January 18, 2018

EERA DeepWind 2018
15th Deep Sea Offshore Wind R&D Conference
Trondheim, Norway

Data Insights from an Offshore Wind Turbine Gearbox Replacement

Alexios Koltsidopoulos Papatzimos[1,2]
Tariq Dawood[2]
Philipp R. Thies[3]

[1]Industrial Doctorate Centre for Offshore Renewable Energy (IDCORE), Edinburgh, EH9 3JL
[2]EDF Energy R&D UK Centre, London, CR0 2AJ
[3]University of Exeter, Cornwall, TR10 9FE

Contents

1. Introduction and Motivation

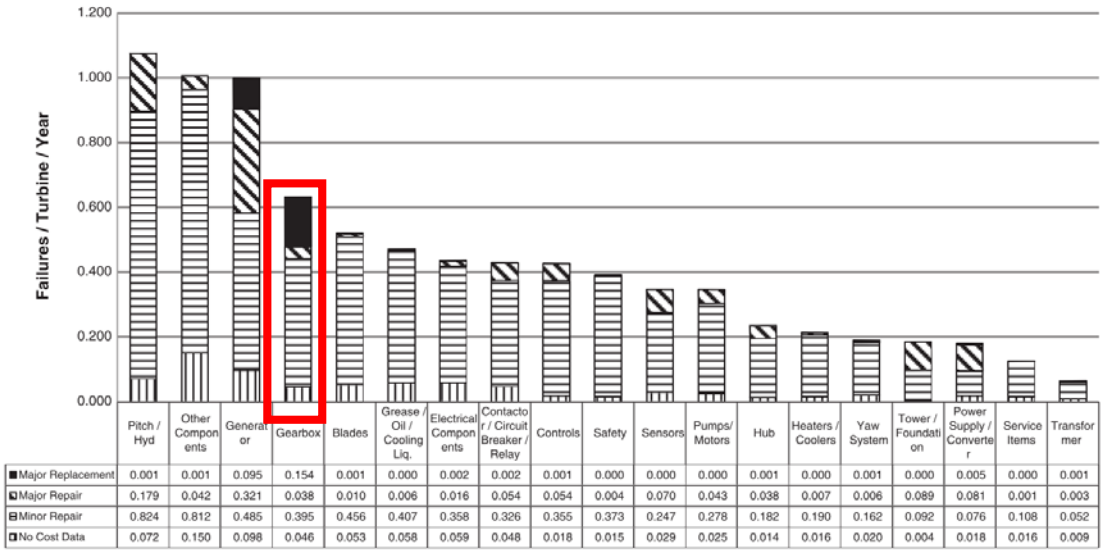
Introduction- EDF Group Offshore Assets

- Teesside Offshore Wind Farm
  - 27 2.3MW turbines
  - 1.5 km offshore
  - 7-15m water depth
  - Installation completed in June 2013
- Blyth Demonstrator Project
  - 5 Vestas 8.3MW turbines
- Future assets
  - Totalling 1.5GW

Motivation

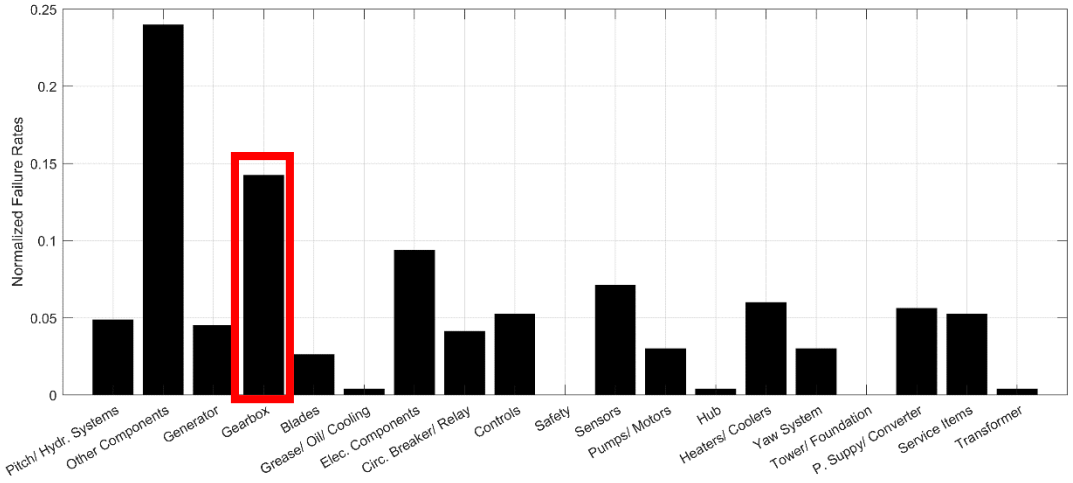
- Gearbox replacement @ Teesside
- Gearboxes are designed to last for the lifetime of the asset- IEC 61400-4
- Majority of onshore and offshore wind turbines have a geared drivetrain
- Currently largest installed wind turbine (V164-8.0 MW) has a gearbox
- Early detection by OEM
  - Reduce downtime
  - Reduce component lead time
  - Understand component reliability
- Perform future fault prediction and diagnosis

2. Wind Turbine Gearbox Failures



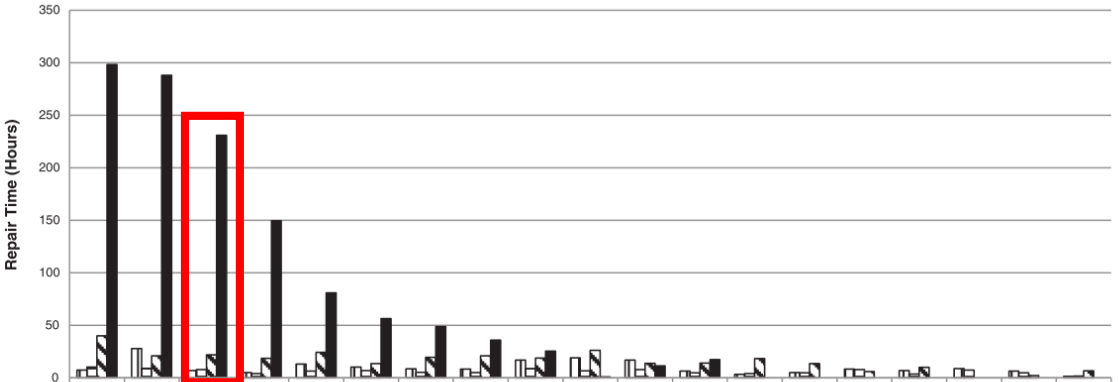
	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contactor / Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps/ Motors	Hub	Heaters / Coolers	Yaw System	Tower / Foundation	Power Supply / Converter	Service Items	Transformer
Major Replacement	0.001	0.001	0.095	0.154	0.001	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.005	0.000	0.001
Major Repair	0.179	0.042	0.321	0.038	0.010	0.006	0.016	0.054	0.054	0.004	0.070	0.043	0.038	0.007	0.006	0.089	0.081	0.001	0.003
Minor Repair	0.824	0.812	0.485	0.395	0.456	0.407	0.358	0.326	0.355	0.373	0.247	0.278	0.182	0.190	0.162	0.092	0.076	0.108	0.052
No Cost Data	0.072	0.150	0.098	0.046	0.053	0.058	0.059	0.048	0.018	0.015	0.029	0.025	0.014	0.016	0.020	0.004	0.018	0.016	0.009

[1]



