7MW LDT Pitch System Health monitoring with Machine Learning

TIGER - supply chain engagement event

Hyunjoo Lee, | Leader of Drivetrain Knowledge Area

CATAPULT Offshore Renewable Energy

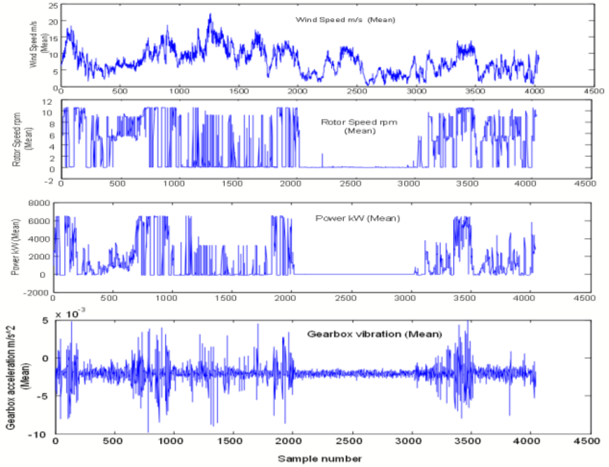
Agenda

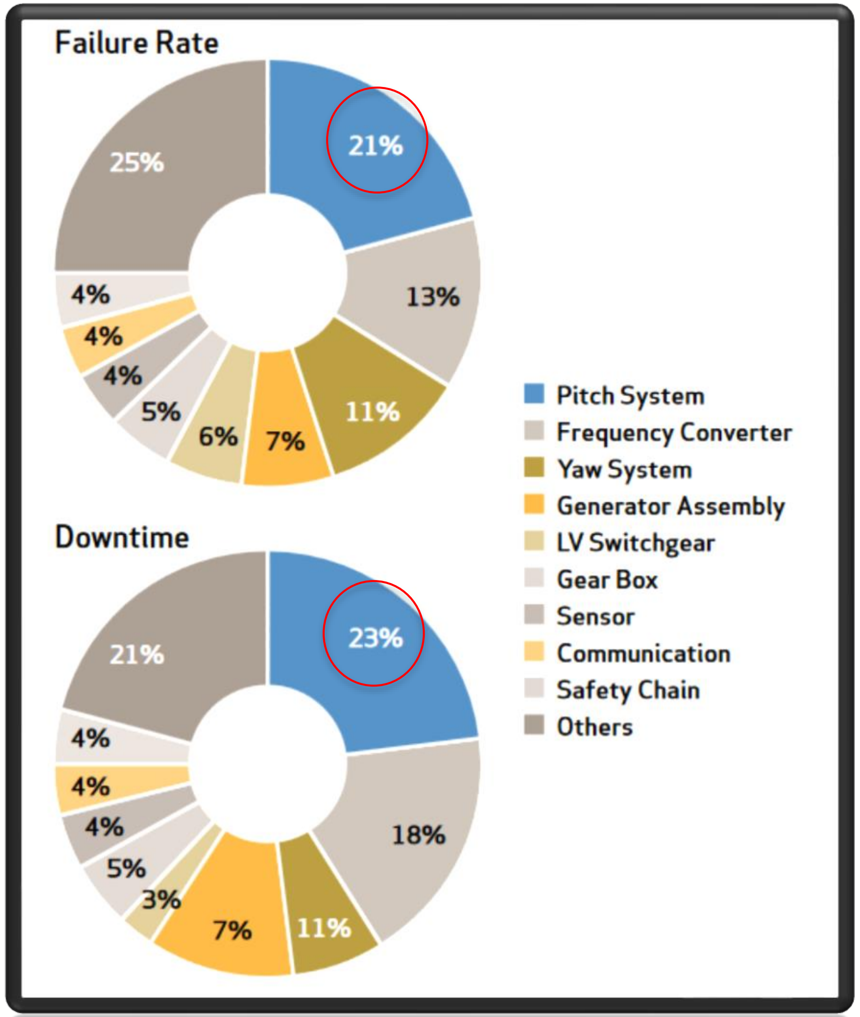
- Study approach and conditions/assumptions
  - Why Pitch system
  - Target turbine
  - Operational characteristics and damages
  - Investigation concept
  - Pitch cycle and load estimation method
  - Bearing life estimation method
  - Data sets and conditions for study
- Study result and observations
  - 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

