Wind Turbine Condition Monitoring

Cost Effective Retrofit Condition Monitoring
Structure of This Presentation

- Introduction & Overview
- Component #1: DLI
- Component #2: CCJensen
- Component #3: Macom Particle Counter
- Typical Installation
- Financial Justification
Section 1

Introduction & Overview
Cost-effective, integrated expert diagnostic system for WTG condition monitoring:

Core tool for monitoring wind turbine machine health

- Condition Information plus prevention
- Drives wind turbine enterprise management
  - lifecycle optimization
  - predictive maintenance programs

- Integrated Technologies:
  - Mechanical vibration monitoring
  - Oil particle counter
  - Filtration system
  - Speed sensor for test condition information
  - Temperature sensors

- Expert system with automated diagnostics:
  - Provides plain language diagnostics
  - Relieves burden of data analysis
Intelligent Integration of Technologies:

**Direct Benefits:**

- **Automated diagnostics** Provides practical, real-time information
  - Machinery fault statements
  - Repair recommendations
  - All in plain-language, easy to action format

- Facilitates efficient remote monitoring by specialists
  - Specialist effort concentrated on machines with reported problems
  - Supplements in-house expertise
System Components & Architecture

- **Diagnostics Technology**
  - DLI Expert Diagnostic System

- **Data Sources**
  - Vibration Monitoring and Analysis
  - Temperature & Speed Monitoring
  - Oil Particle Counting and Trending
    - MACOM Technologies TA-10

- **Prevention Element**
  - CC Jensen CJC FineFilter HDU 15/25 System
Sensor Suite on Typical Wind Turbine

- Main bearing
  - 2 Accelerometers, low frequency/high sensitivity
  - 1 Tachometer, Proximity switch type

- Gearbox
  - 1 MACOM TA-10 Oil Particle Counter
  - 1 CC Jensen CJC™ Fine Filter HDU 15/25 oil filter system
  - 4 standard accelerometers
  - 1 combined accelerometer/temperature sensor

- Generator
  - 3 standard accelerometers
  - 1 combined accelerometer/temperature sensor

- System readily configurable to all turbine models
NOTE:
Customer owns the data and controls access throughout the process.

Expandable to include any number of Wind Turbine assets regardless of geography.
Section 2: WindRisk PdM Component #1

DLI Engineering
Automated Diagnostics Expert System & Vibration Analysis
DLI Expert Diagnostic System

- Origin
  - 1988 US Navy Funded Program for Automated Machine Condition Assessment – Award winning

- Refinement
  - 1990 – Present: Through commercial applications

- Applicability
  - Turbines, Motors, Generators, Gears
  - Pumps, Fans, Compressors
  - Machine Tools, Separators

- Accuracy
  - 97% fault detection accuracy documented in studies

- Scope of Use
  - Provides remote monitoring of over 10,000 machines
  - Used in Hundreds of Industrial Portable Systems
  - Used in dozens of Online Machine Monitoring Systems
Typical Installation
Sprite MAX and multiplexer
Typical Wiring

Typical Wind Turbine
Sensor Arrangement and Wiring Diagram

channel number
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

Generator

Particle Counter

GEARBOX

Turbine Shaft

Main Bearing

RO485 – USB Converter
Vibration System Diagnostic Capabilities

- Main bearing wear, abnormal nacelle motion
- Gear wear
- Gearbox bearing wear
- Generator bearing wear, imbalance, misalignment
- Generator winding faults, uneven air gap, phase imbalance
Communication of Results

- Mimic display
- Web page
- Web connect
- ExpertALERT Analysis Program
  - Server stores 2 readings a day in master database
  - Clients synchronize with server
    - When convenient
    - Via DLI ftp site access
### Main Display

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<th>Switch Display</th>
<th>Turbine Status</th>
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<th>Fault Status Low Speed</th>
<th>Gear Temperature (°C)</th>
<th>Generator Speed</th>
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### Conditions

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<tr>
<th>Wind Speed</th>
<th>Wind Gust</th>
<th>Current</th>
<th>Daily High</th>
<th>Daily Average</th>
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<td>13.4 mph</td>
<td>14.0 mph</td>
<td>21.6 km/h</td>
<td>22.0 mph / 30.4 km/h</td>
<td>11.8 mph / 12.1 km/h</td>
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**Forecast**

This afternoon: Mostly sunny, with a steady temperature around 14. Wind chill values between -7 and zero. West wind around 14 mph.