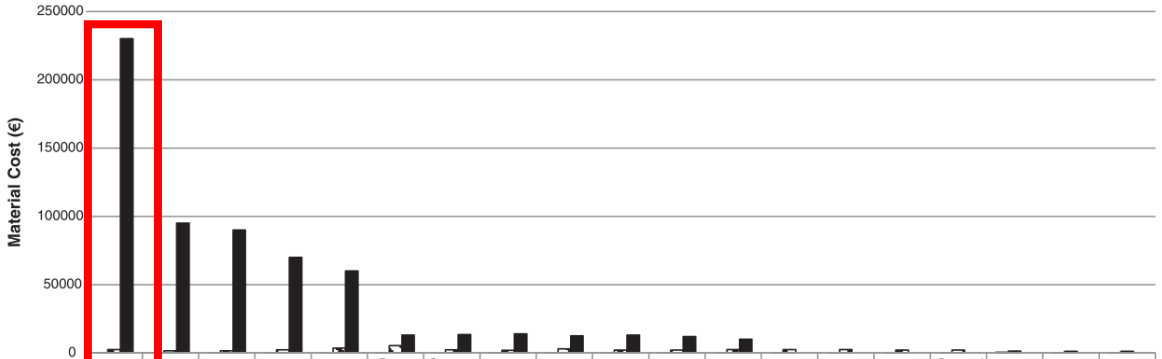
[2]

2. Wind Turbine Gearbox Failures



	Hub	Blades	Gearbox	Contactor / Circuit Breaker / Relay	Generator	Power Supply / Converter	Yaw System	Other Components	Pitch / Hyd	Transformer	Controls	Electrical Components	Grease / Oil / Cooling Liq.	Heaters / Coolers	Sensors	Pumps/Motors	Service Items	Tower / Foundation	Safety
No Cost Data	8	28	7	5	13	10	9	8	17	19	17	7	3	5	8	7	9	6	2
Minor Repair	10	9	8	4	7	7	5	5	9	7	8	5	4	5	8	4	7	5	2
Major Repair	40	21	22	19	24	14	20	21	19	26	14	14	18	14	6	10		2	7
Major Replacement	298	288	231	150	81	57	49	36	25	1	12	18	0	0	0	0	0	0	0

[1]



	Gearbox	Hub	Blades	Transformer	Generator	Power Supply / Converter	Contactor / Circuit Breaker / Relay	Pitch / Hyd	Yaw System	Controls	Electrical Components	Other Components	Sensors	Safety	Pumps/ Motors	Grease / Oil / Cooling Liq.	Heaters / Coolers	Service Items	Tower / Foundation
Minor Repair	125	160	170	95	160	240	260	210	140	200	100	110	150	130	330	160	465	80	140
Major Repair	2500	1500	1500	2300	3500	5300	2300	1900	3000	2000	2000	2400	2500	2400	2000	2000	1300	1200	1100
Major Replacment	230000	95000	90000	70000	60000	13000	13500	14000	12500	13000	12000	10000	0	0	0	0	0	0	0

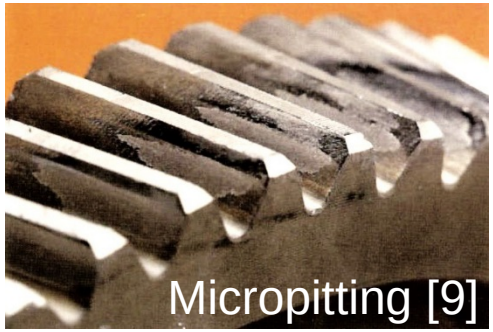
[1]

2. Wind Turbine Gearbox Failures

Most common failure causes [3, 4]:
- Fundamental gearbox design errors
- Manufacturing or quality issues
- Underestimation of operational loads
- Variable and turbulent wind conditions
- Insufficient maintenance

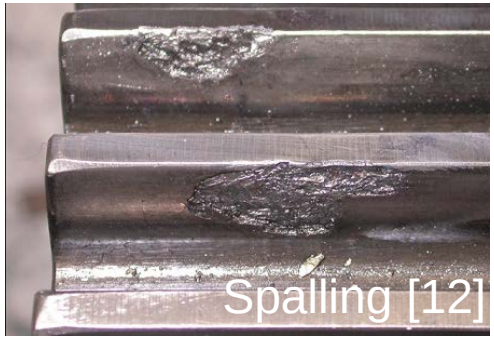
Most common failure locations [4-8]:
- HS Bearing
- IMS bearing
- Planet bearing

Most common failure modes:


Micropitting [9]

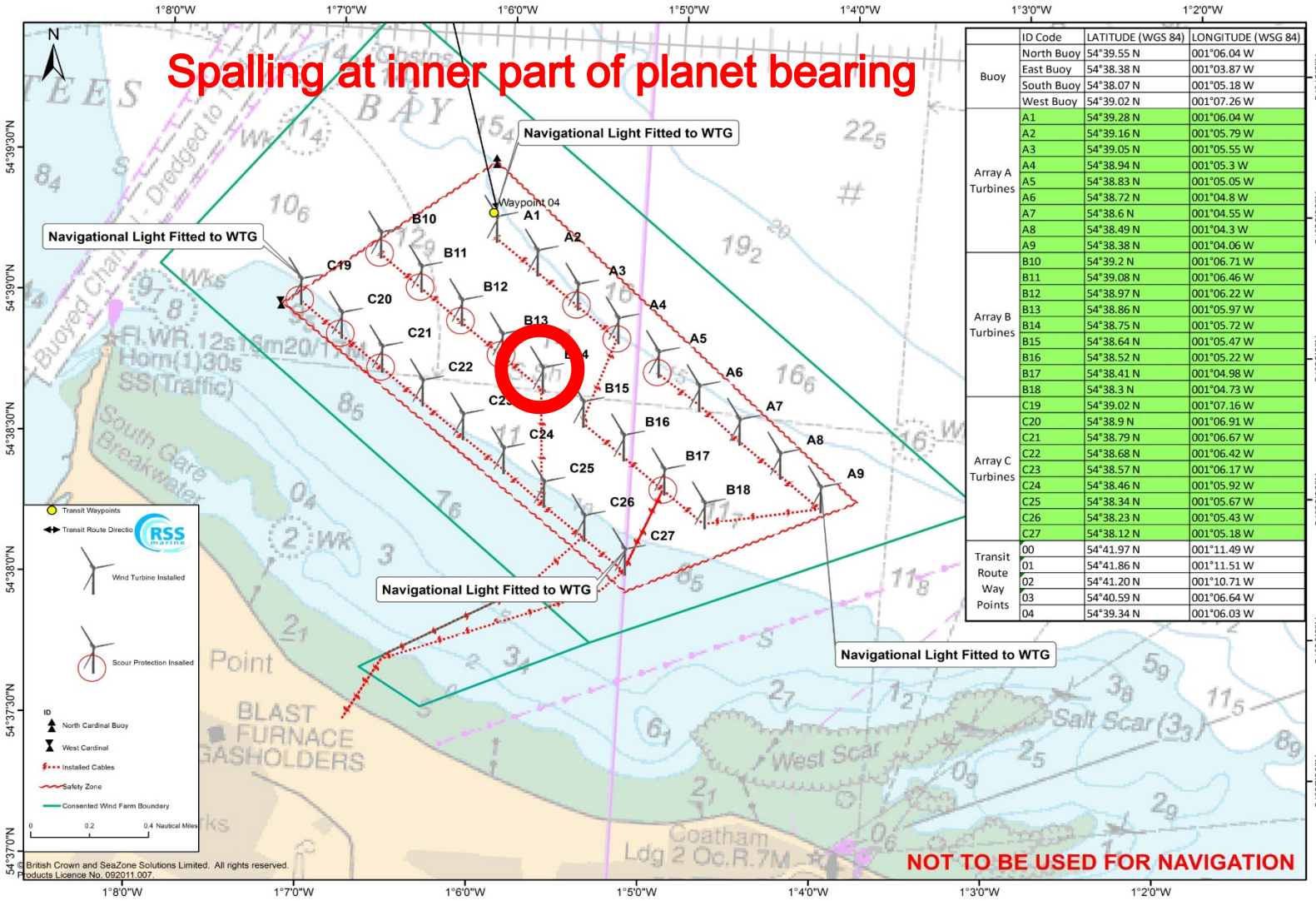

Tooth breakage [10]