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





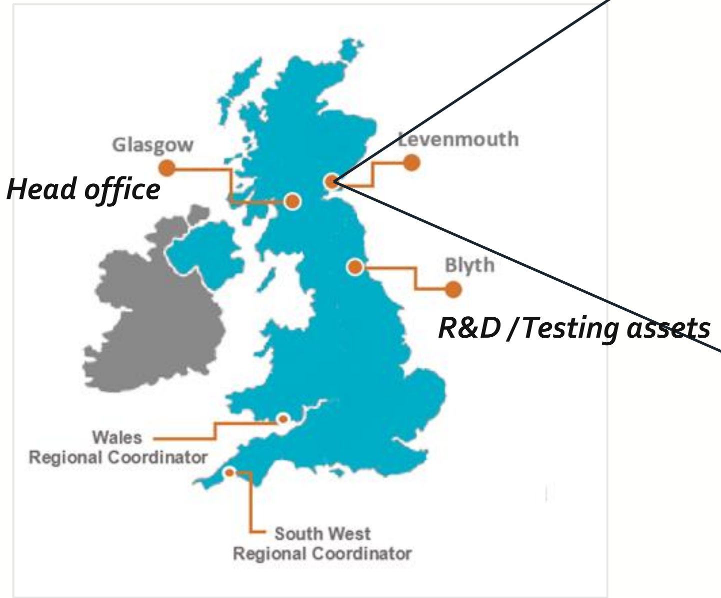
Source: windeurope.org

Project aim : Pitch system health monitoring with existing SCADA

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

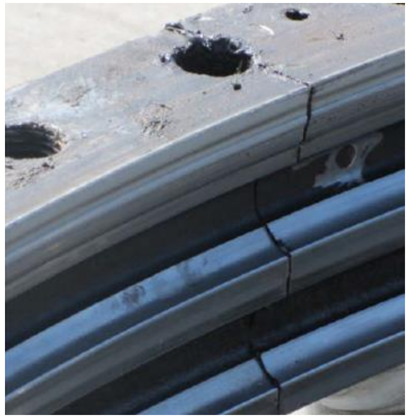
Target Turbine

- 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

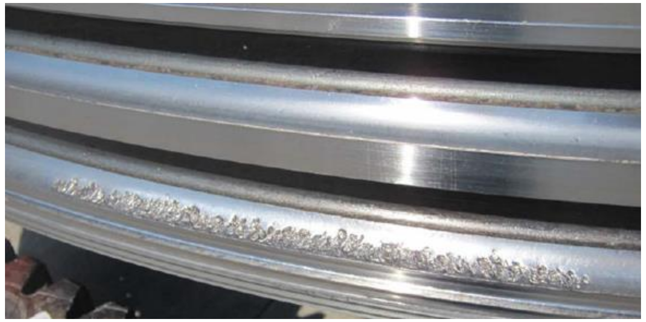


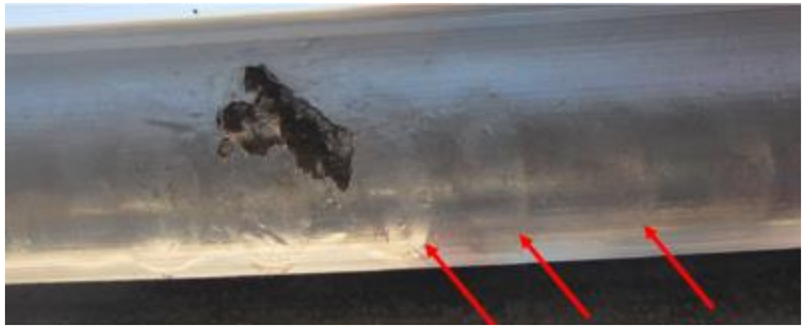
Operational Characteristics and Damages

- 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

Investigation Concept – Cause of issue

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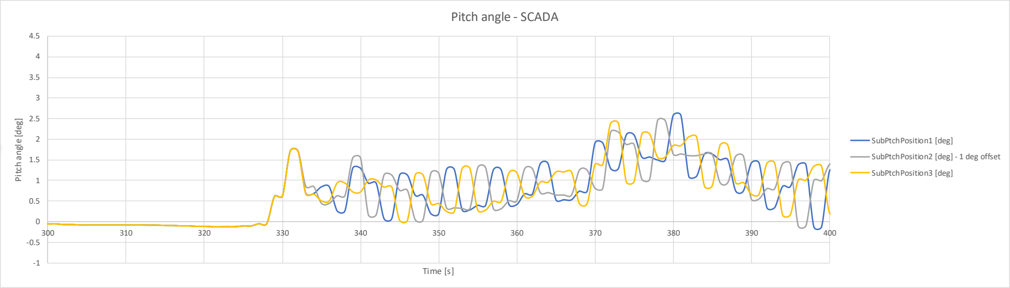
CONTROL STRATEGY

