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Condition monitoring of electrical machines: current state, challenges and opportunities

by

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1st International Symposium on Smart Grid Methods, Tools and Technologies,
Shandong University, Jinan
May, 2015

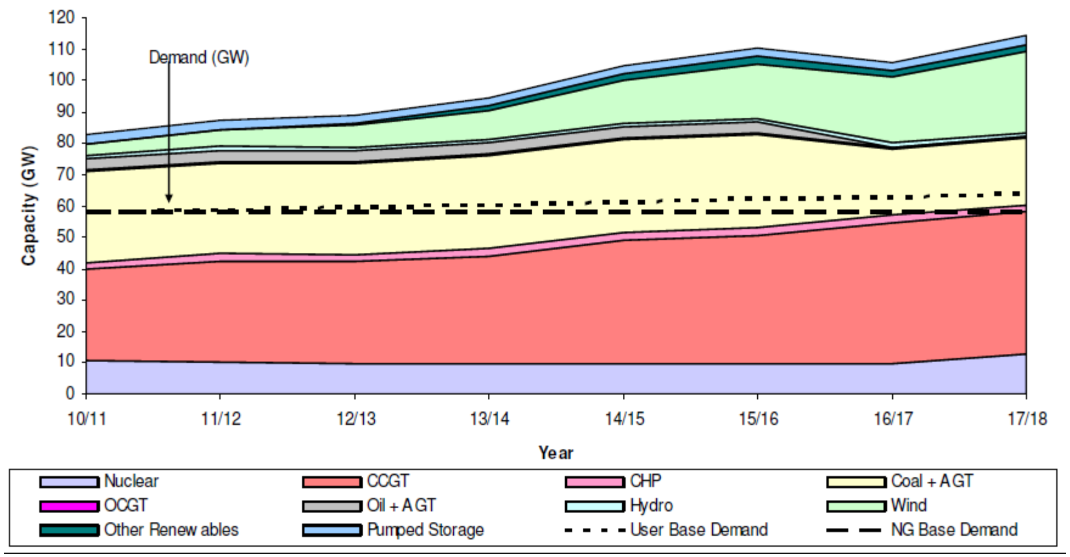
Introduction

- Rotating machinery failure rates still high in industrial applications - in most process plants, rotating equipment tends to be the least reliable component and strongly contributes to the O&M cost increase
- On-line condition-based monitoring has been proven to provide significant O&M cost savings in many industrial applications – this can be critical in industries where devices are exposed to extreme conditions
- Bearing and winding faults dominant – mechanical faults usually most common but this can vary depending on machine size/application
- We will take a look at current status and future challenges of generator/drive train on-line CM in the wind industry

Wind power in the UK – current status

- UK National Grid - rough numbers:
  - installed capacity just over 80GW, peak demand just over 60GW
  - ≈20GW decommissioned by ≈2020, (12GW coil/oil, 7.5GW nuclear)
  - projected capacity expansion up to ≈ 113GW by ≈ 2018

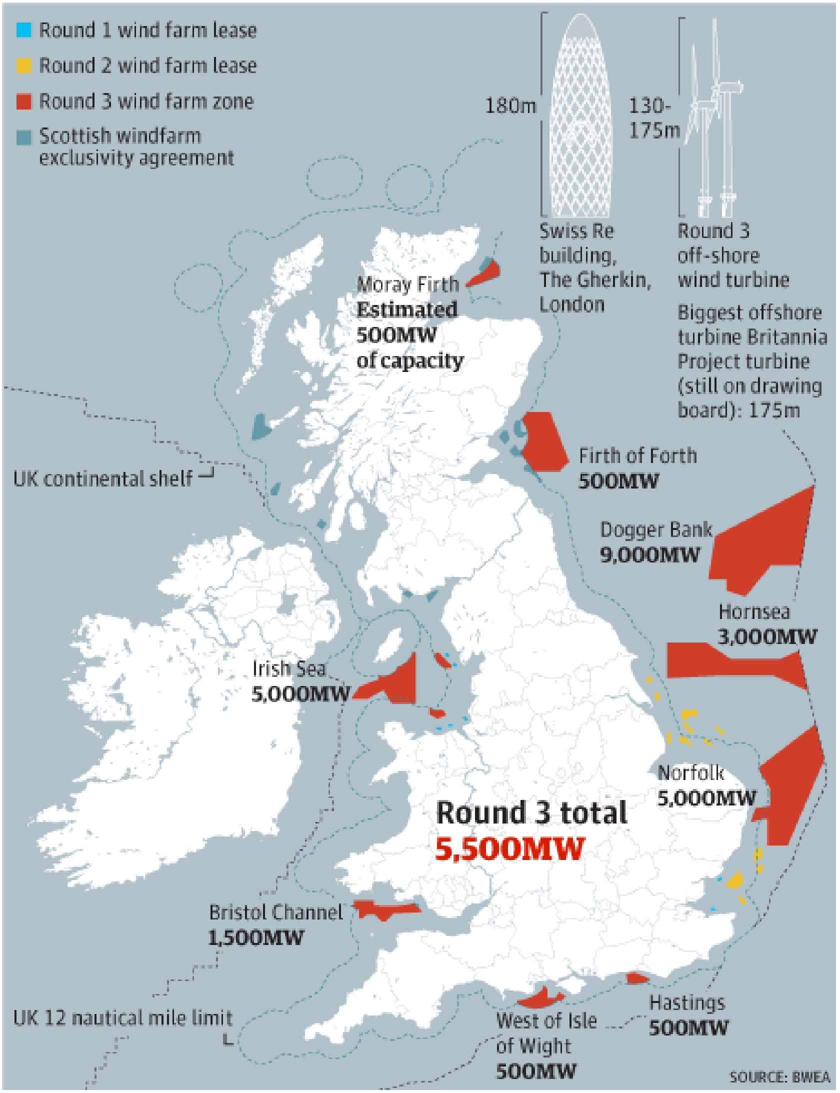
- EU Target 2020 for UK - 15% energy from renewables!