Pitting [11]


Spalling [12]


Scuffing [11]

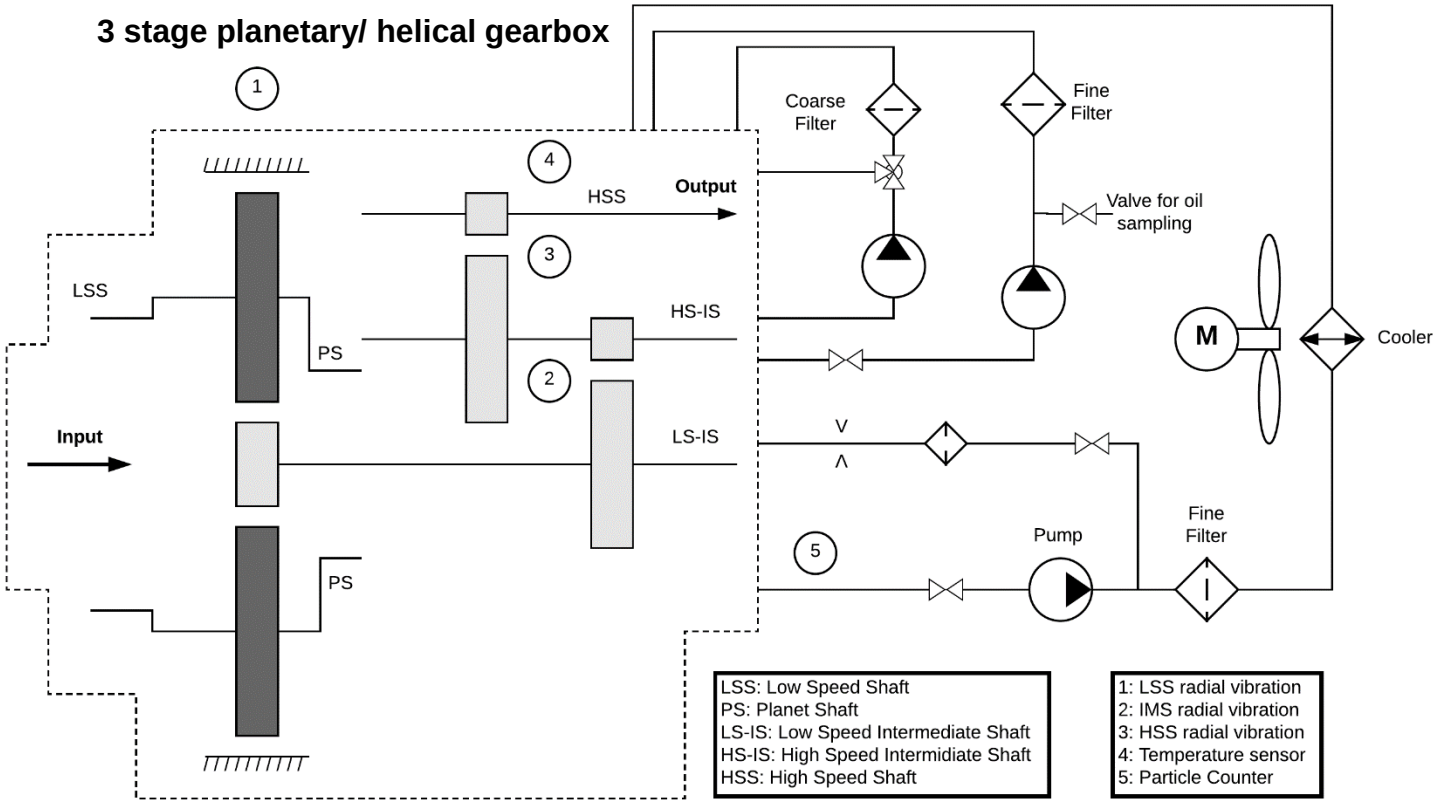
2. Wind Turbine Gearbox Failures



	ID Code	LATITUDE (WGS 84)	LONGITUDE (WSG 84)
Buoy	North Buoy	54°39.55 N	001°06.04 W
	East Buoy	54°38.38 N	001°03.87 W
	South Buoy	54°38.07 N	001°05.18 W
	West Buoy	54°39.02 N	001°07.26 W
Array A Turbines	A1	54°39.28 N	001°06.04 W
	A2	54°39.16 N	001°05.79 W
	A3	54°39.05 N	001°05.55 W
	A4	54°38.94 N	001°05.3 W
	A5	54°38.83 N	001°05.05 W
	A6	54°38.72 N	001°04.8 W
	A7	54°38.6 N	001°04.55 W
	A8	54°38.49 N	001°04.3 W
	A9	54°38.38 N	001°04.06 W
Array B Turbines	B10	54°39.2 N	001°06.71 W
	B11	54°39.08 N	001°06.46 W
	B12	54°38.97 N	001°06.22 W
	B13	54°38.86 N	001°05.97 W
	B14	54°38.75 N	001°05.72 W
	B15	54°38.64 N	001°05.47 W
	B16	54°38.52 N	001°05.22 W
	B17	54°38.41 N	001°04.98 W
	B18	54°38.3 N	001°04.73 W
Array C Turbines	C19	54°39.02 N	001°07.16 W
	C20	54°38.9 N	001°06.91 W
	C21	54°38.79 N	001°06.67 W
	C22	54°38.68 N	001°06.42 W
	C23	54°38.57 N	001°06.17 W
	C24	54°38.46 N	001°05.92 W
	C25	54°38.34 N	001°05.67 W
	C26	54°38.23 N	001°05.43 W
	C27	54°38.12 N	001°05.18 W
Transit Route Way Points	00	54°41.97 N	001°11.49 W
	01	54°41.86 N	001°11.51 W
	02	54°41.20 N	001°10.71 W
	03	54°40.59 N	001°06.64 W
	04	54°39.34 N	001°06.03 W

3. Wind Turbine Gearbox Monitoring

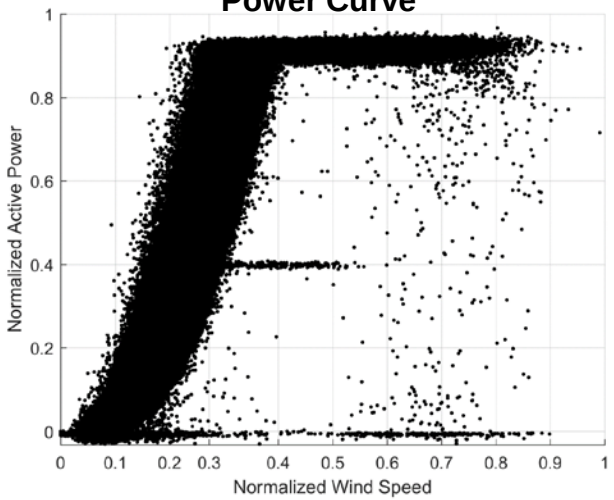
- SCADA
  - Temperature, pressure, vibration, current, rotational speed, etc.
    - Timeseries
- CMS
  - Vibration
    - Sampling in time instances
    - Pre-processed (Envelopes, FFTs, Cepstrum, RMS, etc)
  - Oil Particle Counter