SCADA signals from actual turbine

Comparison/correlation

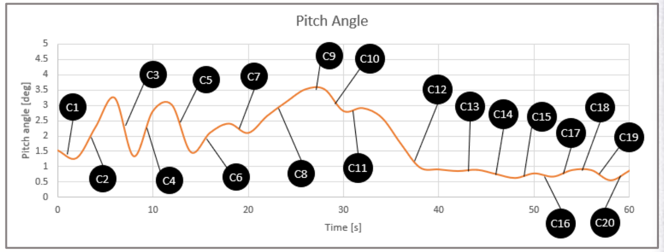
Aeroelastic simulation (Bladed model)

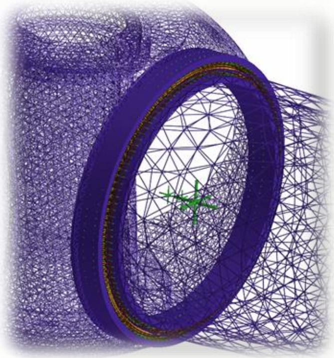
Time-series simulation



Oscillation cycle counting algorithm

Bearing performance & life simulation





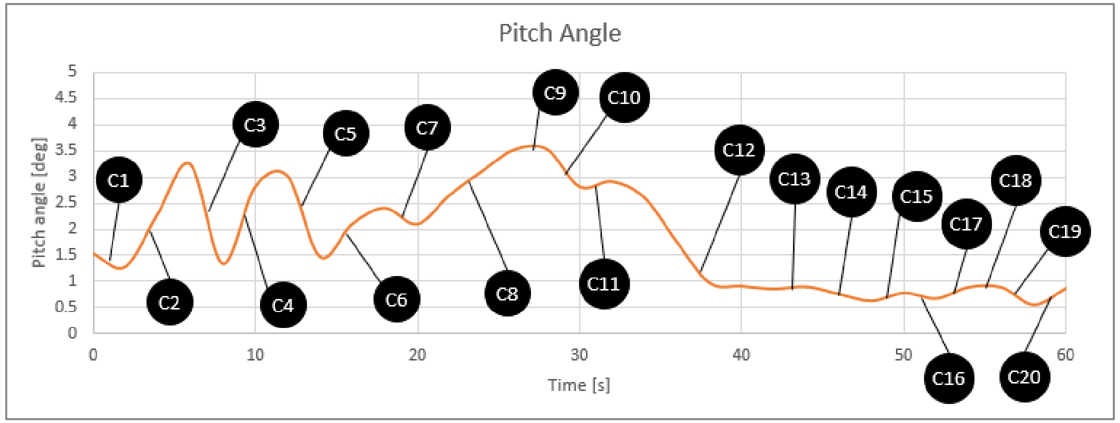
Pitch bearing condition

- **Fatigue damage**
- **Wear damage**

Control strategy feed back/Validation

Pitch Cycle and Load Estimation Method

- 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)