- projected wind capacity increase of up to ≈ 22GW between 2011-18
- current status (2015): ≈ 8GW onshore and ≈ 4GW offshore

Source: *UK National Grid*

Offshore wind development in the UK

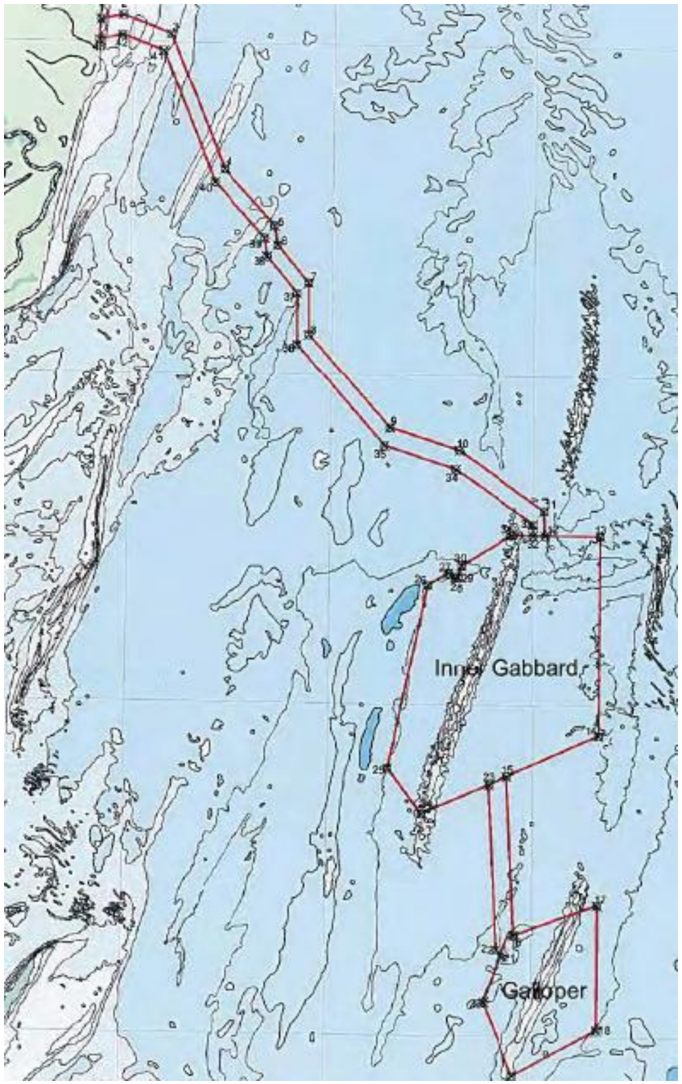


Source: *Crown Estate, EWEA*

- UK is currently the world leader in offshore wind installed capacity
- Developments mostly regulated by the Crown Estate – three development rounds so far
- Round I, 2001: 18 locations in England and Wales, 1.5GW installed capacity
- Round II, 2003: larger areas, further from shore, 7GW installed capacity
- Round III, 2010: nine zones, largest projects so far, a total of more than 24GW already leased to developers
- Current large projects are 30km or more offshore
- Future developments uncertain

Typical Round 2 offshore farm - Greater Gabbard

- Commissioned Sep 2012

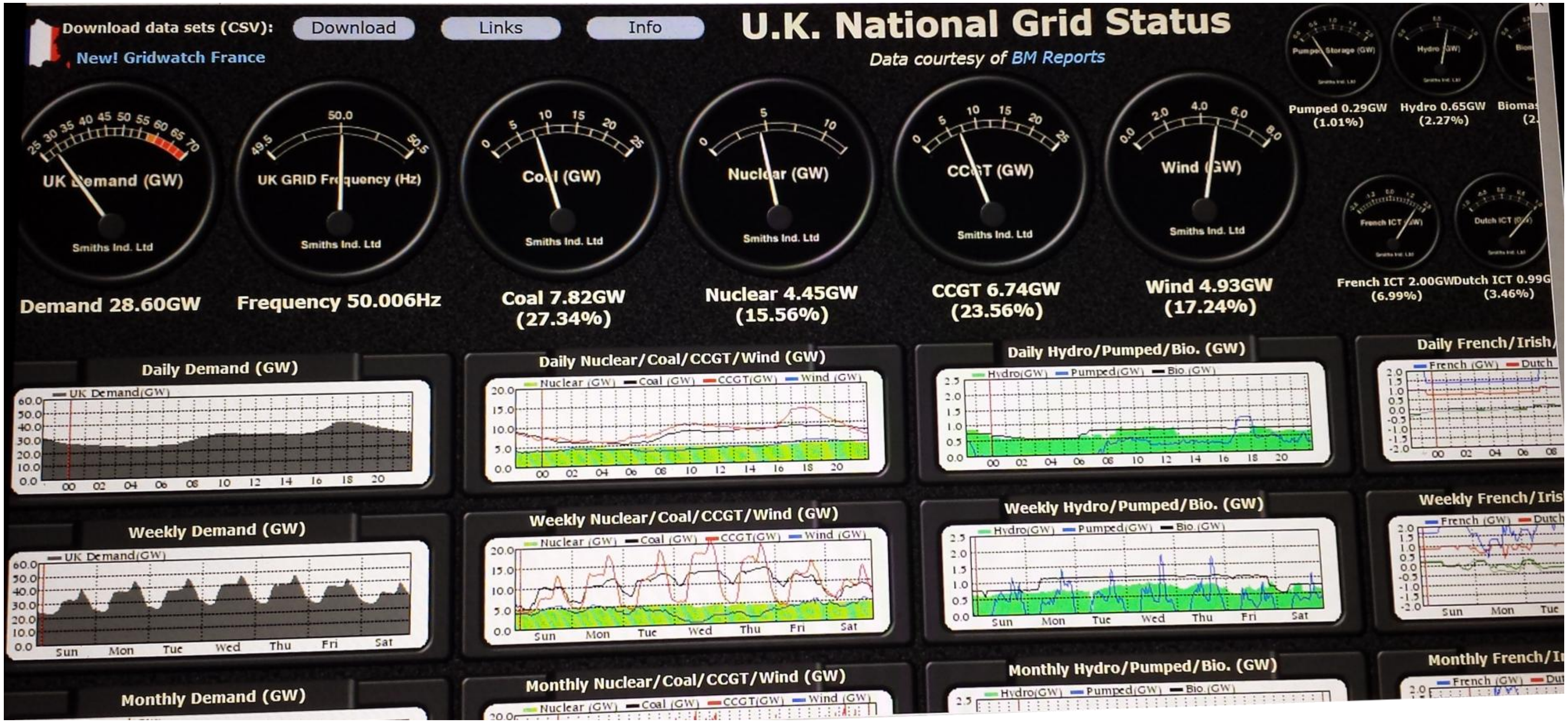


- 504MW installed capacity
- 140 Siemens SWT3.6-107 turbines
- 3.6 MW, rotor 107m, hub height 77.50m
- Mean wind speed 9.4 m/s, area 146km^2
- ≈30km offshore, 20-32m depth
- Connection voltage 132kV, 55km HVAC
- Two 33/132kV offshore transformer stations (3x180MVA, 2x90MVA)
- 147km of power cabling within the farm
- Total development cost ≈£1500 million

Source: 4Coffshore, SSE, RWE

Wind power generation - contribution to UK grid

- Increased contribution to the power system from wind
- Recent records of operational scenarios in which wind contribution overtakes that of some conventional sources – with increased penetration reliability becomes essential



