7MW LDT Pitch System Health monitoring with Machine Learning

2020 VirtualWind II ORE Catapult & Fraunhofer IWES

08, July, 2020 | Hyunjoo Lee

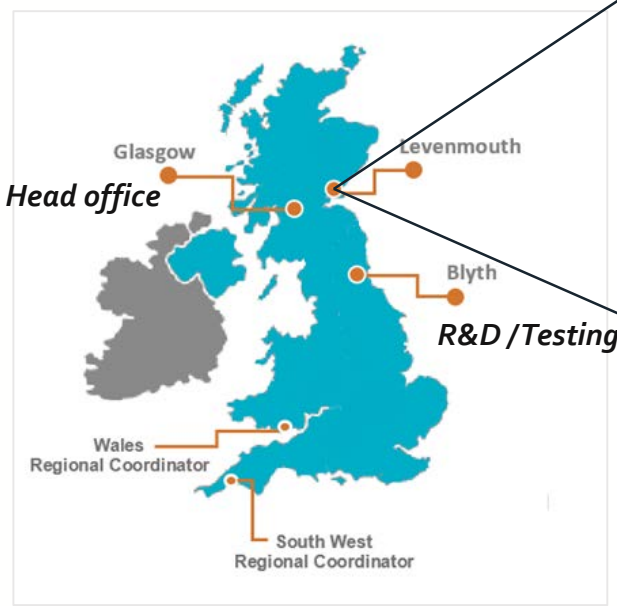
CATAPULT
Offshore Renewable Energy

Agenda

- Study approach and conditions/assumptions
  - Target turbine
  - Operational characteristics and damages
  - Investigation concept
  - Pitch cycle and load estimation method
  - Bearing life estimation method
  - Data sets and conditions for study
- Study result and observations
  - Measured wind speeds & power production
  - Bearing life result comparison
  - Loads & Pitch cycle comparison
  - Change history – IPC control algorithm
  - Wear risk indication
- Closing remarks / Next works

Target Turbine

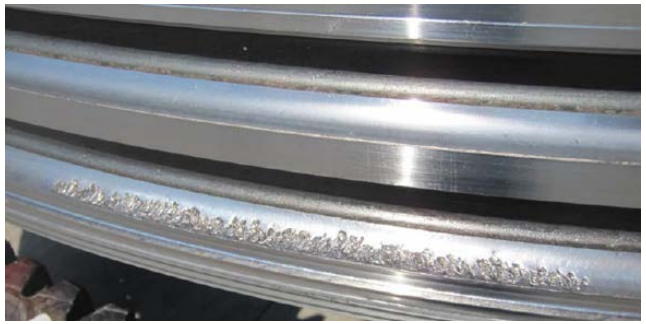
- 7MW Levenmouth Demonstration Turbine (LDT)
  - Developed by SHI (25 years design life)
  - **Collective and individual pitch controlled by internal algorithm** developed by DNV/GL-GH
  - Currently owned by OREC for research purpose

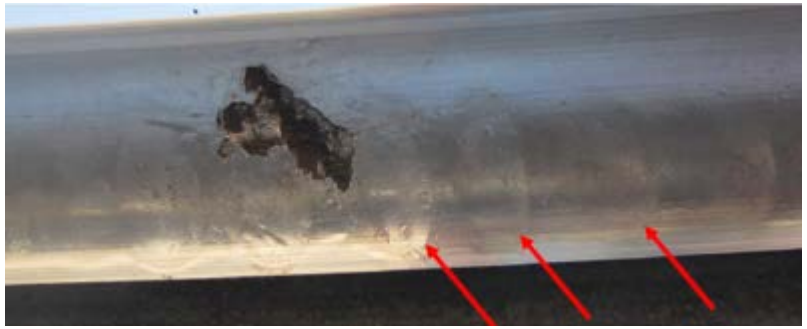


Operational Characteristics and Damages

- Wind turbine pitch bearings are subject to very hostile operating conditions:
  - Huge bending moments whilst low speed oscillating or standing still
  - Large structural deformation due to limited stiffness
  - Transient events, i.e. start / stop
  - **IPC is becoming common in wind turbine (frequent small amplitude oscillation)**

- Associated possible damages:
  - Ring fracture
  - Contact ellipse truncation
  - **Raceway fatigue**
  - **False brinelling / Fretting corrosion**