Tonight: A 30 percent chance of snow. Mostly cloudy, with a low around 2. Wind chill values between -4 and -14. Southwest wind 11 to 16 mph becoming north. New snow accumulation of around an inch possible.


Wednesday Night: Mostly cloudy, with a low around 3. Wind chill values between -6 and -11. West wind between 11 and 13 mph.
Readout – Individual Turbine Display
Turbine -03

Available on any PC with MS Excel and Internet Access
Delivering Machine Intelligence

Detailed Results Web Page
Live CBM test results for each turbine

2-Pilot Turbine High Freq Tests

Automated Machine Condition Results
Produced by: SPRITE-198

CONDITION: SLIGHT

Current Time: 03/19/2007 9:50:07 PM GMT
Acquired: 03/19/2007 6:05 PM GMT
Speed: 1785 RPM
Maximum Level: 96 (-1) VdB [8R] at 1.00x6
FOM: 138

Repair Recommendation:
No Recommendation

Diagnostics:

SLIGHT GEAR MESH #2 PROBLEM is indicated by:
85 (+20) VdB [2T] at 5.53x
85 (+12) VdB [2R] at 5.53x

Produced by DLI Watchman® SpriteMAX ID: SPRITE-198
XML Feed Location: http://online.dliengineering.com/sprite198/DLIOntlineRGS.xml

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Detectable Faults

- TURBINE BEARING WEAR
- INDICATION OF TURBINE IMBALANCE
- GEAR MESH #1 PROBLEM
- GEAR MESH #2 PROBLEM
- GEAR MESH #3 PROBLEM
- GEARBOX BALL BEARING WEAR
- GEARBOX INPUT SHAFT LOOSENESS
- INTERMEDIATE SHAFT #1 LOOSENESS
- INTERMEDIATE SHAFT #2 LOOSENESS
- INTERMEDIATE SHAFT #3 LOOSENESS
- GEARBOX OUTPUT SHAFT LOOSENESS
- GEARBOX TO GENERATOR PARALLEL MISALIGNMENT
- GEARBOX TO GENERATOR ANGULAR MISALIGNMENT
- HIGH SPEED SHAFT COUPLING WEAR
- INDICATION OF POSSIBLE COUPLING WEAR OR LOOSENESS
- GENERATOR IMBALANCE
- GENERATOR FREE END BEARING LOOSENESS
- GENERATOR DRIVE END BEARING LOOSENESS
- GENERATOR COMMUTATOR OR STATOR PROBLEM
- GENERATOR DRIVE END BALL BEARING WEAR
- GENERATOR FREE END BALL BEARING WEAR
- GENERATOR THRUST BEARING PROBLEM
ExpertALERT Advanced analysis kit
Allows display and full detailed analysis of data that underlies the system’s summary reports
ExpertALERT
Trends of temperatures and particles
Section 3: Optional PdM Component #2

CC Jensen
3 Micron Oil Filter
CJC Fine Filter HDU 15/25
Clean Oil is Essential to Life Extension & Improved Reliability

MacPherson Graph

MacPherson proved that removal of very small particles (<10 micron) from lubricating oil has a very useful effect on the life of bearings: The finer the filtration, the longer the life.

The MacPherson Graph is based upon an accelerated test of 10 rolling element bearings. The oil was contaminated with particles from gearboxes.