Wind power reliability/cost – significance of CM

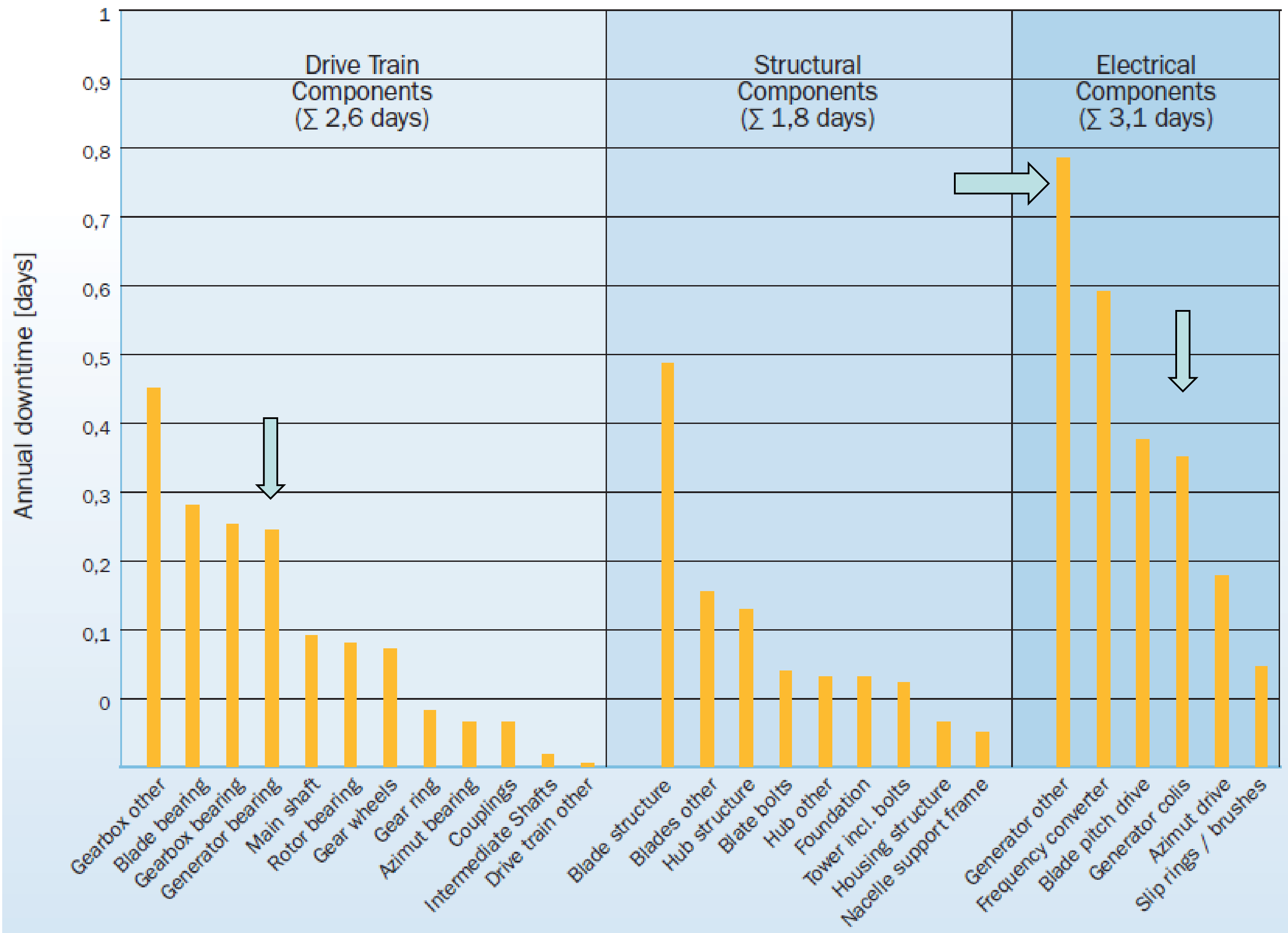
- Wind power cost/competitiveness and success of large scale integration highly dependent on availability/reliability
- This is predominantly underpinned by operational availability of wind turbine components (when wind is blowing!)
- Turbine failures still a major operational/financial issue – this a significant challenge for ongoing offshore developments
- Recent rough O&M costs estimates:

  ≈ up to $7000/MW/year for a single onshore turbine

  ≈ up to $40000/MW/year for a single offshore turbine
- Turbine O&M costs can represent ≈10 % of the total cost of produced energy for onshore turbines, and up to ≈35 % for offshore turbines
- Generator faults are one of the top contributors to O&M cost/annual downtime

Source: *EWEA*

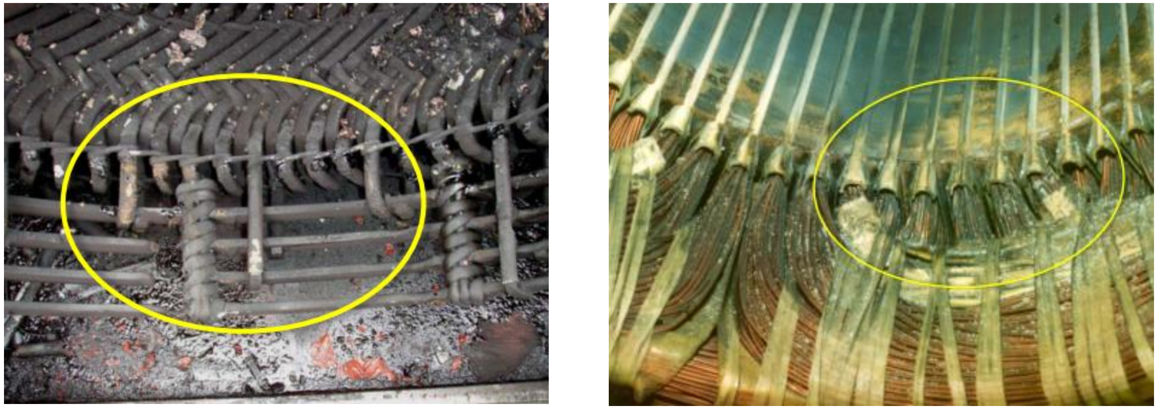
Reliability statistics for wind turbine components



Source: *EWEA*

Examples of WT generator failure modes

- Electrical:



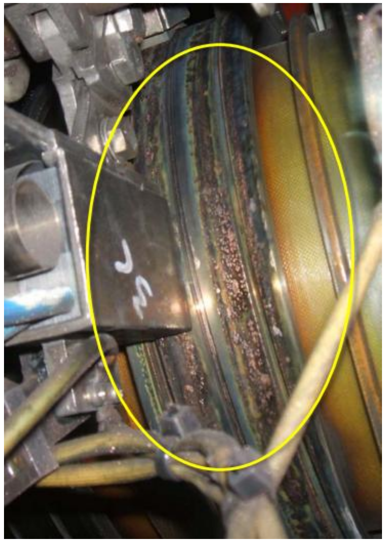
Stator winding faults

Rotor Lead Failure

- Mechanical:

Bent Shaft

Bearing Inner Race Failure



Collector Failure

On-line condition monitoring for WT generator systems

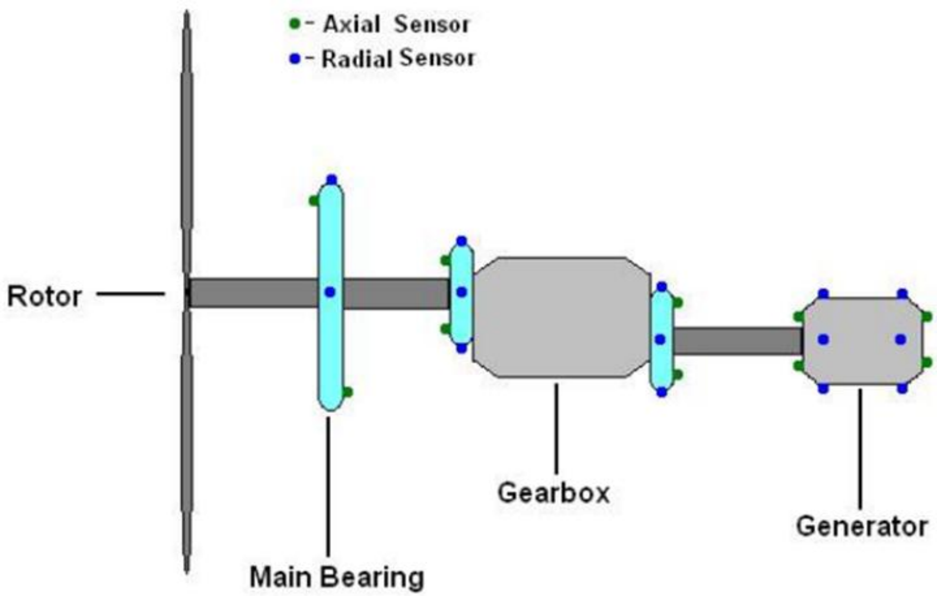
- The aim is to:
  - provide automated incipient fault detection with high reliability
  - mitigate potential damage to other turbine parts by reliably detecting the degree and nature of fault
  - enable the operator to understand the device operational integrity status and likelihood/timescale of failure
  - provide early warning to enable planned maintenance/avoid unscheduled outages
  - enable development of control measures to extend device lifetime
  - Reduce/optimise turbine downtime and O&M cost

- Current solutions:
  - Industry practices (high / low fidelity CM systems)
  - Alternatives provided by recent/ongoing research and technological developments ?

Industrial practices - CM systems for WT drivetrains

Supervisory control and data acquisition (SCADA) systems monitor average operating conditions/parameters in regular 5-10 minute intervals.

- Monitors: vibration, generator currents/voltages, winding/bearing temperatures, wind/shaft speed, active/reactive power output etc.
- Vibration transducers (accelerometer) are mounted on individual drive train components, in order to determine the condition of rotating equipment such as generator, gearbox and bearings



Challenges:

- Insufficient bandwidth for electrical fault monitoring
- Very low diagnostic capability
- Generally cost effective but can require costly mechanical sensors

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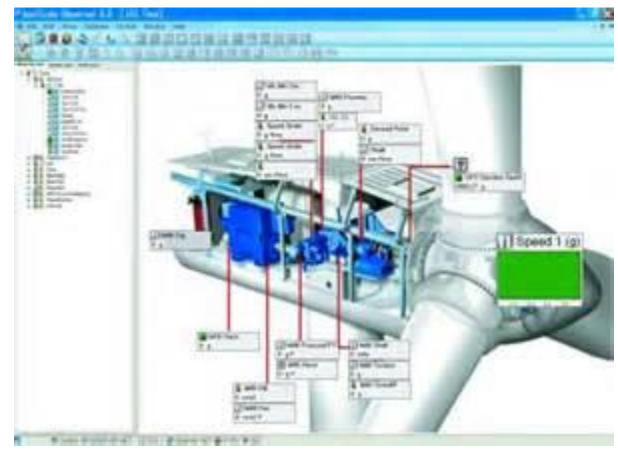
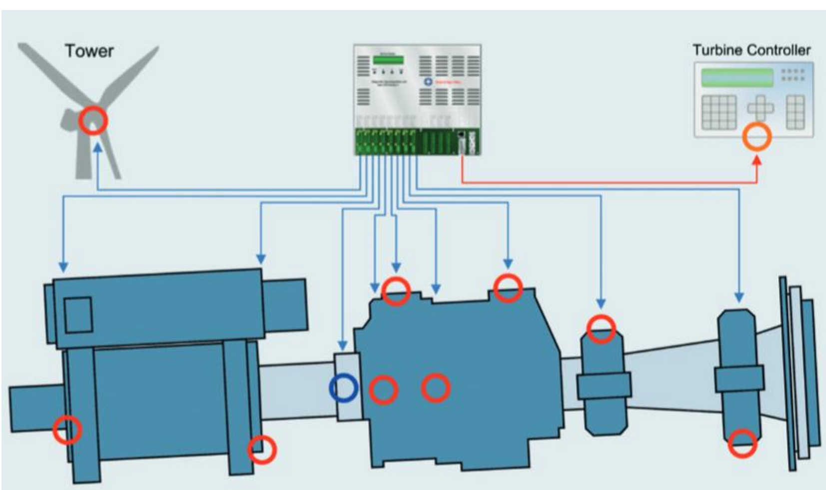
Industrial practices – high fidelity CM systems

A range of commercial solutions provided for dedicated turbine remote condition monitoring (SKF Windcon, B&K Vibro etc) that provide:

- High bandwidth (>10kHz) monitoring of turbine operational parameters (almost exclusively vibration based, but some also monitor electrical signals, temperature etc.) with significant focus on drive train components
- Automated fault threshold recognition and alarm management
- Proprietary hardware/software platforms for high performance data analysis

SKF Windcon





B&K Vibro

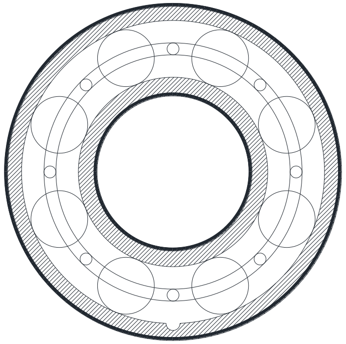
<u>Challenges:</u>

- High cost, excess of data
- Interpretation complexity
- Improved diagnostic reliability

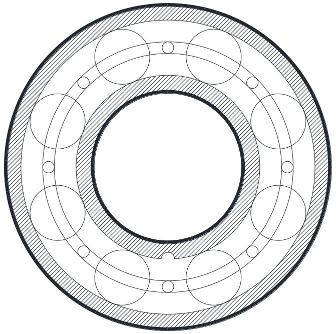
Source:SKF, B&K

CM diagnostic reliability – challenges

- Low diagnostic reliability - common factor in commercial CM systems
- Large numbers of false alarms generated – unreliable systems that can lead to expensive and unnecessary maintenance work
- Fault detection based on conventional vibration signal analysis currently favoured – relatively effective for mechanical fault analysis but largely ineffective for electrical failure modes
- Recent attempts to utilise electrical signals and acoustic emissions for diagnostic purposes
- Knowledge of fault development and indicators needs improvements