4. Data Pre-processing

Filtering

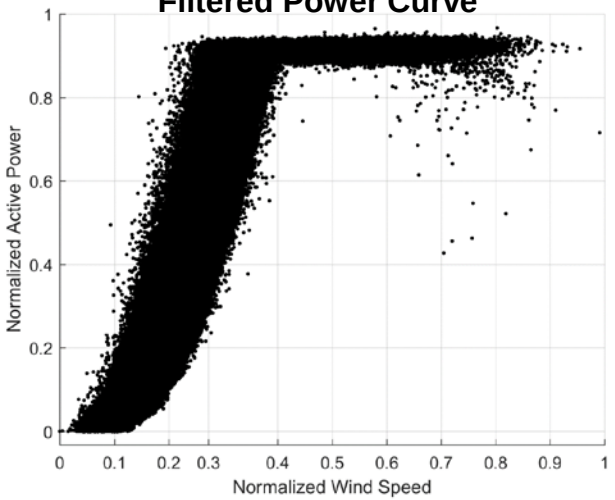
Power Curve



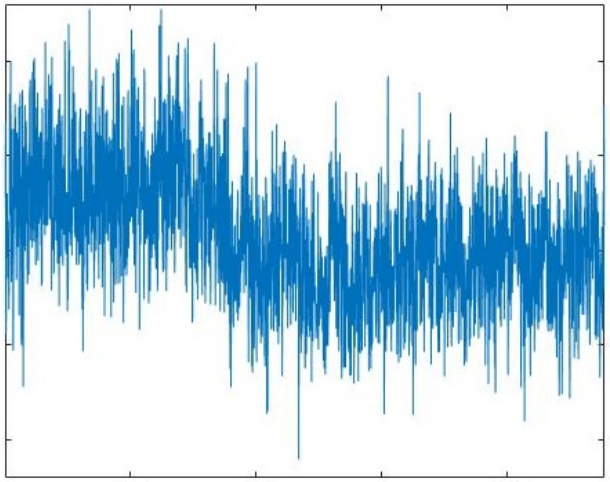
SCADA Alarms + maintenance log timestamps have been removed that include:

Yaw, Pitch, Generator, Electrical, Grid, Sensor failures, Environmental conditions, Maintenance operations