Controlling Contamination Decelerates Wear Rates

- *Mild* wear is unavoidable
- *Severe* wear can be controlled
- Contamination is a root cause in the four most common wear mechanisms
- Controlling contamination will slow down wear rates
Section 4: Optional PdM Component #3

Macom Technologies
TechAlert™ 10
Oil Particle Counter
Wear Debris Sensor TechAlert TA 10

- Plumbed into CCJ filtration system
  - Continuous On-Line Particle detection
  - Polled continuously by DLI Online system

- **Sensitivity**
  - Ferrous: 50µm to >1000µm
  - Non-Ferrous: 150µm to >1000µm

- **Size Discrimination**
  - Data separated into 10 size bins
    - 5 for ferrous
    - 5 for non-ferrous
TechAlert TA10
Principles of operation

- **Sensor design:**
  - RF oscillator & crystal oscillator
  - both operating at 6Mhz

- **Response to Particles:**
  - Inductance change in sensor coil
  - Inductance change causes phase change

- **Ferrous particles**
  - Positive pulse output due to permeability effect

- **Non-ferrous particles**
  - Negative pulse output due to eddy current effect
Section 5

Typical Installation
Typical Installation
View from rear of nacelle
Typical Installation
Main Bearing
Typical Installation
Gearbox input shaft
Typical Installation
Gearbox output shaft
Typical Installation
Generator free end
Typical Installation
Generator drive end
Hurdles that can come up:

- **IT:**
  - TCP/IP based data transfer protocol
  - Needs some kind of internet access to provide remote monitoring

- **Pricing:**
  - Initial system cost can be difficult to absorb in O&M budget
Solutions to the hurdles:

- **IT**
  - Installing Wireless LAN
  - Cell phone modems

- **Pricing**
  - 5-10 year lease options
  - Insurance bundling
Section 6

Financial Justification
Financial Study

- Predictive Maintenance
  - EPRI Study on maintenance strategies
    (US Electric Power Research Institute)
  - Extrapolated to Wind Turbines

- Examples
  - Gearbox 20 years with and without CBM
  - Generator 20 years with and without CBM

- Lost Revenue Savings
EPRI Study Results on Predictive Maintenance

- EPRI study results:
  - Historical costs of maintenance strategies:
    - Reactive (run to failure) $17/Hp/yr
    - Preventative (scheduled) $13/Hp/yr
    - Predictive (CM-based) $9/Hp/yr

- Study used an industry cross-section
  - Typical power plant machinery
  - Considered average cost over the life of the plant
EPRI Study Application to Wind Turbines

- Wind turbine example
  - Using the EPRI Study cost figures:
  - 660kW Turbine
  - Gearbox = 890 Hp
  - Generator = 890 Hp
  - Total equipment rating = 1780 Hp
EPRI Comparative Maintenance Costs
660 kW Wind Turbine

- 660 kW Turbine Maintenance Costs
  (averaged over the 20 year lifespan)
  - Reactive: $30k /turbine/year
  - Preventative: $23k /turbine/year
  - Predictive: $16k /turbine/year
EPRI Comparative Maintenance Costs
1.5 MW Wind Turbine

○ 1.5 MW Turbine Maintenance Costs (averaged over the 20 year lifespan)
  - Reactive: $69k /turbine/year
  - Predictive: $53k /turbine/year
  - Preventative: $36k /turbine/year
EPRI CM Financial Justification - 20 years

- 660 kW turbine over 20 year life:
  - Saving of between $142,800 and $285,200
  - CM system cost $12,000 approx
  - Benefit to Cost of between 12 and 24 to 1

- 1.5 MW turbine over 20 year life:
  - Saving of between $324,000 and $648,000
  - CM system cost $12,000 approx
  - Benefit to Cost of between 27 and 54 to 1
Maintenance Schedule:
Gearbox - No condition monitoring

- Standard scheduled turbine maintenance
  
  (based on current gearbox failure data)

  Year 3: unplanned minor overhaul
  Year 5: major overhaul
  Year 7: unplanned minor overhaul
  Year 10: major overhaul
  Year 13: unplanned minor overhaul
  Year 15: major overhaul
  Year 18: unplanned minor overhaul
  Year 20: major overhaul
Maintenance Schedule: Gearbox - with condition monitoring

- **Basis:** Current gearbox failure data:
  - **Known Failure modes:**
    - 85% bearing failures
    - 15% gear failures
  - **Actual:** Average gearbox life between 3.5 and 5 years
  - **Conservative:** Life extension of x 2 is expected with the CM system –
    - Due to preventative (oil filtration) and advanced warning of bearing and gear wear.