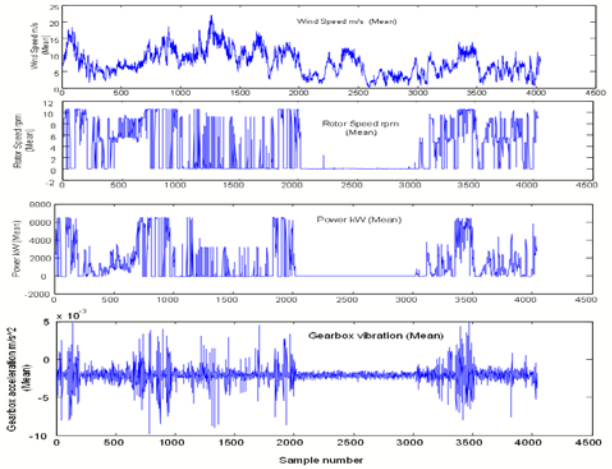


Photos reference: RBB engineering

Pitch System failure & Approach

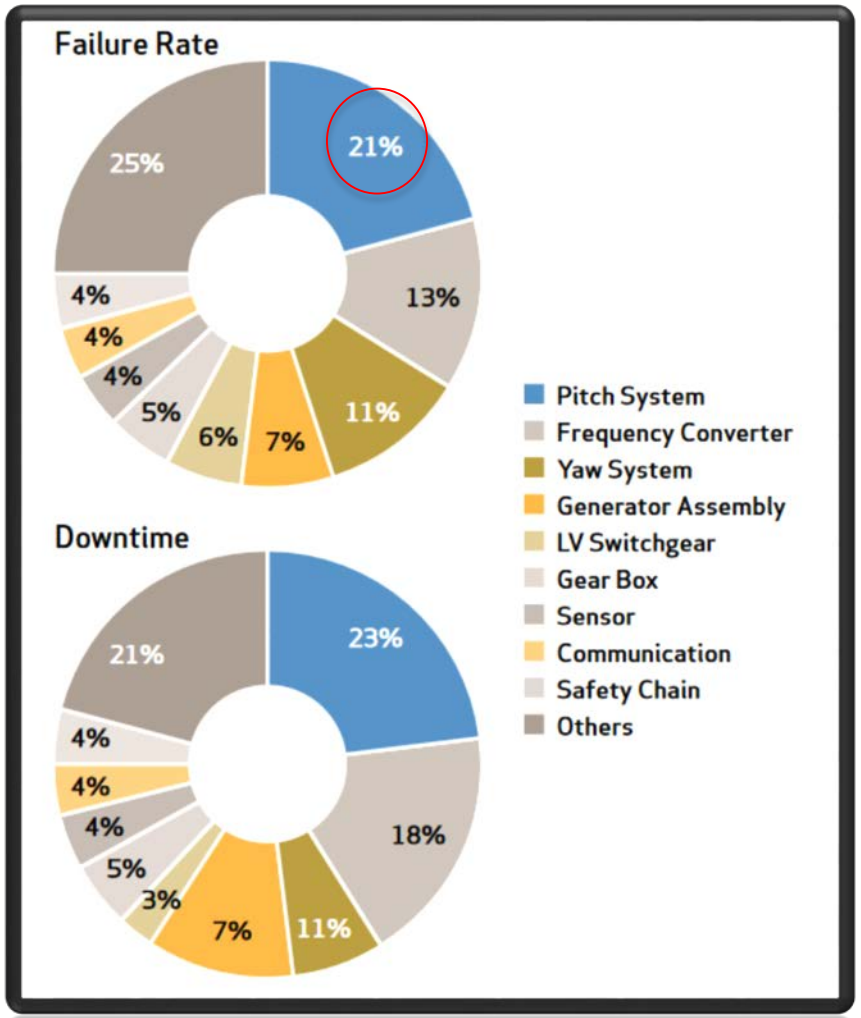
- Pitch system failures account for most downtime
- Failures are even more critical on offshore 10 MW+ turbines
- No effective detection method for whole pitch system

SCADA based Pitch system health monitoring with Machine Learning



Project aim : Pitch system health monitoring with existing SCADA

- **No extra hardware**
- **Automatic Warning/Alarm in advance**
- **Reduce the unplanned maintenance**



Source: windeurope.org

Investigation Concept – Cause of issue

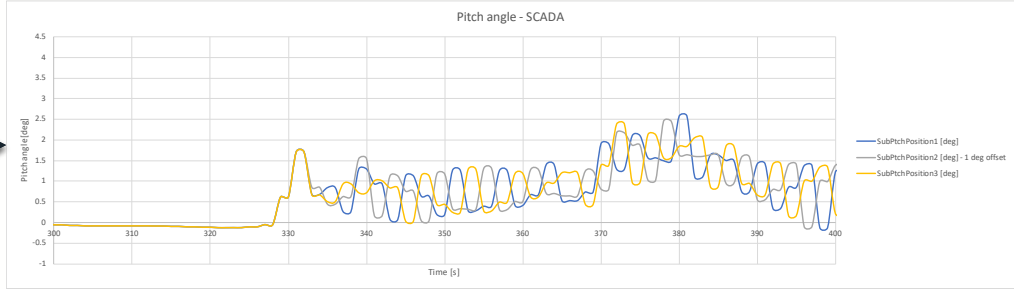
CONTROL STRATEGY

SCADA signals from actual turbine

Comparison/correlation

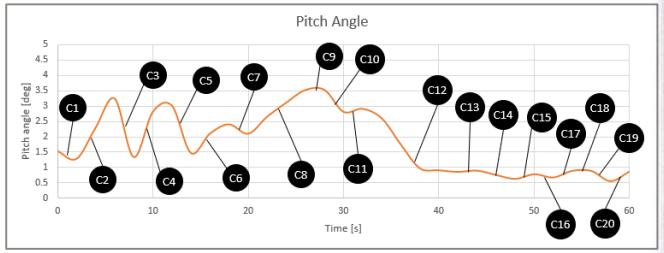
Aeroelastic simulation (Bladed model)