Filtered Power Curve

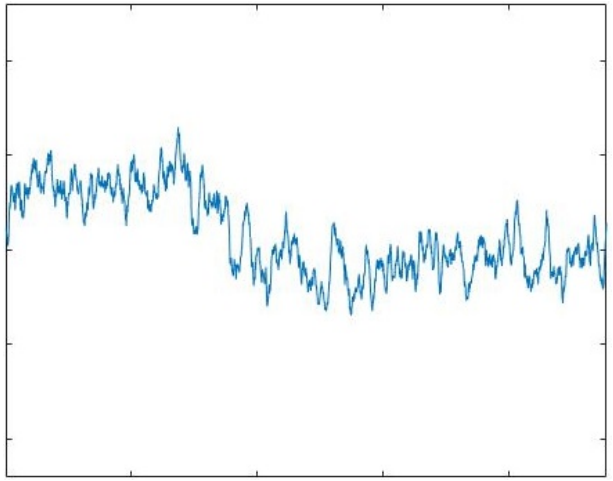


Vibration Signal



Savitzky–Golay filter

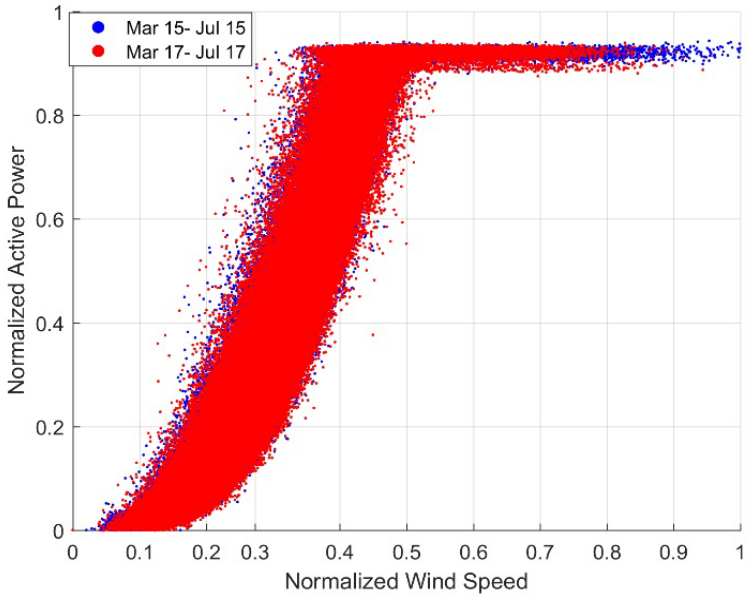
Vibration Signal



4. Data Pre-processing

Filtering

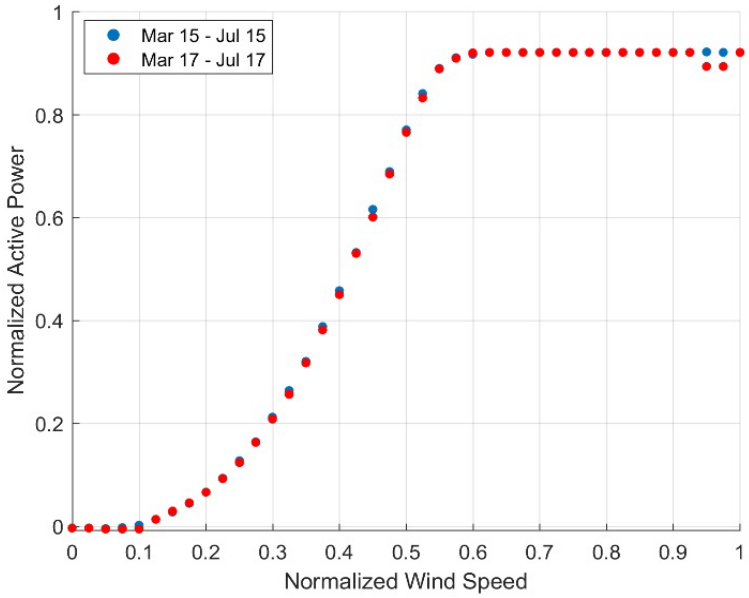
Filtered Power Curve



Bins

IEC 61400-1-22

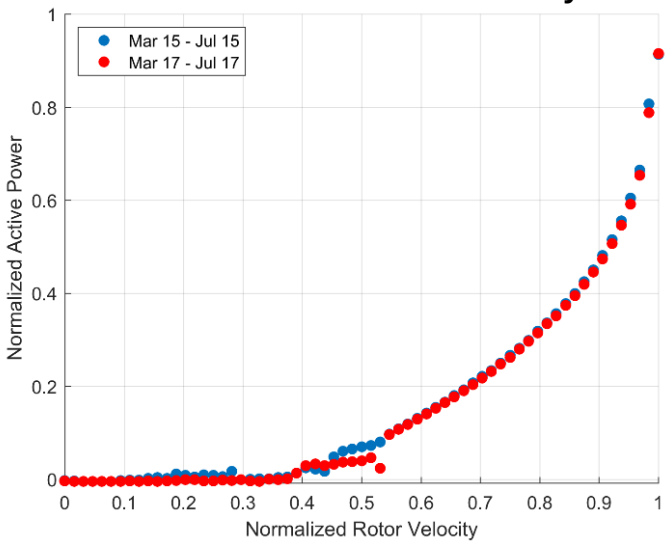
Binned Power Curve



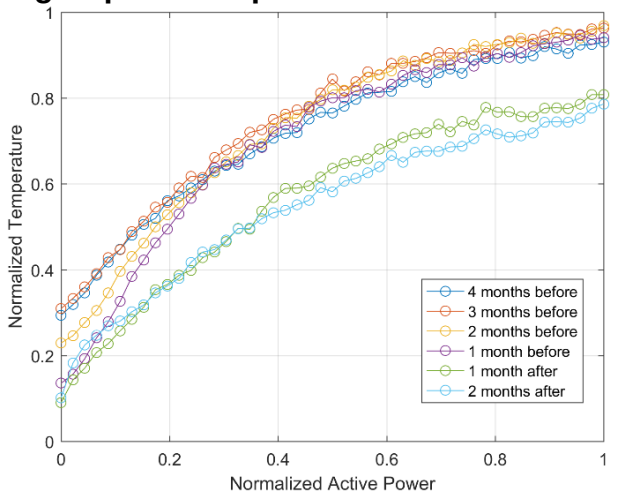
5. Failure Detection & Diagnosis

SCADA

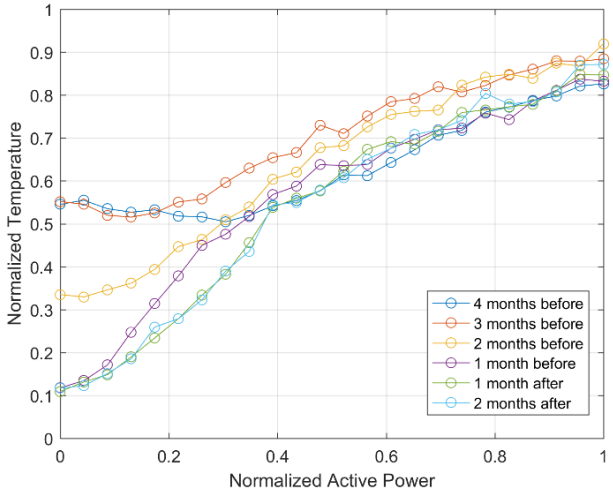
Active Power vs Rotor Velocity



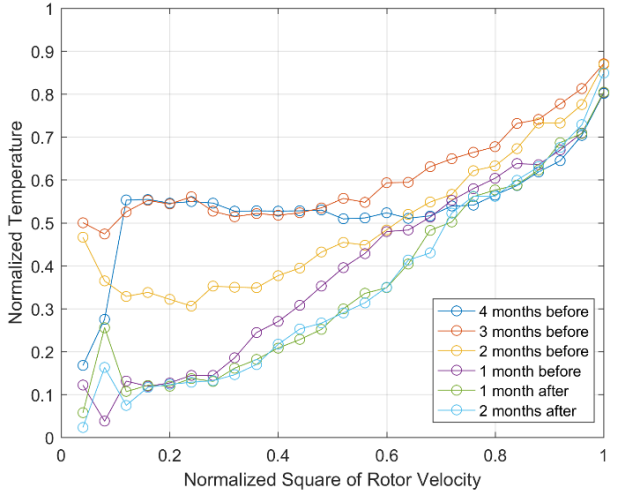
High Speed Temperature vs Active Power



Gearbox Oil Temperature vs Active Power

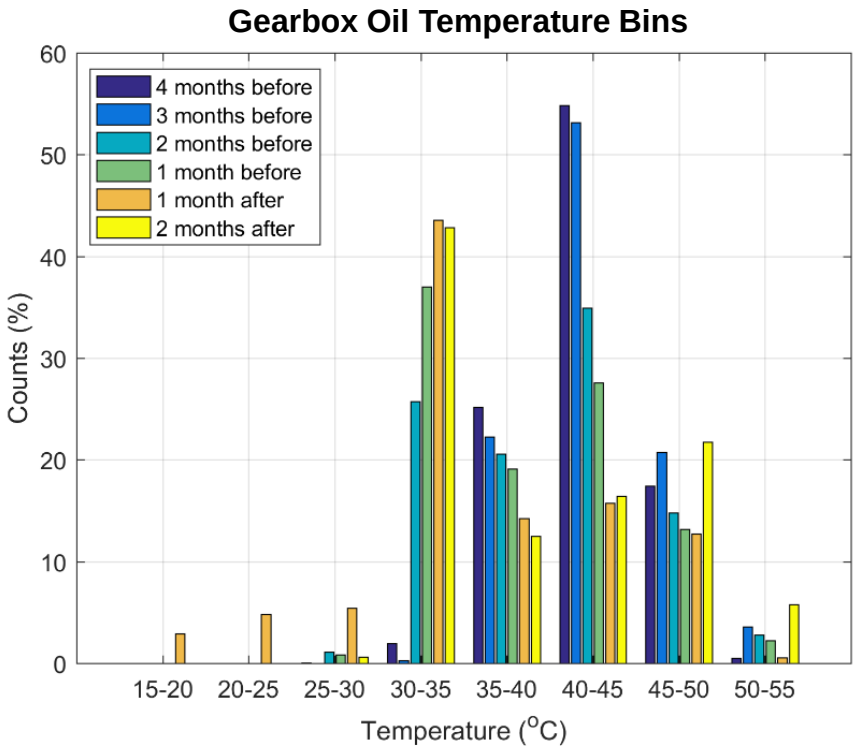


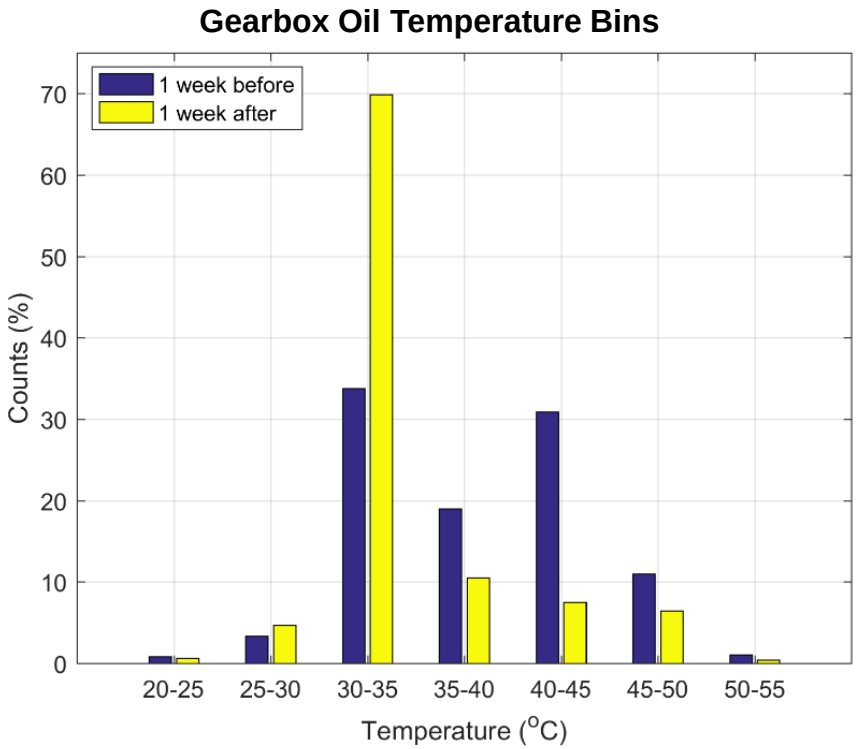
Gearbox Oil Temperature vs (Rotor Velocity)^2