- **With CM, target maintenance activities**
  - *In response to predictive maintenance CM data*
    - **Year 5:** minor overhaul (bearing + shaft realignment)
    - **Year 10:** major overhaul (all bearings, all gears)
    - **Year 15:** minor overhaul (bearing + shaft realignment)
CM Financial Justification
Gearbox Cost Comparison
1.5 MW Turbine over 20 year period

- **Standard scheduled maintenance**
  - 4 major overhauls @ $150k each
  - 4 unplanned minor overhauls @ $75k each
  - Total = $900k

- **With predictive maintenance**
  - 2 major overhauls & 2 minor overhauls
  - Total = $450k

- Additional savings due to:
  - Reduced outage time
  - Parts availability & inventory/refurbishment stock management
  - Crane scheduling
Maintenance Schedule:
Generator - No condition monitoring

- **Expected Maintenance Activities**
  - Typical unexpected break downs
    - Bearing failure
    - Coupling failure due to misalignment
    - Bearing failure due to misalignment.
  - Assumed schedule:
    - Year 1-10: 1 or 2 unplanned failures
    - Year 10 refurbishment (coupling and bearing change)
    - Year 10-20: 1 or 2 unplanned failures
    - Year 20 refurbishment (coupling and bearing change)
Maintenance Schedule: Generator - with condition monitoring

- Using Predictive Maintenance
  - Generator is monitored for:
    - Alignment, Bearing wear, Imbalance
    - Loose rotor bars, uneven rotor air gap, phase imbalance

Expected maintenance Targets with Predictive Maintenance:

- Year 1-10: faults are detected early and condition is rectified without catastrophic failure
- Year 10: generator is only overhauled to the extent indicated by CM
- Year 10-20: faults are detected early and condition is rectified without catastrophic failure
CM Financial Justification
Generator Cost Comparison
1.5 MW Turbine over 20 year period

- **Maintenance Cost with No CM:**
  - 2 major overhauls @ $50k each
  - 4 minor repairs @ $15K each
  - Cost over 20 years = $160k

- **Maintenance Cost with Predictive:**
  - 1 major overhaul @ $50k
  - 2 minor repairs @ $15K
  - Cost over 20 years = $80k
  - Plus additional savings due to:
    - Reduced outage time
    - Parts availability & inventory/refurbishment stock management
    - Crane scheduling
CM Financial Justification
Lost Revenue Savings Example

- Based on 1.5 MW WTG, 25% CF, and $0.08/kWh
  - Lost Revenue for Unscheduled Activity
    - Ordering parts and the crane resulting in:
      - 4 week downtime
      - Loss of revenue 1.5MW turbine = $21,840
  - Lost Revenue for Scheduled Activity
    - Parts and crane are ready and resulting in
      - 1 week downtime.
      - Loss of revenue 1.5MW turbine = $5,460

- Net Revenue Savings using CM system for planned predictive maintenance: $16,380
CM Financial Justification

Overall

- Basis: Gearbox and Generator of 1.5 MW turbine over 20 year turbine life

- Scheduled Maintenance repair costs:
  - $1,060,000

- Using Predictive Maintenance, repair costs:
  - $530,000 ($530,000 benefit)
  - CM system cost $12,000 approx
  - **Benefit to Cost Ratio = 44:1**
  - **Payback period = 5-6 month**
CM Financial Justification

Assumptions:

- Assumed failure rates of gearboxes and generators are based on the “world average normal turbine designs”

- Prototypes and obviously poor turbine design examples were excluded.
  - Some turbine types for example had 3 gearboxes or generators replaced in the first 2 years (these are excluded).