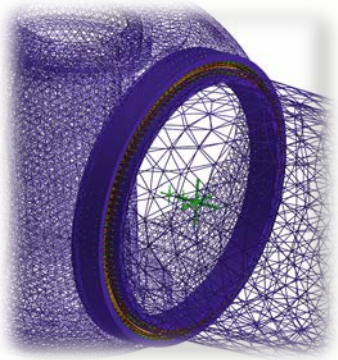
Time-series simulation



Oscillation cycle counting algorithm

Bearing performance & life simulation





Pitch bearing condition

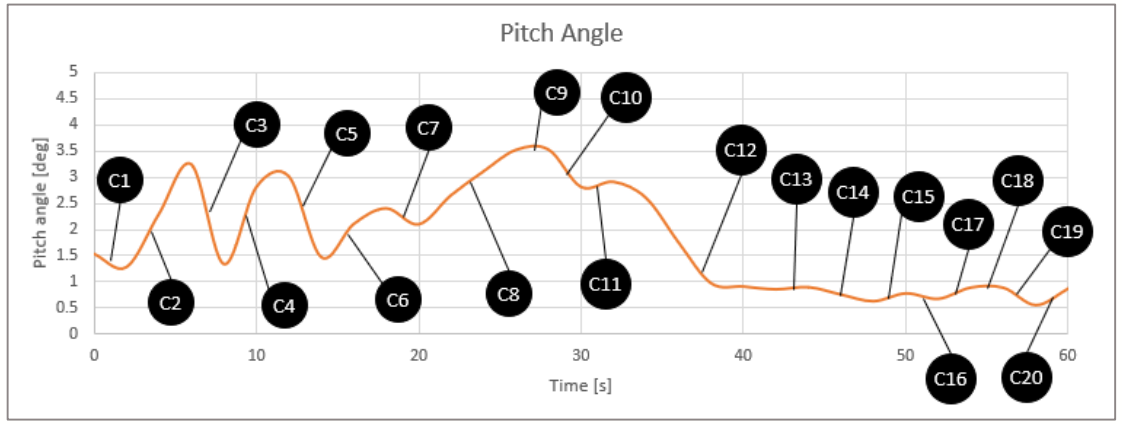
- Fatigue damage
- Wear damage

Control strategy feed back/Validation

Pitch Cycle and Load Estimation Method

- Recent reference from IWES:
  - *Cycle counting of roller bearing oscillations – case study of wind turbine individual pitching system, 2018*
  - Oscillation cycle counting achieved by range-pair counting method
  - Load estimation supplemented by bin counting method

- Cycle counting MatLab code developed by OREC project team with the suggested core algorithm
  - Handling the time series input from both Bladed simulation and SCADA data signal



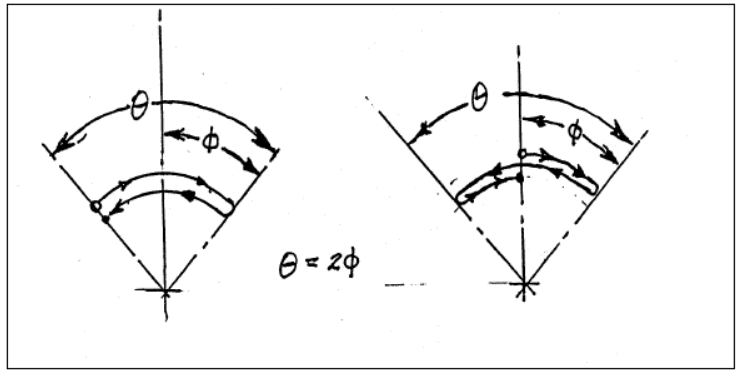
Cycle counting concept (range-pair)

Bearing Life Estimation Method

- Pitch bearing is subject to oscillation movement, so life calculation method for oscillating bearing is required for this investigation

- Calculation method suggested by NREL (Harris method) was used for this study:
  - *Wind Turbine Design Guideline DG03: Yaw and Pitch Rolling Bearing Life, 2009*

Amplitude angle of one cycle oscillation



$$L_{10} = \left(\frac{C_{a,osc}}{P_{ea}} \right)^3$$

in million cycles

$$C_{a,osc} = C_a \left(\frac{180^\circ}{\theta} \right)^{1/p} \quad \text{when } \theta \geq \theta_{crit}.$$

$$C_{a,osc} = C_a \left(\frac{180^\circ}{\theta} \right)^{3/10} Z^{0.033} \quad \text{when } \theta < \theta_{crit}.$$

$$P_{ea} = 0.75 F_r + F_a + \frac{2M}{d_m}$$

Critical amplitude angle, $\theta_{crit} = \dfrac{720^\circ}{Z(1 \mp \gamma)}$

$$L_{10} = \left(\sum_{k=1}^{k=n} \frac{t_k}{L_{10k}} \right)^{-1} \qquad \sum_{k=1}^{k=n} t_k = 1 \qquad P_{ea} = \left(\frac{\sum_{k=1}^{k=n} P_{eak}^p N_k t_k \theta_k^x}{\sum_{k=1}^{k=n} N_k t_k \theta_k^x} \right)^{1/p}$$