Outer race fault



Inner race fault

Mechanical frequencies

$$f_{co} = \frac{N_b}{2}\left(1 - \frac{D_b}{D_c}\cos\beta\right)$$

$$f_{ci} = \frac{N_b}{2}\left(1 + \frac{D_b}{D_c}\cos\beta\right)$$

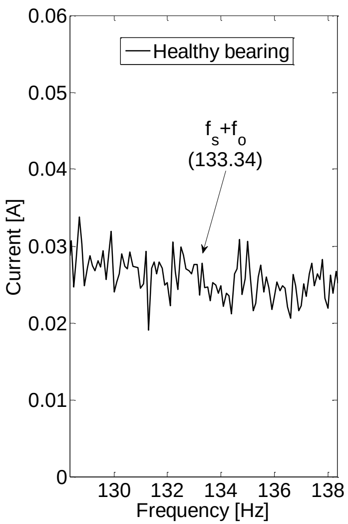
Diagnostic reliability improvement – opportunities

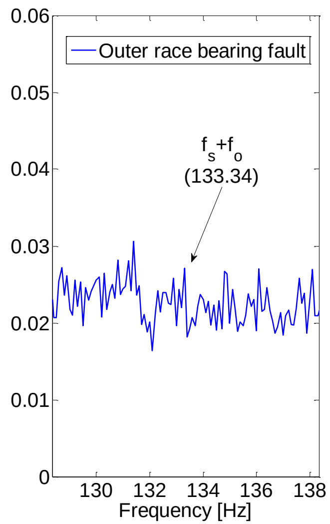
- Multi source solutions - develop a knowledge base of single fault type signature in multiple generator/drive signals and crosscorelate
- Example: electrical signal use for mechanical fault analysis:

Possibility of generator bearing fault detection using current signals

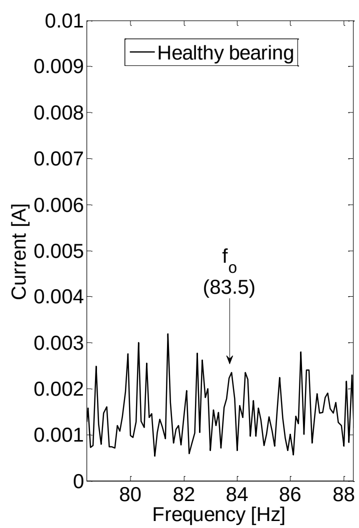
complement and enhance the existing vibration based CM systems

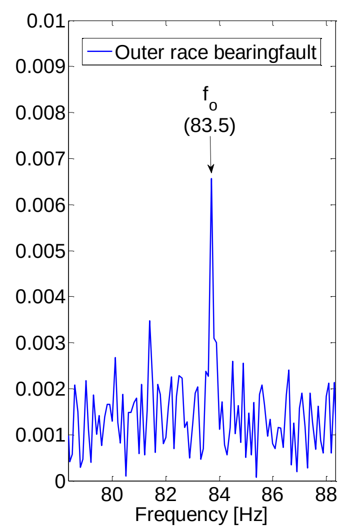
ongoing academic and industrial research



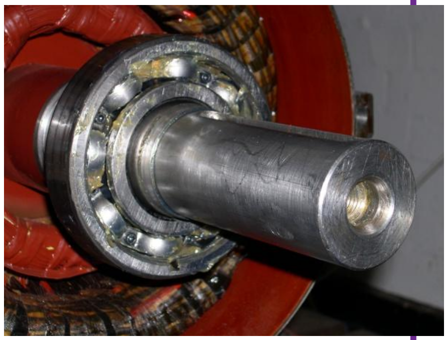


Normal stator current spectrum: no clear signal to indicate bearing problem





Instantaneous negative sequence current spectrum: clear frequency signal relating to bearing fault.



Generator outer race bearing fault - test rig

Diagnostic reliability improvement – opportunities

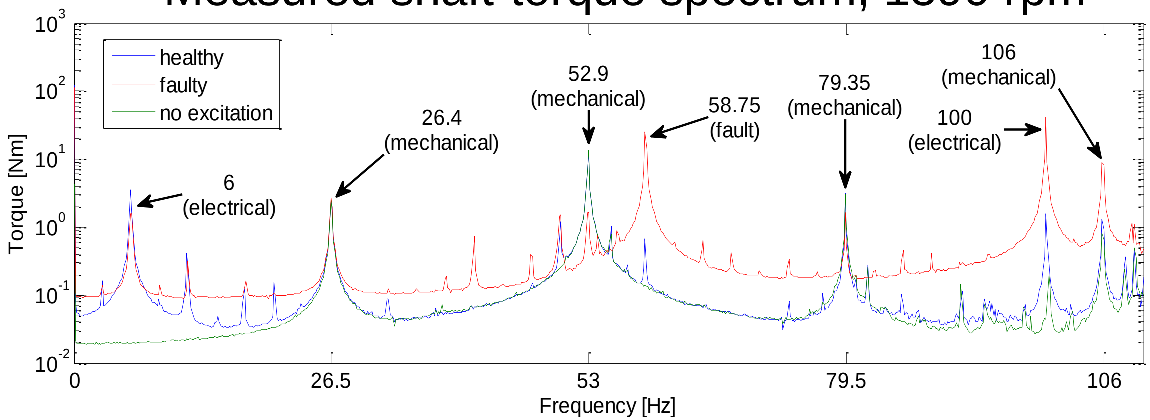
- Example: Mechanical signal use for electrical fault analysis:

Vibration/torque monitoring for generator electrical fault detection:

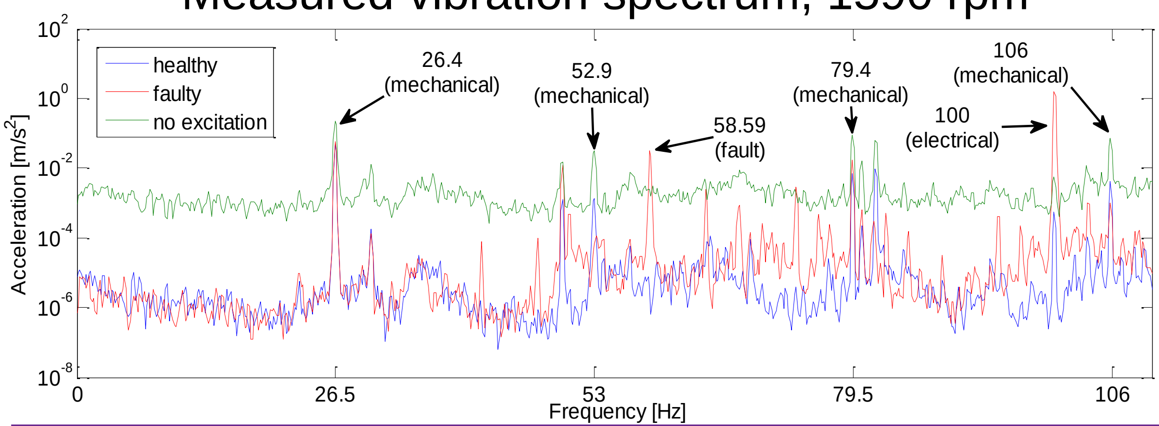
complements electric signal based techniques

can enhance the capability and reliability of existing CM Systems - currently investigated by B&K