- 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

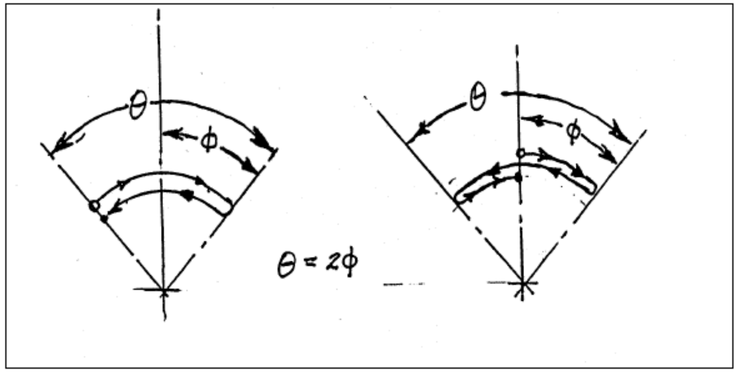
Bearing Life Estimation Method

- 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



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

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

in million cycles

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

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

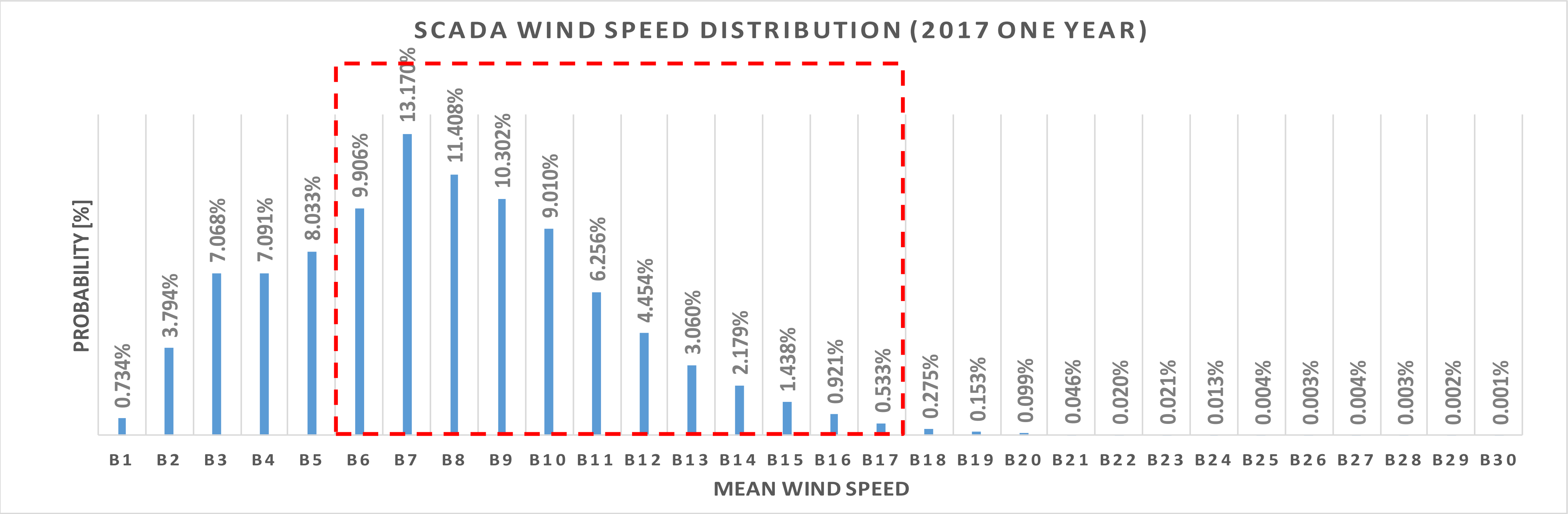
$$P_{ea} = 0.75F_r + F_a + \frac{2M}{d_m}$$

$$L_{10} = \left(\sum_{k=1}^{k=n} \frac{t_k}{L_{10k}}\right)^{-1} \qquad \sum_{k=1}^{k=n} t_k = 1$$