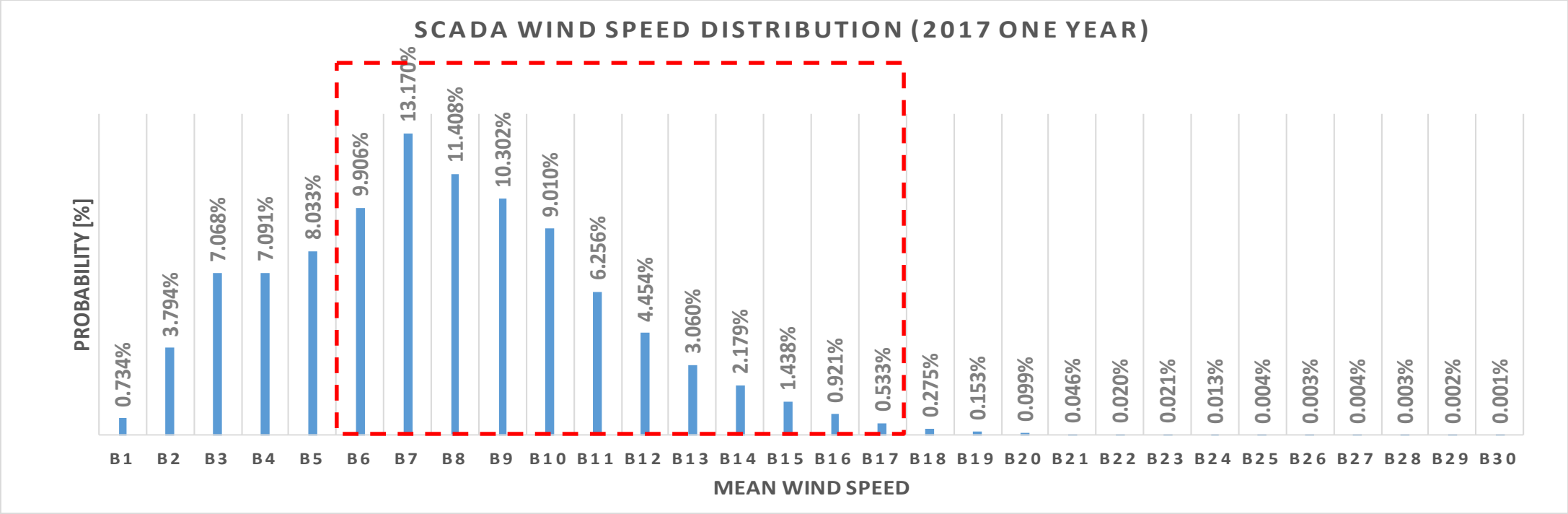
Conditions and Dataset for Study

- Following conditions and dataset were considered just for comparison purpose, not for the suitability assessment toward 25years design life:

  - Bearing reference life with the modification factors of 1.0
  - Mx and My only (major contributory load components)
  - One year SCADA data (2017) under normal power production
  - 1m/s step wind speed bin, 3 SCADA datasets randomly chosen over each wind speed bin (total 36 datasets to be analysed)
  - Wind field to be re-generated in simulation based on the wind speed measured at the hub centre
  - Very small variation less than the amplitude of 0.05 deg to be considered as stationary condition for bearing
  - Double-row 4 point contact ball bearing, approximately 4.4m size

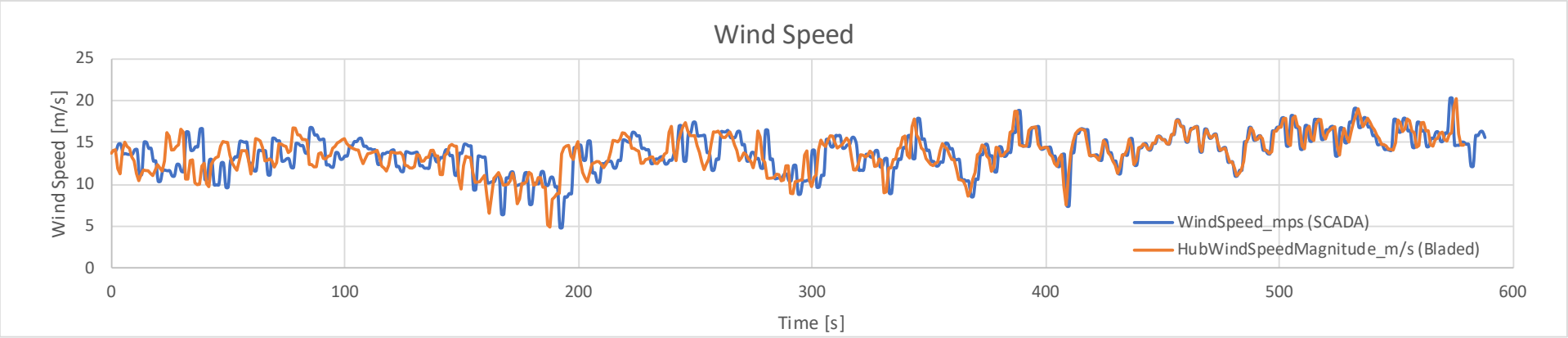
Measured Wind Speed Distribution

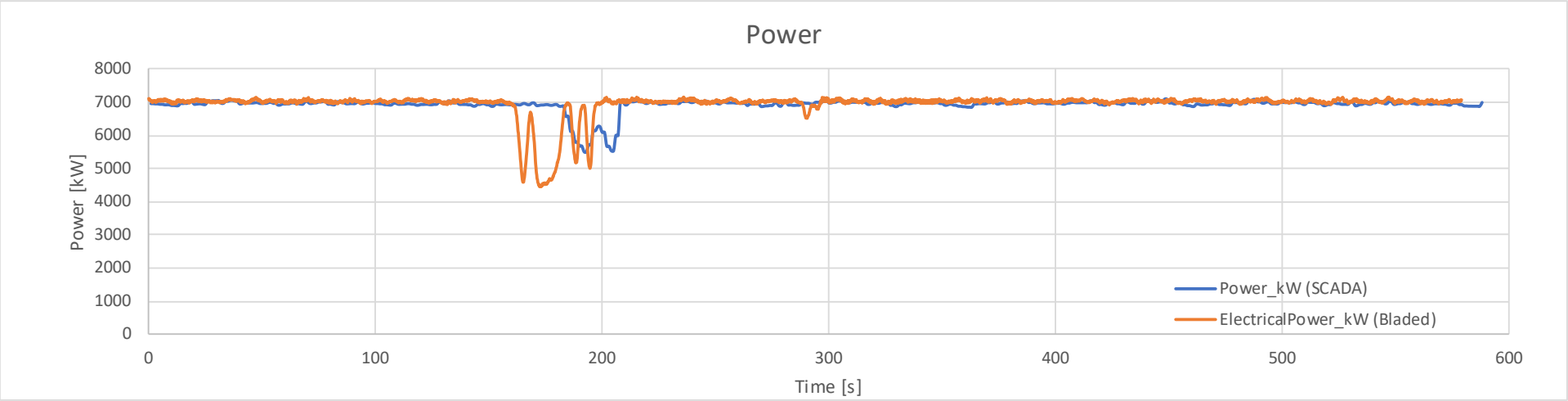
- Occurrence of 10 min average wind speed was recorded from LDT operation during 2017
- Total 36 datasets that were analysed representing normal power production, cover around 73%
- Probability of each mean wind speed to be used for one-year cycle counting and bearing life calculation