5. Failure Detection & Diagnosis

SCADA

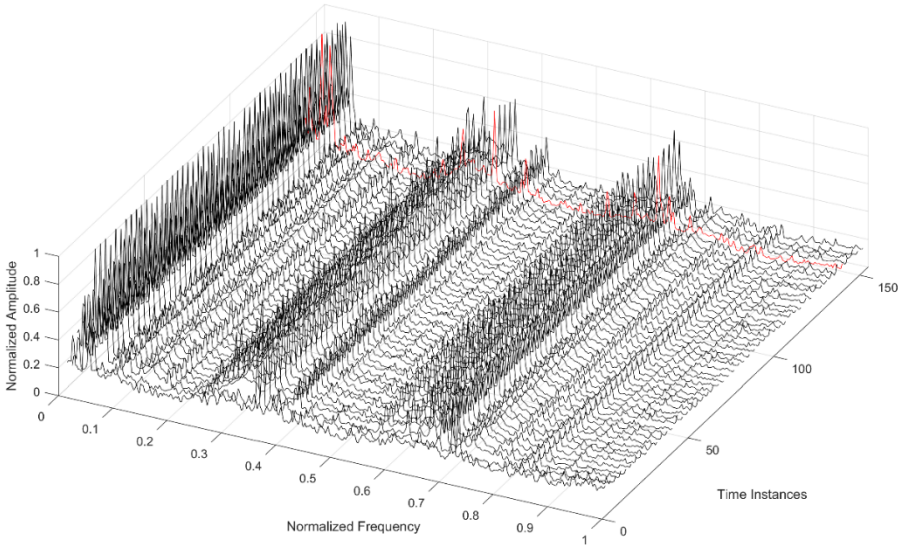




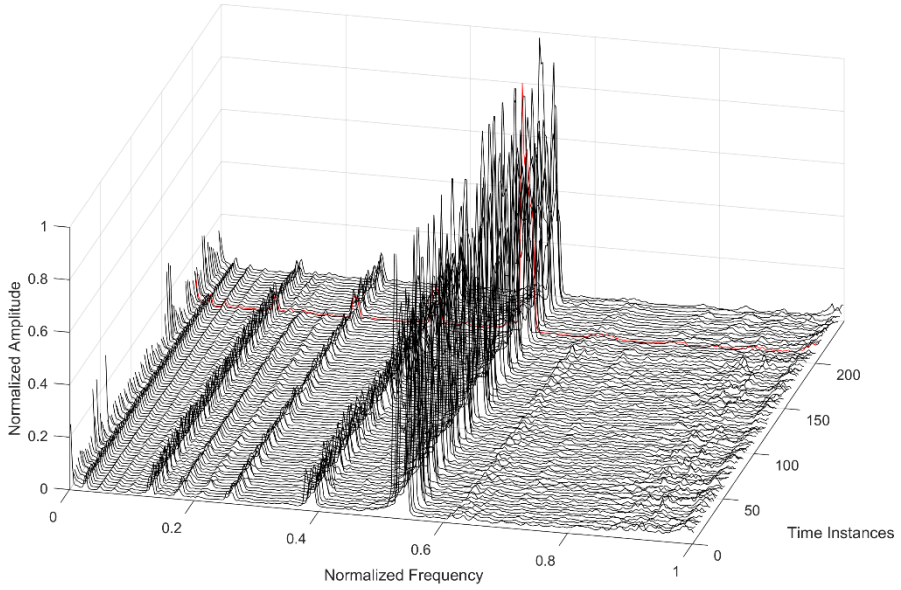
5. Failure Detection & Diagnosis

CMS

Planet Bearing Envelope

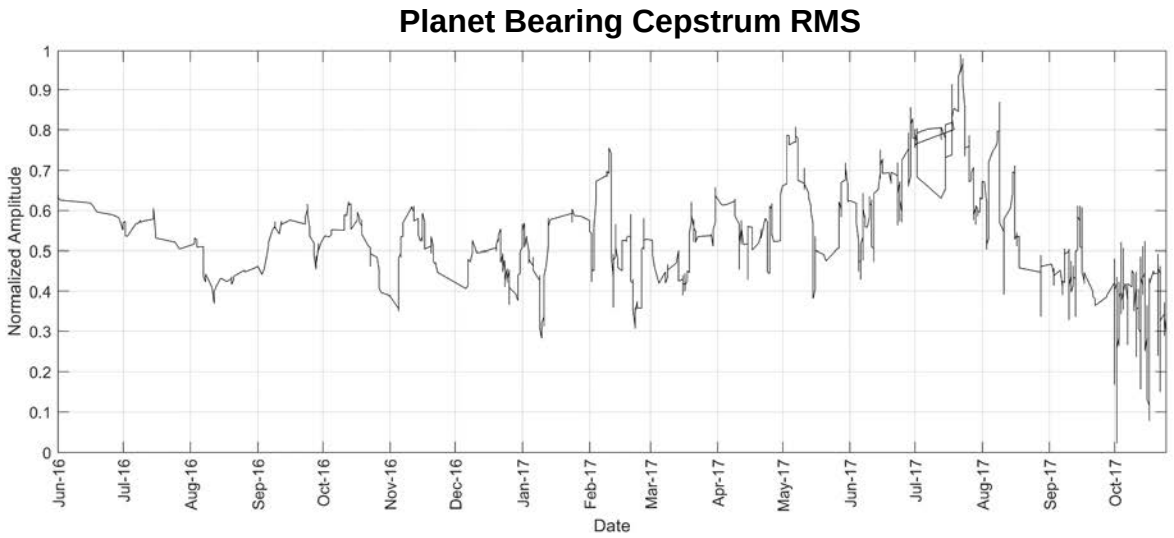


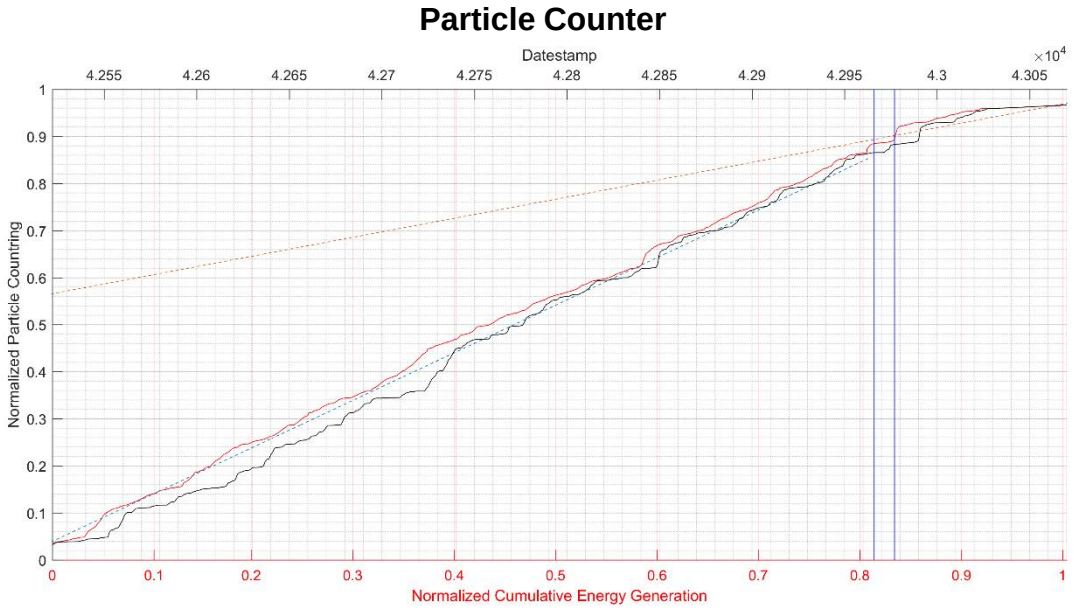
Planet Bearing FFT



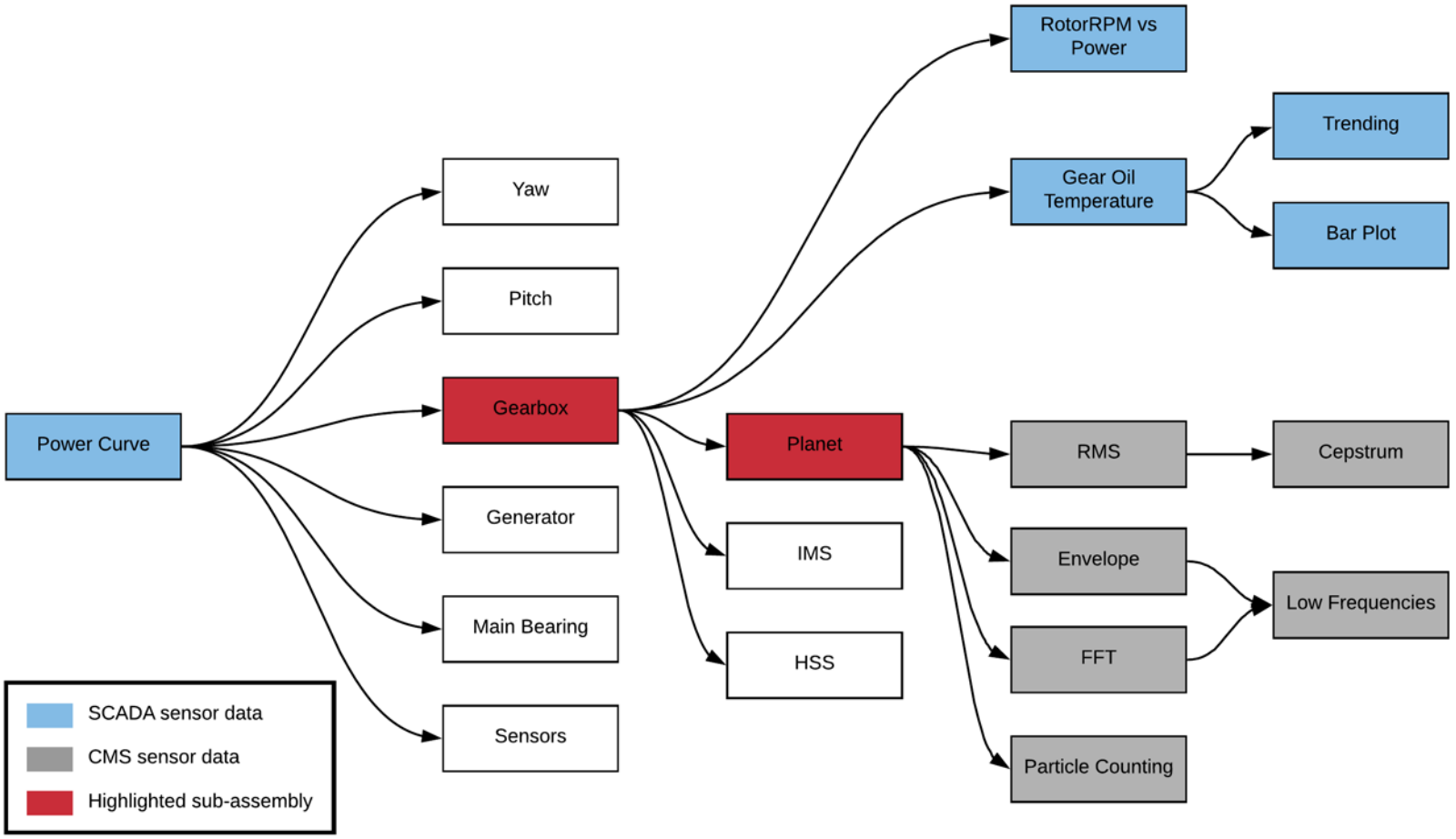
5. Failure Detection & Diagnosis

CMS





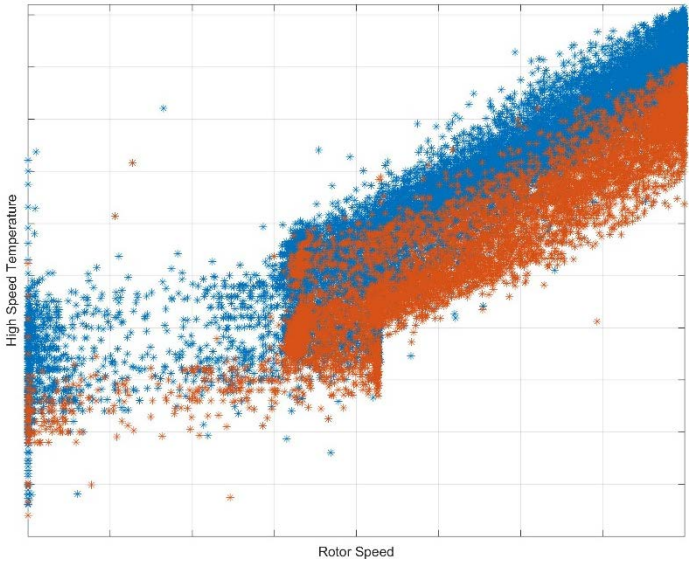
5. Failure Detection & Diagnosis



6. Data-Driven Models