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

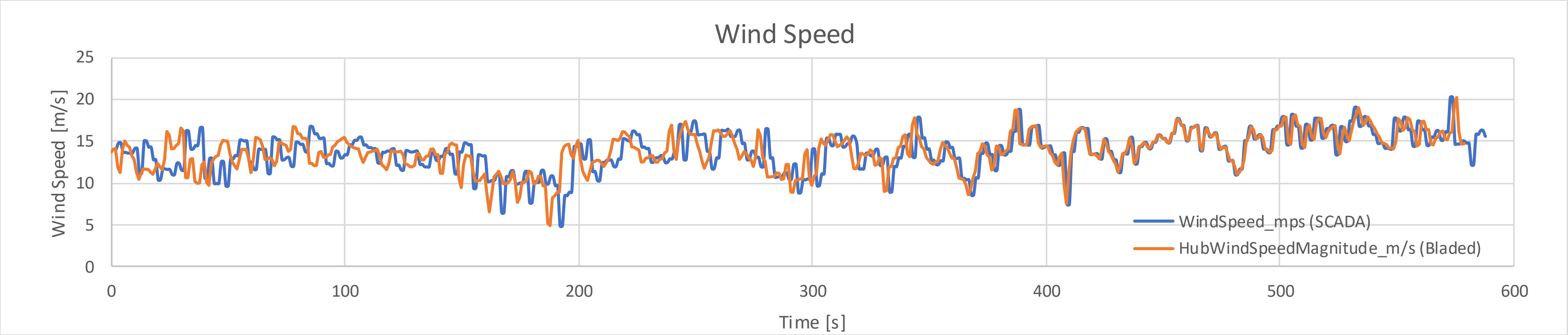
Measured Wind Speed Distribution

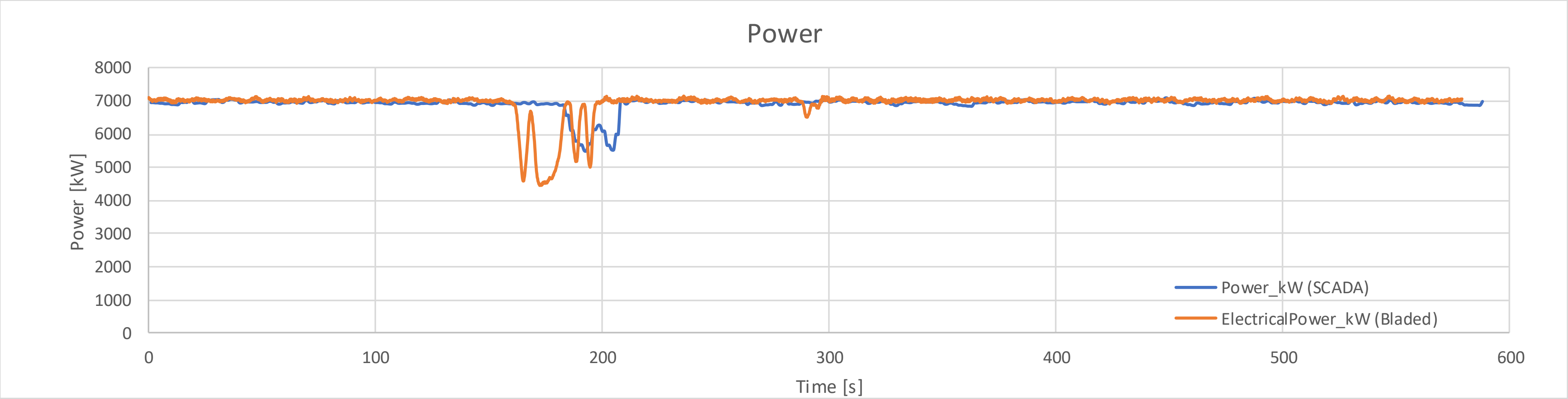
- Occurrence of 10 min average wind speed was recorded from LDT operation
- Total 36 datasets that were analysed representing normal power production, cover around 73%
- Probability of each mean wind speed to be used for one-year cycle counting and bearing life calculation



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 **3.3% 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 3.3% 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 **32.6% based on the corresponding simulated datasets**
- Approximately **10 times more damage than that from SCADA dataset – WHY?**

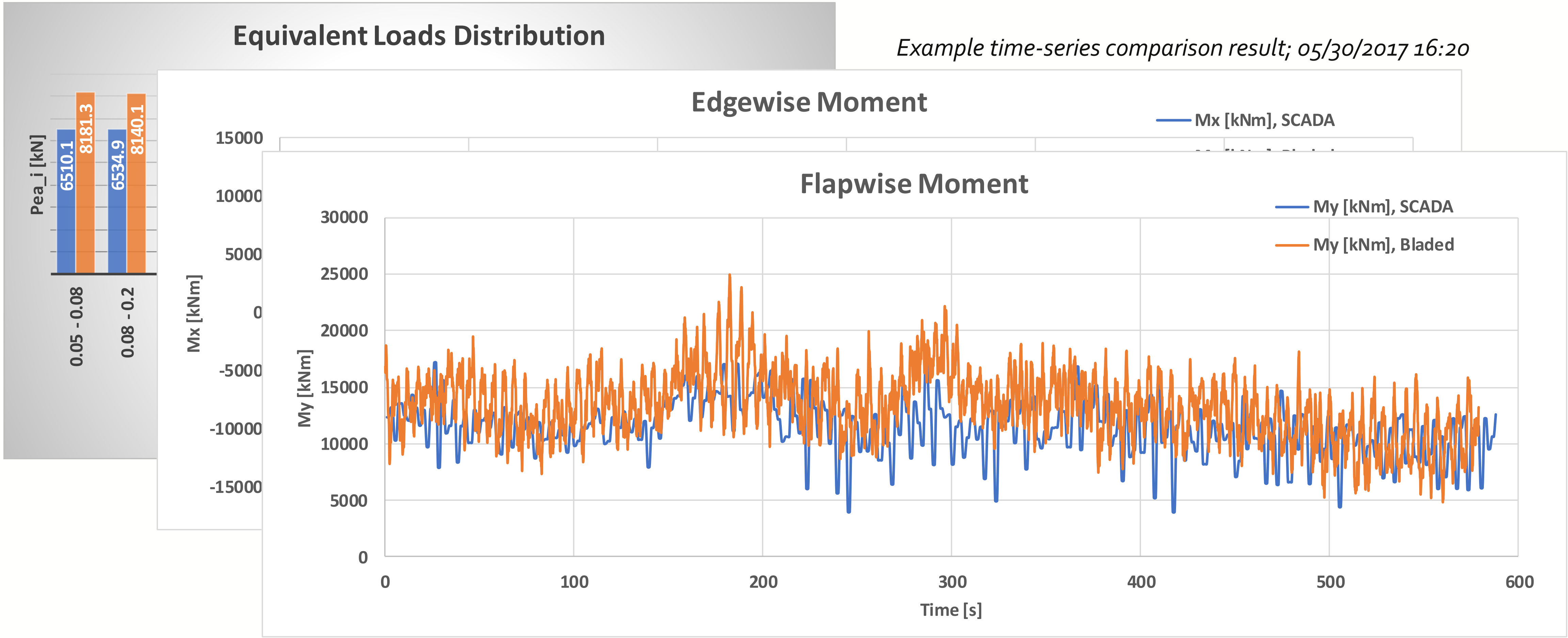
Index, i	Amplitude range, ϴ [deg]	No. of half cycles, ni	Operational time, ti [%]	Mean amplitude, ϴi [deg]	Mean frequency, fi [Hz]	Equv. Loads, Pea_i [kN]	Capacity, Ca,osc_i [kN]	L10h,osc_i [h]	Damage, D [%]
1	0.05 - 0.08	141420	4.57%	0.065	0.166	8181.3	34981	130911	0.090%
2	0.08 - 0.2	251421	12.04%	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 32.6% is estimated for one year** (L10,osc,act [h]: 22,788)