Power Production Comparison

- Wind field was re-generated in simulation based on the wind speed measured at the hub centre
- Consistent wind speed between SCADA and simulation
- Good correlation in power production with small localized deviation





Example comparison result; 05/30/2017 16:20

Bearing Life with Measured Dataset (SCADA)

- Accumulated pitch bearing **fatigue damage from one year operation** was estimated to **1.2% based on the measured SCADA datasets**

Index, i	Amplitude range, Θ [deg]	No. of half cycles, ni	Operational time, ti [%]	Mean amplitude, Θi [deg]	Mean frequency, fi [Hz]	Equv. Loads, Pea_i [kN]	Capacity, Ca,osc_i [kN]	L10h,osc_i [h]	Damage, D [%]
1	0.05 - 0.08	75661	5.40%	0.064	0.098	6510.1	35165	446718	0.024%
2	0.08 - 0.2	270271	18.27%	0.135	0.104	6534.9	28118	213756	0.170%
3	0.2 - 0.5	531292	27.00%	0.342	0.138	6394.7	21260	74152	0.723%
4	0.5 - 1	496469	25.86%	0.707	0.134	6160.8	17094	44177	1.162%
5	1 - 1.5	199939	11.05%	1.200	0.127	5833.6	14586	34283	0.640%
6	1.5 - 2	87926	6.01%	1.713	0.102	5344.3	13110	40049	0.298%
7	2 - 3	51263	4.11%	2.264	0.087	5076.9	12057	42624	0.191%
8	3 - 4	5753	0.56%	3.364	0.071	6397.6	10707	18246	0.061%
9	4 - 5	665	0.07%	4.259	0.063	5457.5	9521	23601	0.006%
10	5 - 10	2276	0.29%	5.304	0.054	4515.1	8850	38594	0.015%
11	10 - 15	1579	0.62%	11.370	0.018	2274.5	6864	427444	0.003%
12	15 - 20	1579	0.75%	16.997	0.015	2750.3	6003	196370	0.008%
13	20 - 25	0	0.00%						
14	25 - 30	0	0.00%						
15	30 - 90	0	0.00%						
sum		1724672	100%				**L10h,osc [h]:**	**60142**	**3.301%**

Considering the pitch activation ratio of 34.92%, the **damage of 1.15% is estimated for one year** (L10,osc,act [h]: 172,209)

Bearing Life with Simulated Dataset (Bladed)

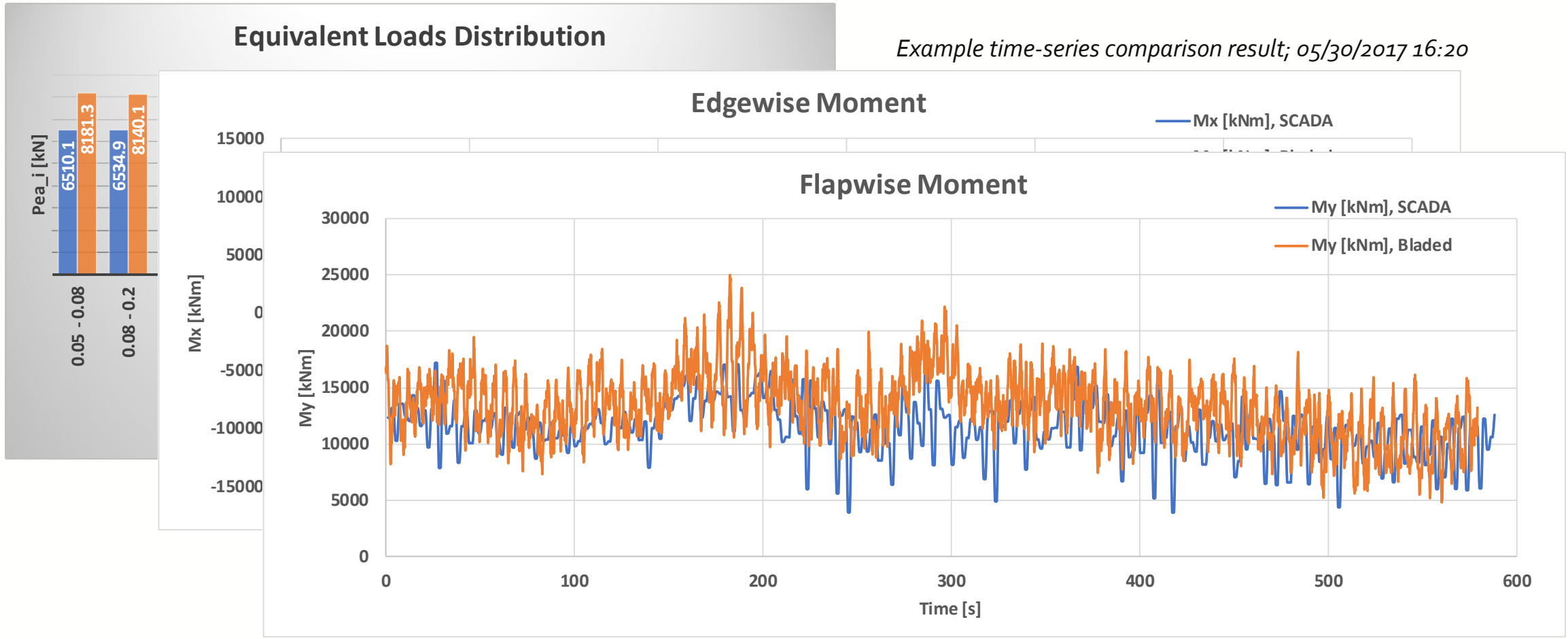
- Accumulated pitch bearing **fatigue damage from one year operation** was estimated to **11.4% based on the corresponding simulated datasets**
- Approximately **10 times more damage than that from SCADA dataset – WHY?**