Measured shaft-torque spectrum, 1590 rpm



Measured vibration spectrum, 1590 rpm



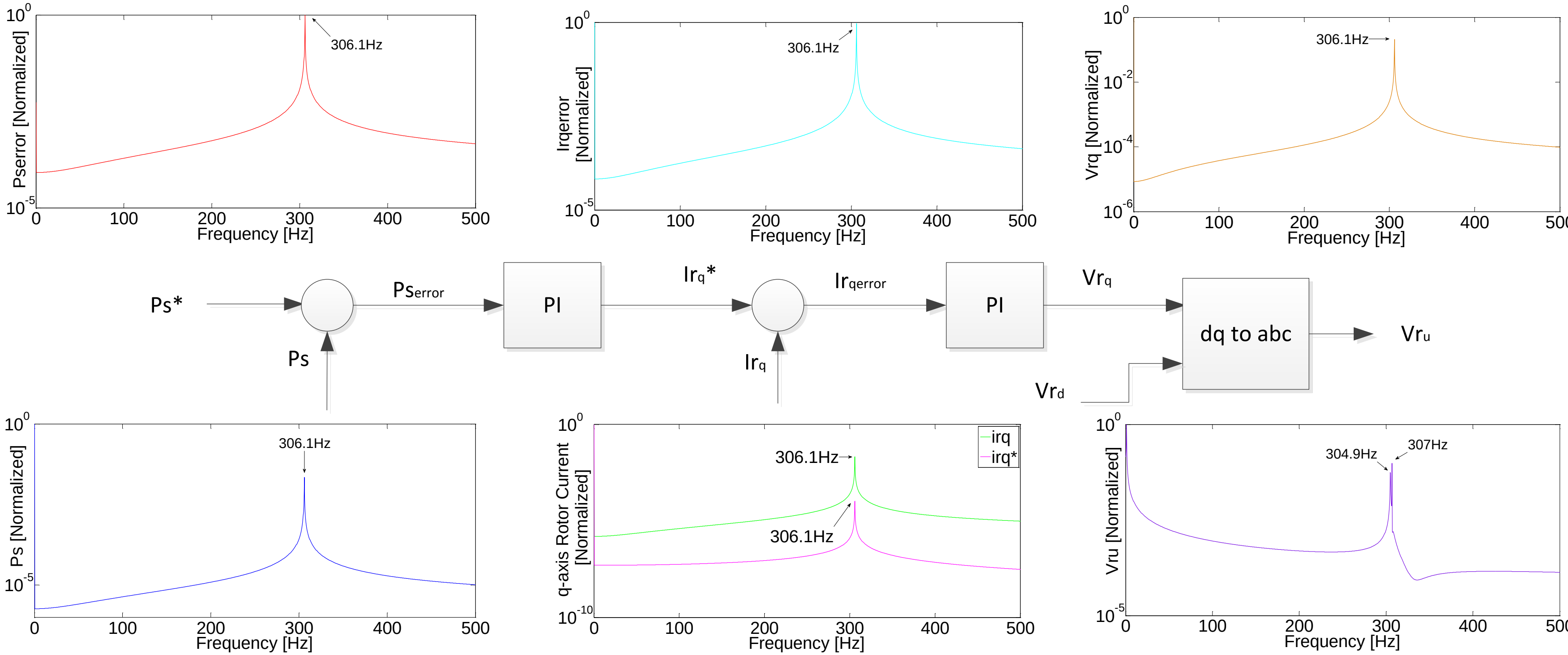
Generator torque/vibration signal frequencies

Winding	Supply	Freq.
Balanced	Unbalanced	$\left\|6k(1-s)\right\| f_s$ $\left\|2 \pm 6k(1-s)\right\| f_s$
Unbalanced	Unbalanced	$\left\|\frac{k}{p}(1-s)\right\| f_s$ $\left\|2 \pm \frac{k}{p}(1-s)\right\| f_s$

Diagnostic reliability – opportunities

- Possibility of drive controller embedded CM schemes
  - non invasive as it utilises available logical signals
  - can provide fault recognition that may otherwise be impossible using conventional signals
- Attractive for machine operation in closed loop controlled applications