SCADA

- “Healthy” state for data 4 months after replacement (orange)
- “Warning” state for data 4 months prior to replacement (blue)

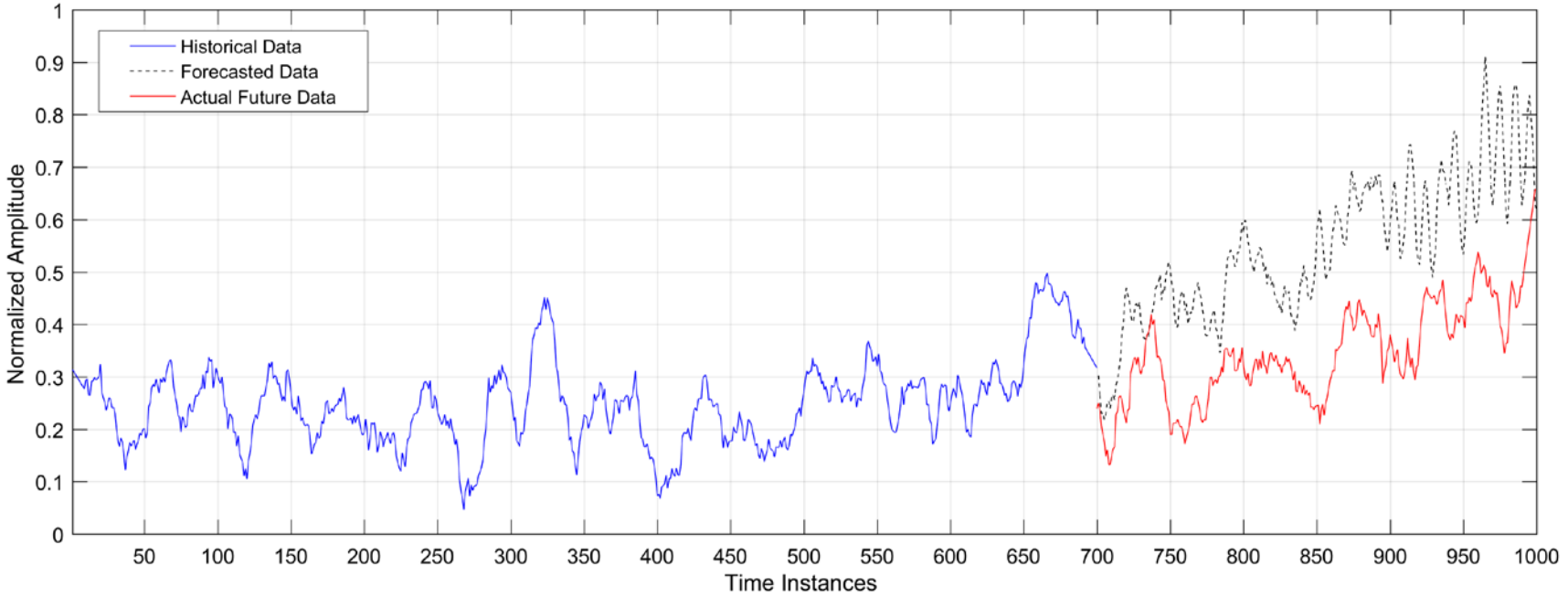


Algorithm	Specifications	True Pos. (Healthy)	True Positive Rate (Warning)
SVM	Gaussian, Scale:0.26	97%	92%
Ensemble	Bagged Trees, Split: 10, learners: 30	96%	91%
KNN	Mahalanobis, NN=10	96%	92%
Decision Tree	Gini's index, max number of splits: 400	95%	86%
SVM	Quadratic, box constraint: 1	93%	81%