Index, i	Amplitude range, Θ [deg]	No. of half cycles, ni	Operational time, ti [%]	Mean amplitude, Θi [deg]	Mean frequency, fi [Hz]	Equv. Loads, Pea_i [kN]	Capacity, Ca,osc_i [kN]	L10h,osc_i [h]	Damage, D [%]
1	0.05 - 0.08	141420	4.57%	0.065	0.166	8181.3	34981	130911	0.090%
2	0.08 - 0.2	251421	12.04%	0.132	0.112	8140.1	28296	104320	0.299%
3	0.2 - 0.5	228530	18.84%	0.337	0.065	8291.8	21345	72983	0.670%
4	0.5 - 1	180950	14.55%	0.730	0.067	8285.2	16935	35637	1.059%
5	1 - 1.5	148474	4.50%	1.268	0.176	8315.3	14347	8084	1.445%
6	1.5 - 2	152520	4.13%	1.736	0.198	8111.8	13057	5855	1.829%
7	2 - 3	408466	12.11%	2.525	0.181	7835.0	11670	5082	6.181%
8	3 - 4	473408	14.46%	3.477	0.175	7604.2	10601	4294	8.737%
9	4 - 5	308828	9.63%	4.456	0.172	7329.5	9379	3389	7.369%
10	5 - 10	162188	5.17%	5.607	0.168	7352.4	8688	2726	4.916%
11	10 - 15	0	0.00%						
12	15 - 20	0	0.00%						
13	20 - 25	0	0.00%						
14	25 - 30	0	0.00%						
15	30 - 90	0	0.00%						
sum		2456205	100%				**L10h,osc [h]:**	**7958**	**32.596%**

Considering the pitch activation ratio of 34.92%, the **damage of 11.38% is estimated for one year** (L10,osc,act [h]: 22,788)

Loads Comparison

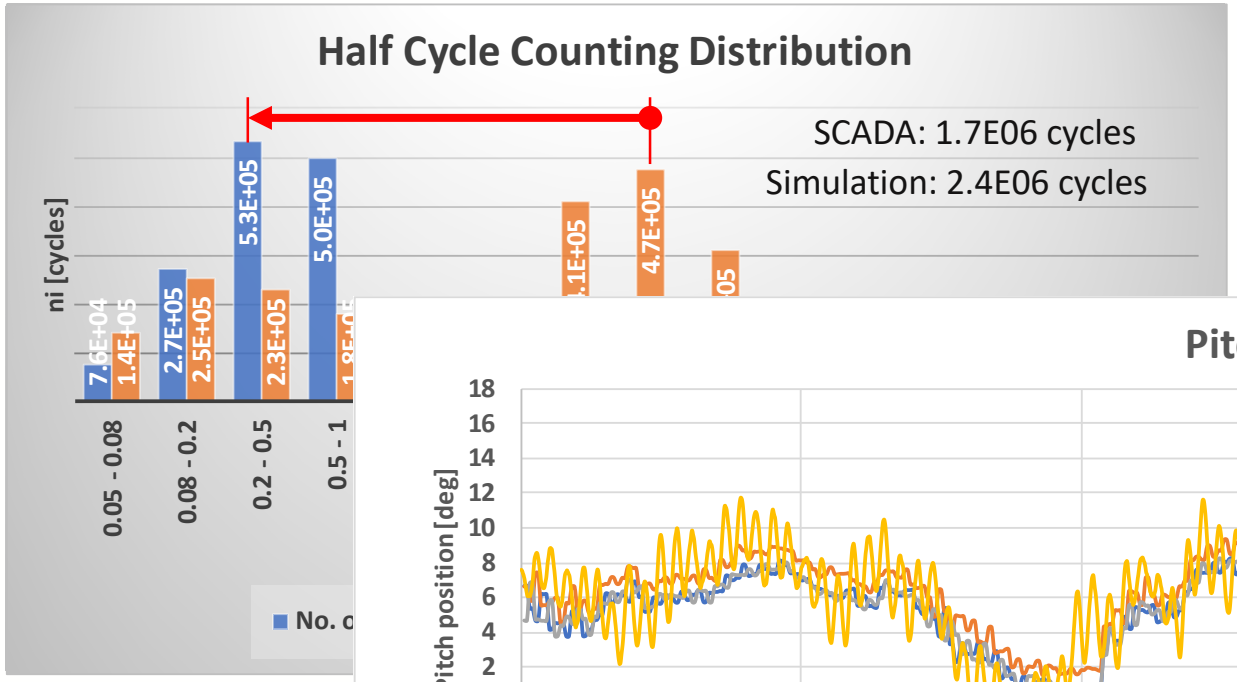
- Simulated loads were approximately 1.5 times higher based on average value