Wind turbine DFIG stator electrical fault recognition

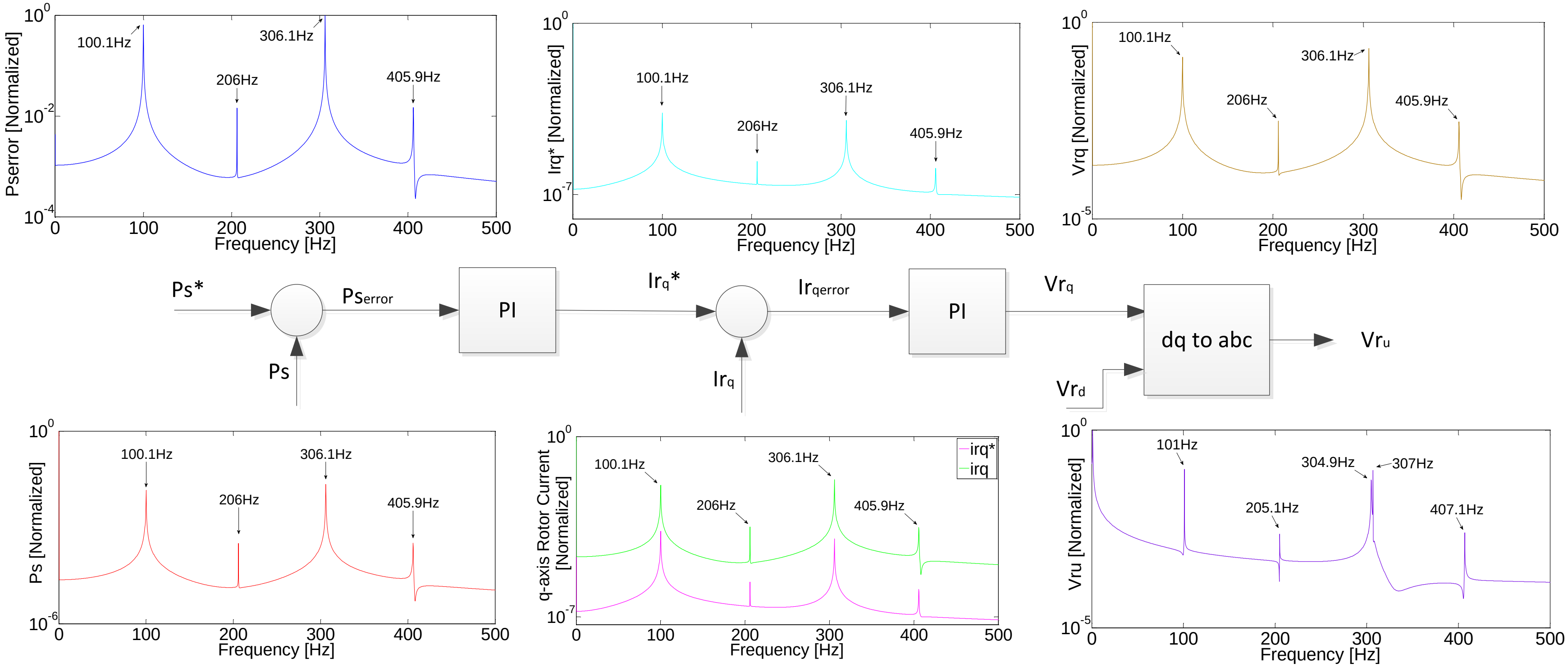


Diagnostic reliability – opportunities

- Alternative information sources - controller loop embedded CM schemes
  - non invasive as it utilises available logical signals
  - can provide fault recognition that may otherwise be impossible using conventional signals

- Attractive for machine operation in closed loop controlled applications

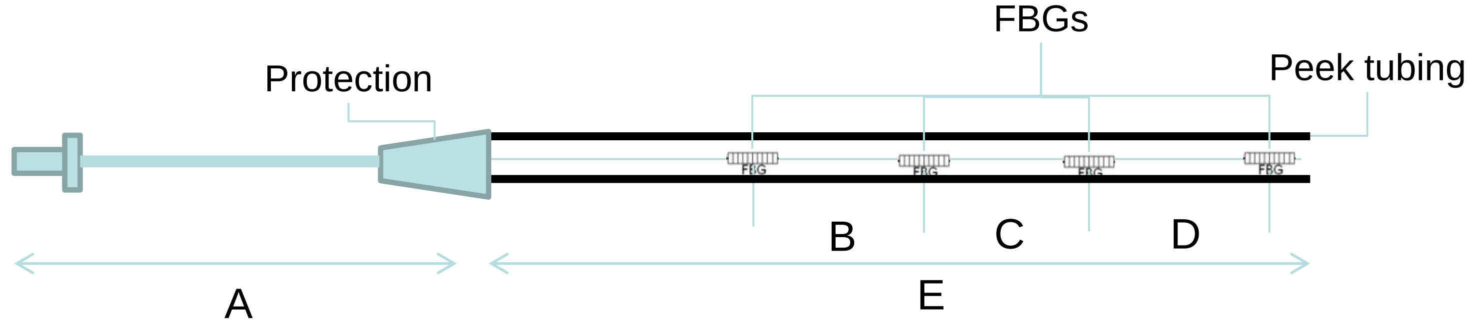
Wind turbine DFIG stator electrical fault recognition



Diagnostic reliability – opportunities

- Application of novel sensing technology solutions – device component embedded sensing
- Provide ‘on failure point sensing’ within the generator structure – limiting factor in existing CM solutions is sensing away from failure points
- Potential to provide previously unattainable levels of high fidelity information on device operational integrity – recent developments in FBG technology enable high bandwidth applications

Schematic – Loose tube array arrangement

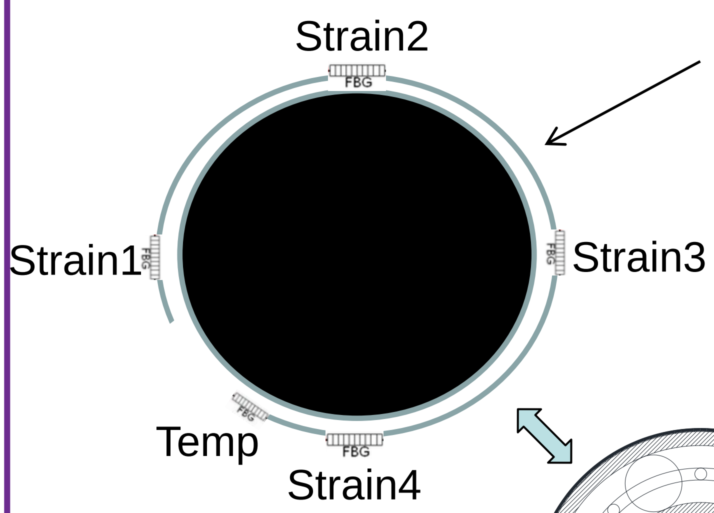


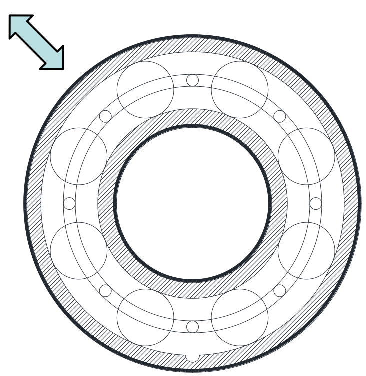
FBG temperature sensor structure – outer diameter can be less than 1mm

Diagnostic reliability – opportunities

- Winding embedded temperature/stress sensing
- Bearing embedded strain/temperature sensing
- Other – frame/shaft strain, rotor temperature/strain sensing

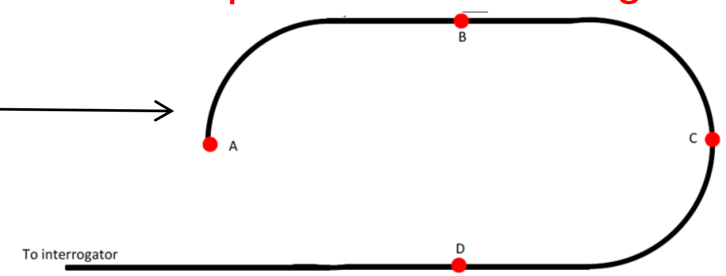
Schematic – on bearing strain & temperature monitoring

