>

UpWind: Design limits and solutions for very large wind turbines, EWEA 2011
Wind generator failure modes

Medium Generators

- Collector Rings: 16%
- Cooling System: 2%
- Other: 4%
- Rotor Leads: 4%
- Stator: 3%
- Bearings: 70%

Large Generators

- Collector Rings: 14%
- Rotor Leads: 4%
- Other: 1%
- Rotor Wedge: 4%
- Stator: 15%
- Bearings: 50%

1-2 MW

>2 MW
Wide Band Vibrofibre

Bandwidth of $\approx 1000$ Hz to cover bearing, stator/rotor electrical faults frequencies achieved by changing the diving board material to Polycarbonate
Performance and Characteristics

Interrogator unit and software interface

Accelerometer Reflection Spectrum

Response at 100 Hz vibration frequency

FBG accelerometer frequency response
Wind turbine generator test rig

Laboratory test bed (viewed from above)

Stator terminal box

Drive end bearing
Sensor performance testing

• Benchmarked against Bruel&Kjaer Pulse vibration platform utilising piezo-electric (PE) accelerometers

• Both sensor types mounted on generator frame

• Typical winding and bearing faults artificially introduced
Rolling bearing race frequencies

Outer race

\[ f_o = f_r \frac{N_b}{2} \left( 1 - \frac{D_b}{D_c} \cos \beta \right) \]

Inner race

\[ f_i = f_r \frac{N_b}{2} \left( 1 + \frac{D_b}{D_c} \cos \beta \right) \]

\( f_r \)=rotational frequency, \( N_b \)=number of rolling elements
\( D_b \)=ball diameter, \( D_c \)=cage diameter, \( \beta \)=contact angle
Bearing Fault Emulation

- Various severity of bearing outer race fault introduced in experiments

- Machined bearing fault (localised outer race fault)

- Laboratory generator bearing design data

<table>
<thead>
<tr>
<th>Drive-end</th>
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<tbody>
<tr>
<td>SKF 6313</td>
</tr>
<tr>
<td>$N_b = 8$</td>
</tr>
<tr>
<td>$f_o=3.07f_r$</td>
</tr>
<tr>
<td>$f_i=4.93f_r$</td>
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</table>
Spectrum showing bearing fault effects

Piezoelectric (top) and FBG (bottom) vibration frequency spectra
3mm outer race bearing fault at 1590 rpm
Zoom-in View

B&K, bearing fault vibration spectrum, 1590 rpm

QPS, bearing fault vibration spectrum, 1590 rpm

FE sensor

FBG sensor
Typical Stator Winding Faults

Winding configurations:

- **Healthy**
- **Open-circuit fault**
- **Short-circuit fault**

<table>
<thead>
<tr>
<th>Winding</th>
<th>Torque frequencies</th>
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</thead>
<tbody>
<tr>
<td>Balanced</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td>Unbalanced</td>
<td>$</td>
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</tbody>
</table>

- Achieved experimentally using stator terminal box

$k=0,1,2,3…$
$s=$slip
$p=$pole pairs
$f_s=$supply frequency
Spectrum showing short circuit fault effects

Piezoelectric (top) and FBG (bottom) vibration frequency spectra
stator short-circuit fault at 1590 rpm
Spectrum showing open circuit fault effects

Piezoelectric (top) and FBG (bottom) vibration frequency spectra

stator open-circuit fault at 1590 rpm
Variable Speed Operation

- Emulating realistic wind turbine variable speed operating conditions
- Open-circuit winding fault introduced and PE and FBG platforms compared

Typical measured generator speed profile
Transient vibration signal spectrum

Piezoelectric (top) and FBG (bottom) vibration short-time FFT spectra for variable speed operation with and without open-circuit fault.
Single fault frequency zoom-in

3d spectrogram, PE sensor

3d spectrogram, FBG sensor
Summary

• Wideband VibroFibre was shown to provide comparable performance to high cost PE sensor under electrical and mechanical fault conditions

• Improvements ongoing in sensor characteristics and signal processing to further enhance performance and bring it closer to PE benchmark

• Future work will show distributed vibration sensing and investigate sensor design with simultaneous temperature and vibration sensing ability

• VibroFibre can become a competitive alternative to current high cost sensing solutions
Thank You

Questions?