6. Data-Driven Models

CMS

- Not constantly monitored systems
- Automation of forecasting models
- Autoregressive model for RMS signal
    - Predicted same slope for 26 out of 27 turbines



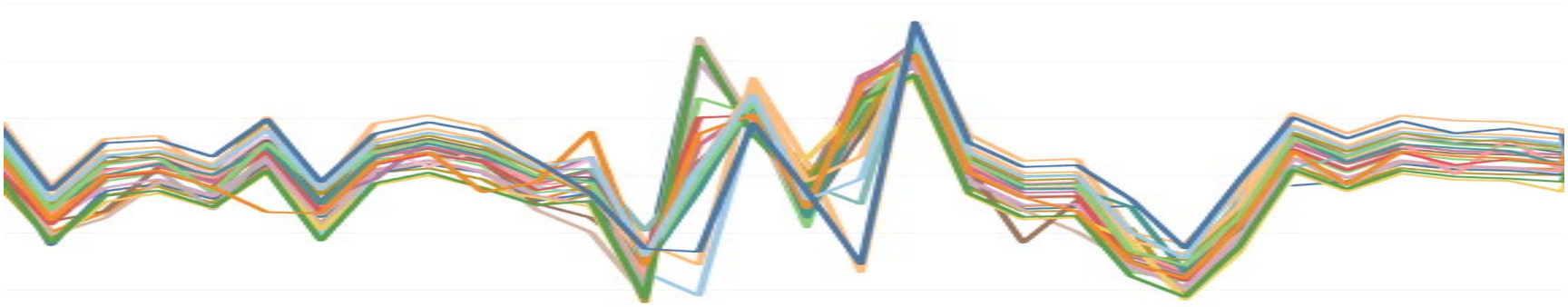
7. Conclusions and Future Work

Conclusions

- Planet stage bearing spalling on a 3-stage 2.3MW turbine gearbox
- Similar studies investigated catastrophic gearbox failures
- Identify and diagnose the failure by using SCADA and CMS data
  - Temperature readings
  - RMS vibration
- Data driven models to predict future failures

Future Work

- Further test the models in other failure modes and wind turbine models
- Investigate the environmental conditions' impact on the results



References

[1] Carroll J, McDonald A and McMillan D 2016 Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines *Wind Energy* **19** 6 1107-19

[2] Koltsidopoulos Papatzimos A, Dawood T and Thies PR 2017 An integrated data management approach for offshore wind turbine failure root cause analysis *Proc. 36th Int. Conf. on Ocean, Offshore and Arctic Engineering* (Trondheim) vol. 3B (New York: ASME)

[3] Qiu Y, Chen L, Feng Y and Xu Y 2017 An Approach of Quantifying Gear Fatigue Life for Wind Turbine Gearboxes Using Supervisory Control and Data Acquisition Data *Energies* **10** 1084

[4] Musial W, Butterfield S, McNiff B 2007 Improving Wind Turbine Gearbox Reliability *European Wind Energy Conference*

[5] Nejad AR, Gao Z, Moan T 2014 Fatigue Reliability-Based Inspection and Maintenance Planning of Gearbox Components in Wind Turbine Drivetrains *Energy Procedia* **53** 248-57

[6] Nejad AR, Gao Z and Moan T 2015 Development of a 5MW reference gearbox for offshore wind turbines *Wind Energy* **19** 6 1089–1106

[7] McVittie D 2006 *Wind turbine gearbox reliability* Online: https://goo.gl/gqLSv8

[8] Smolders K, Long H, Feng Y and Tavner PJ 2010 Reliability Analysis and Prediction of Wind Turbine Gearboxes *Proc. European Wind Energy Conference* (Warsaw: EWEA)

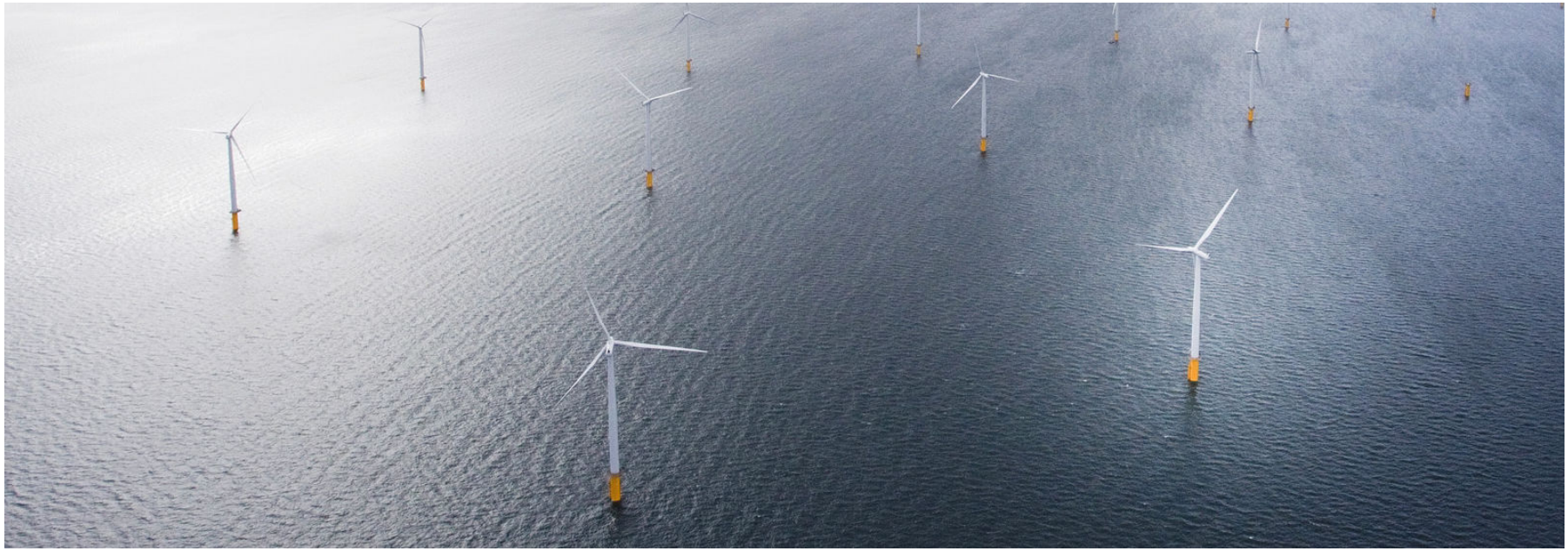
[9] https://www.gearboxfailure.com/wp-content/uploads/2016/07/MicropittingOn_Misaligned_Gear.jpg

[10] http://media.noria.com/sites/archive_images/Backup_200101_Gear3.jpg?__hstc=108323549.07430159d50a3c91e72c280a7921bf0d.1514764800116.1514764800117.1514764800118.1&__hssc=108323549.1.1514764800119&__hsfp=528229161

[11] https://www.novexa.com/en/intervention/gears/defects-treated.html

[12] http://www.rttech.com.au/wp-content/uploads/2010/06/mt6.jpg

Questions



Alexios.Koltsidopoulos@edfenergy.com

Acknowledgement:
This work is funded by the Energy Technology Institute and the Research Council Energy Programme as part of the IDCORE programme (grant EP/J500847).