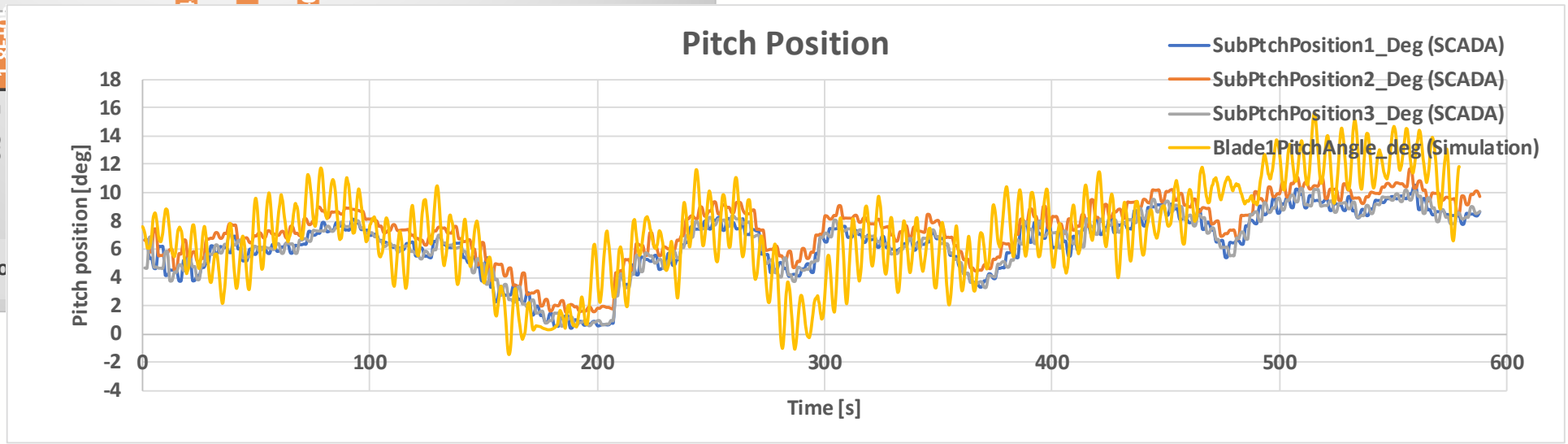


Example time-series comparison result; 05/30/2017 16:20

Pitch Cycle and Amplitude

- **Reduced total cycles** for SCADA, **most frequent amplitude shifted toward far smaller range** – WHY?
- Consistent collective pitch behaviour but **large difference in amplitude under IPC**