Loads Comparison

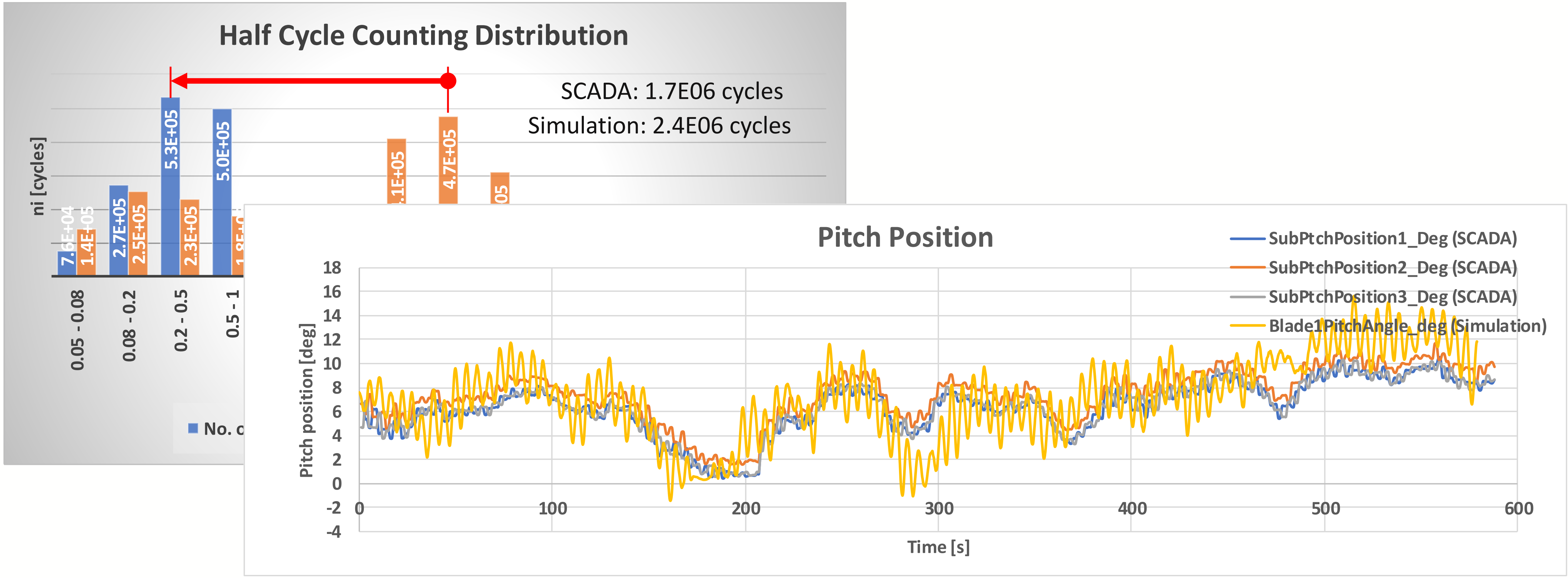
- Simulated loads were approximately 1.5 times higher based on average value