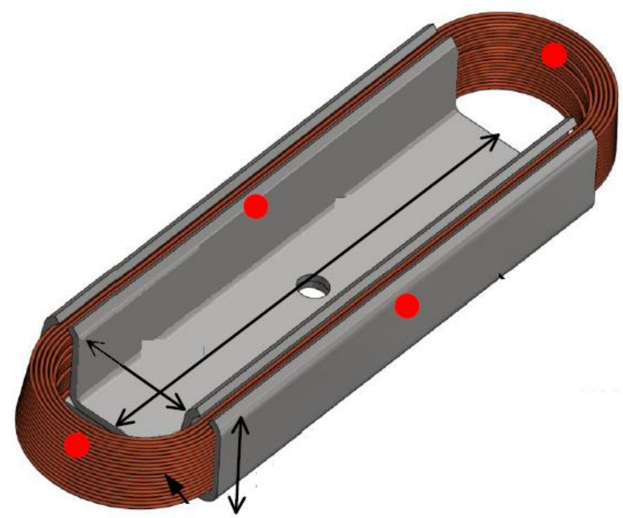


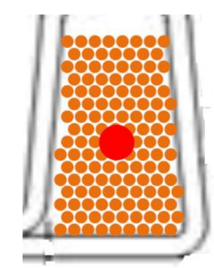


Sensing fibre

Schematic – winding embedded temperature monitoring

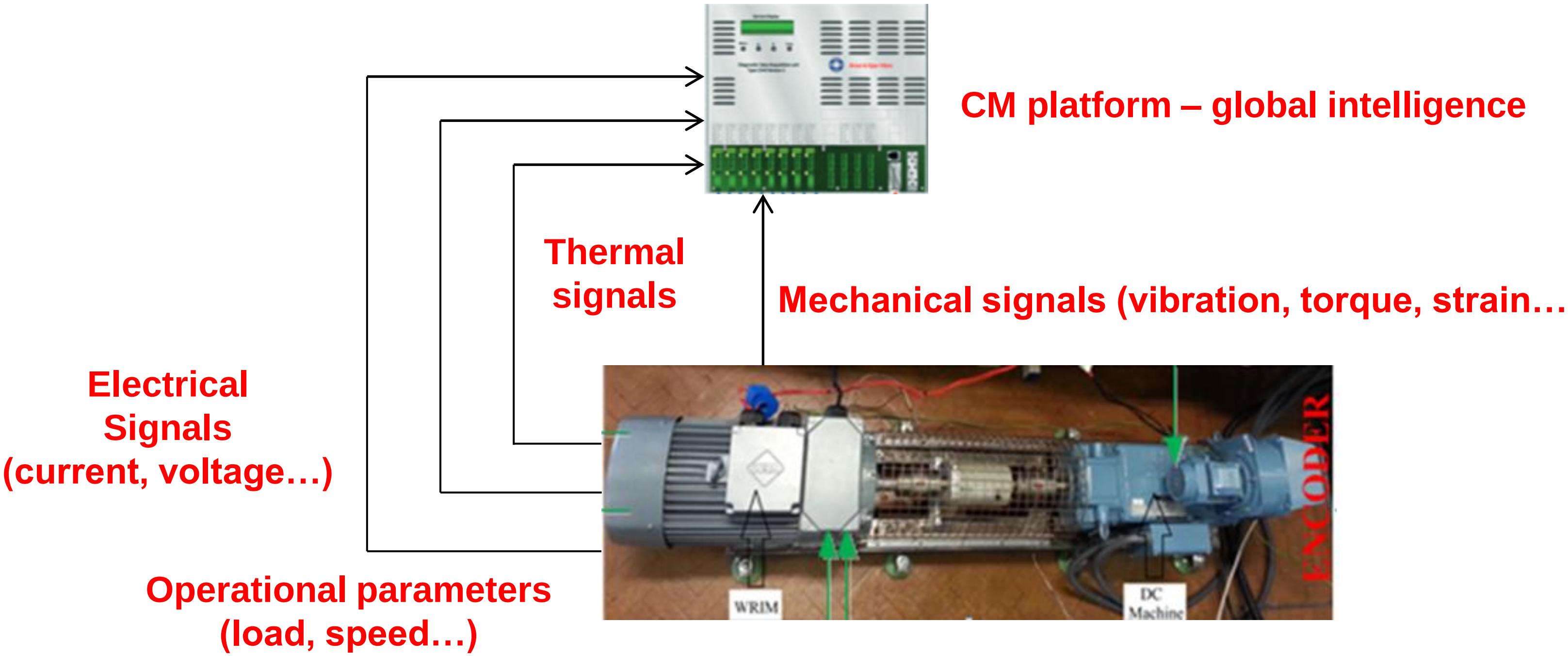






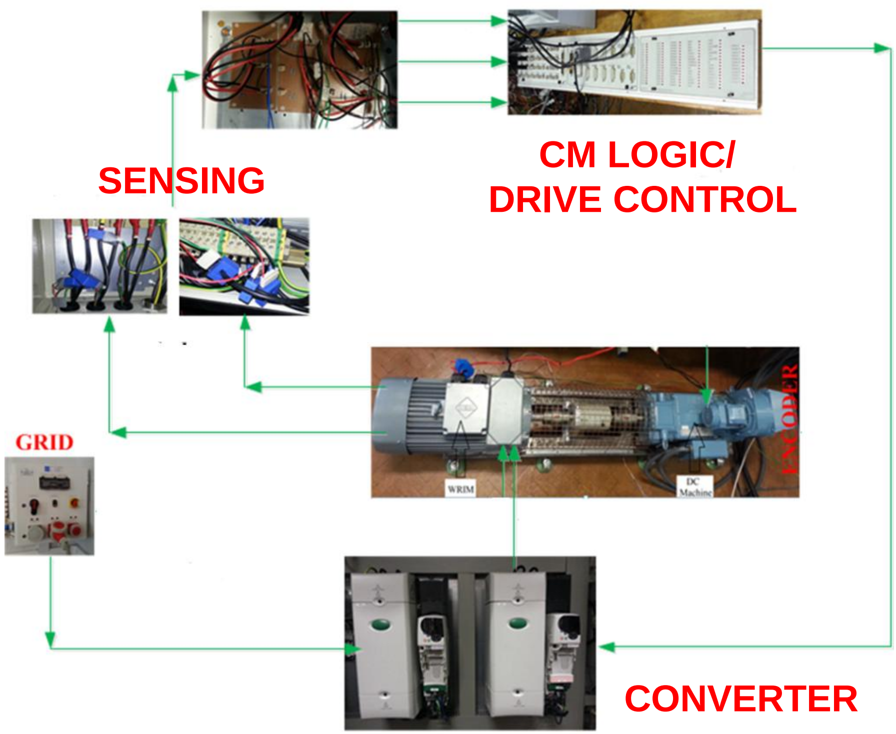
Diagnostic reliability – opportunities

- Multiple signal signature fusion to achieve global high reliability CM indexes – more sources of information contributing to decision making!
- Can be used to define hierarchical fault severity thresholds maps – this would enable effective failure mode progression monitoring
- Potential to provide high diagnostic reliability solutions – likely to be high cost however!



CM driven drive management

- Utilise operational integrity information provided by the CM system to establish proactive drive management solutions for component life time extension
- Torque injection schemes to mitigate mechanical fault/load induced stress in the drivetrain
- Current loading management based on embedded thermal sensing feedback



Smart grid system integration: automated proactive management for lifetime extension and optimisation

Towards the intelligent 'self healing' system!

Conclusions

- Current electrical machinery CM solutions widely reported not to meet the desired impact in reducing O&M cost
- Diagnostic reliability improvements needed
- Major challenges in identifying more reliable fault indicators
- Novel sensing technology could help
- Development of proactive CM driven control algorithms for lifetime extension?
- The goal is an automated management system capable of incipient fault recognition and lifetime optimisation
- Presented for wind industry applications but equally important elsewhere

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