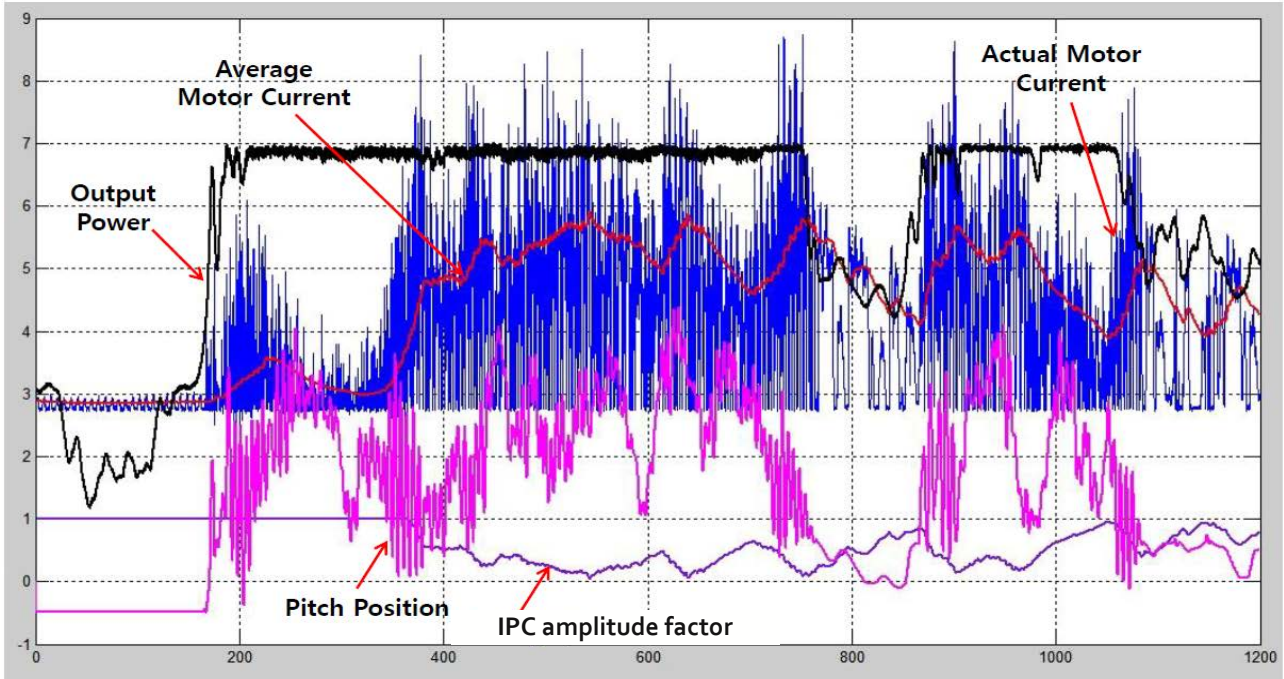




Example time-series comparison result; 05/30/2017 16:20

Evolution – IPC Control Algorithm

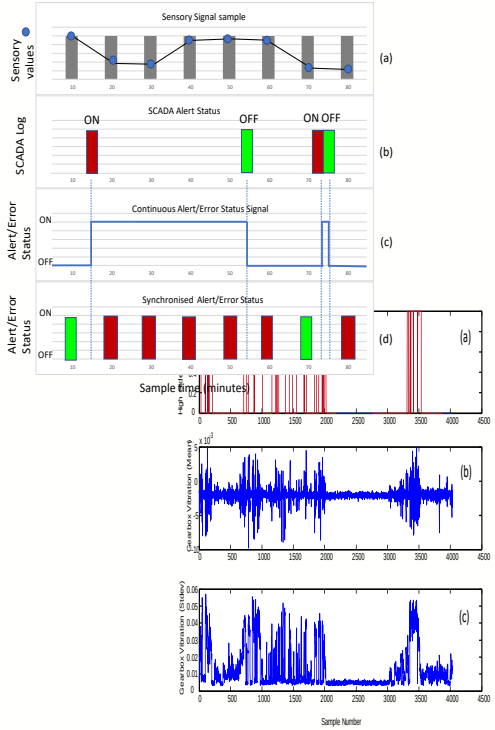
- Controller tuning from prototype commissioning (2012)
- IPC operation > increase of actuator motor current > excessive current over the rated current > current cut-off > fault event
- Improvement action: **IPC amplitude factor** introduction to IPC control algorithm – **Continuous adjustment of IPC amplitude against actuator motor current signal**
- The introduced **IPC amplitude factor is not applied to Bladed simulation model, leading to the major difference in IPC behaviour** that have been observed

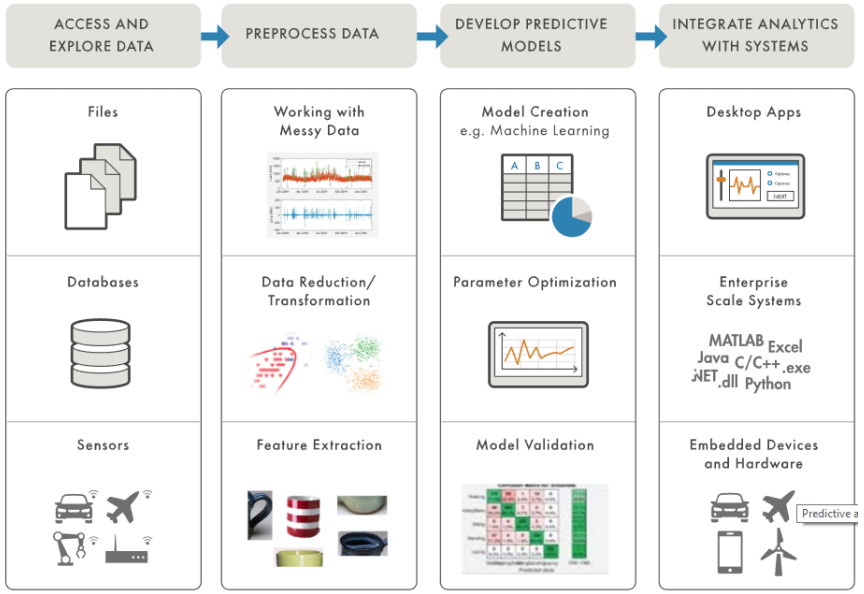


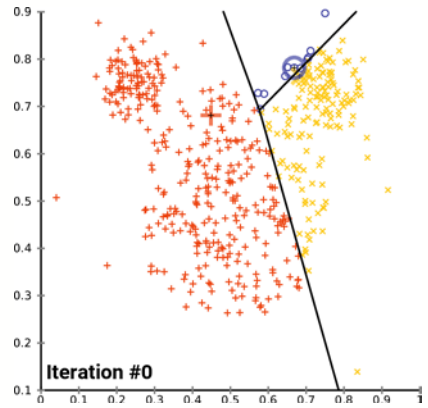
Utilising the Power of A.I. (Machine Learning)

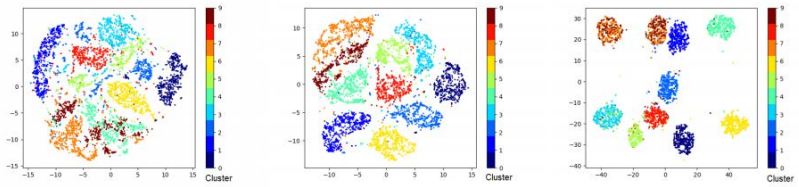
- There can be 1,000s of non-linear turbine operating modes
- Analysis is too difficult using conventional method
- Currently most collected SCADA data is unused

=> We apply advanced machine learning to detect abnormal condition









(a) k-Means (b) Autoencoder + k-Means (c) Proposed

Closing Remarks

- Process to evaluate the influence of turbine controller on pitch bearing performance defined

- **Case study showed the evaluation result with the simulated dataset largely deviated from that with the measured dataset (SCADA):**
    - Observed difference in pitch behaviour under IPC was majorly caused by previous control algorithm improvement action with IPC amplitude factor introduction (not applied to simulation controller), leading to less total cycles having smaller amplitude
    - With lower measured moment loads, resulting in much **less fatigue damage for actual turbine**. However, **increasing the portion of possible wear regime**

- Advanced machine learning algorithm is applied to detect abnormal condition

- Note that the case can differ over turbines due to different controller

- Recommend to monitor pitch system to evaluate the design life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