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



Pitch Cycle and Amplitude

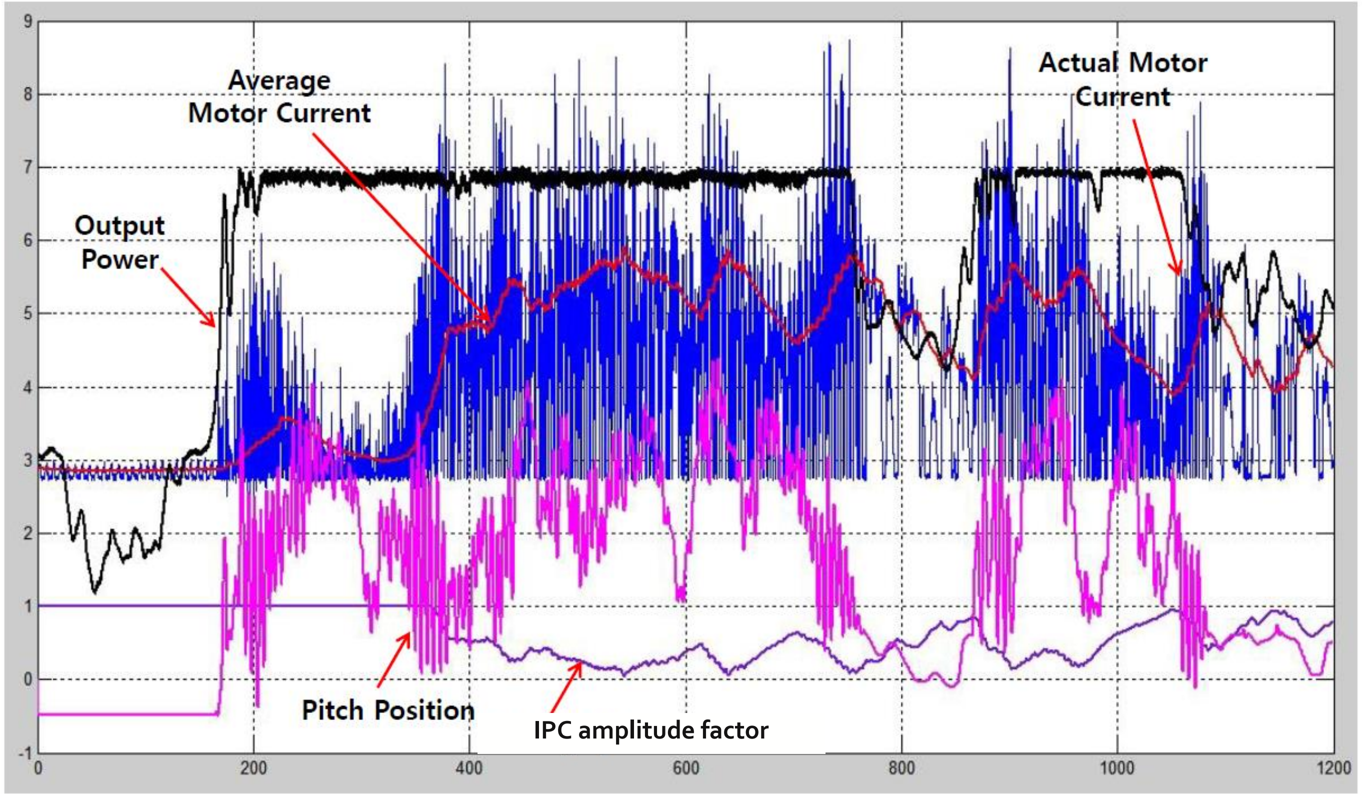
- **Reduced total cycles** for SCADA, **most frequent amplitude shifted toward far smaller range** – WHY?
- Consistent collective pitch behaviour but **large difference in amplitude under IPC**



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

Evolution – IPC Control Algorithm

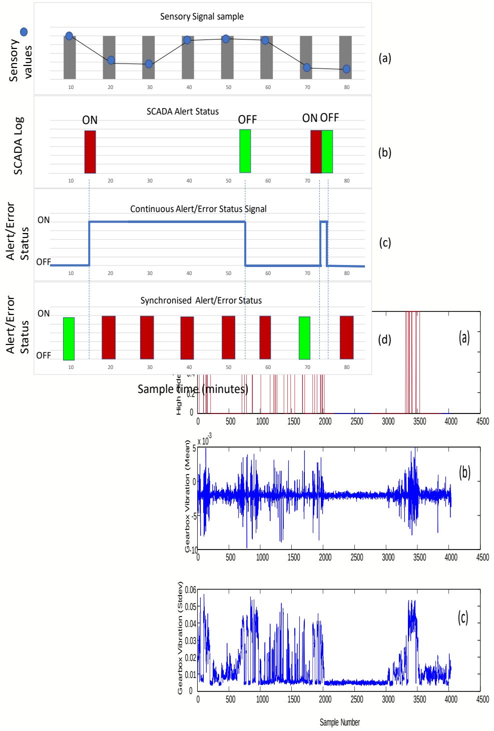
- Controller tuning from prototype commissioning (2012)
  - **IPC amplitude factor** introduction to IPC control algorithm – **Continuous adjustment of IPC amplitude against actuator motor current signal**
  - The introduced **IPC amplitude factor is not applied to Bladed simulation model, leading to the major difference in IPC behaviour** that have been observed

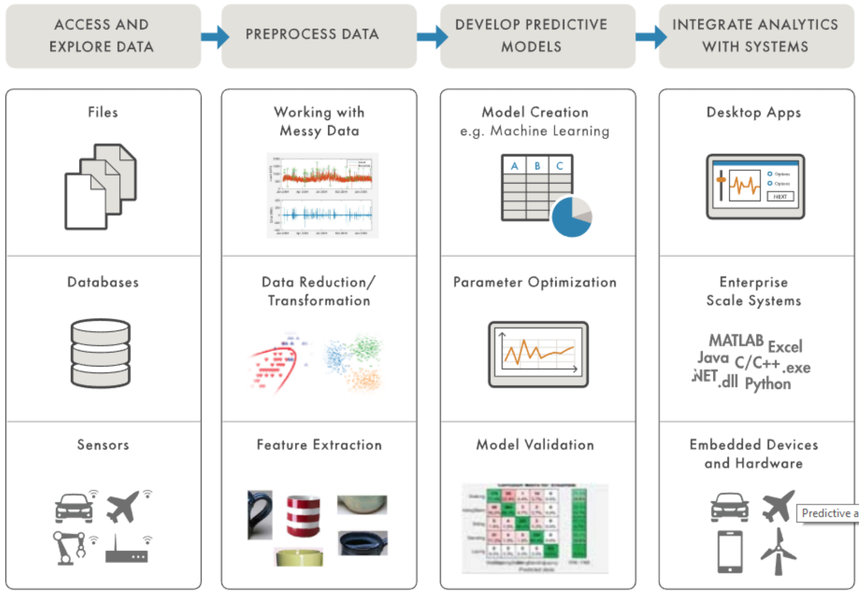


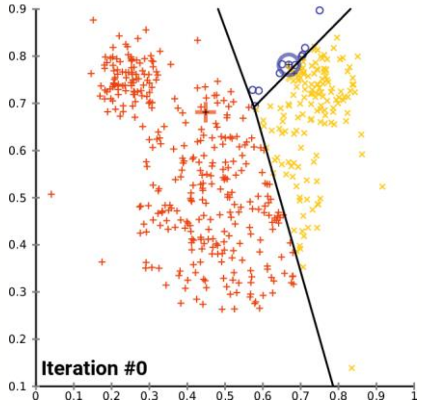
Utilising the Power of A.I. (Machine Learning)

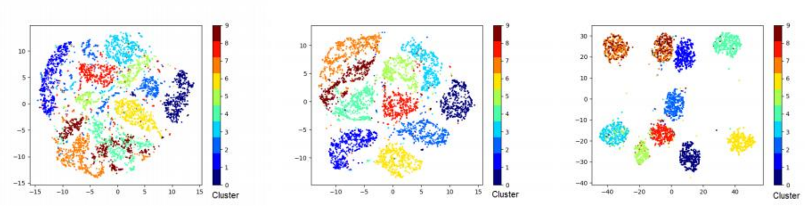
- There can be 1,000s of non-linear turbine operating modes
- Analysis or prediction is almost impossible with conventional method
- Currently most collected SCADA data is unused

=> Advanced machine learning to detect abnormal condition









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

Conclusion and Recommendation

- **Case study showed the evaluation result with the simulated dataset largely deviated from that with the measured dataset (SCADA):**
    - With lower measured moment loads, resulting in much **less fatigue damage for actual turbine**. However, **increasing the portion of possible wear regime**

- **Lesson learn** from Wind industry for Tidal developers
    - Pitch control system can improve the power output especially large size turbine (>1MW)
    - Design assumption, simulation and calculation should be evaluated during field commissioning
    - No. of loading cycle can be hugely differ from design simulation => should be measured
    - With state-of arts data processing technology, early stage fault can be detected by using basic SCADA system

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