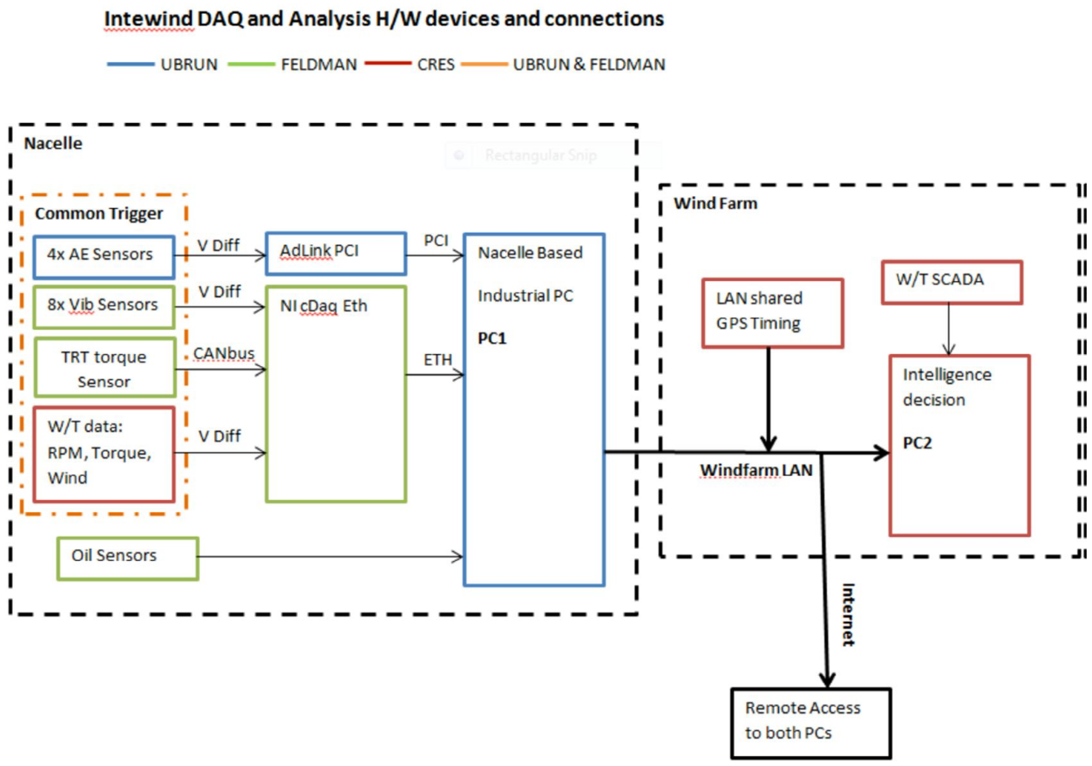


Figure 1 Block diagram of the data acquisition, analysis and communication structure

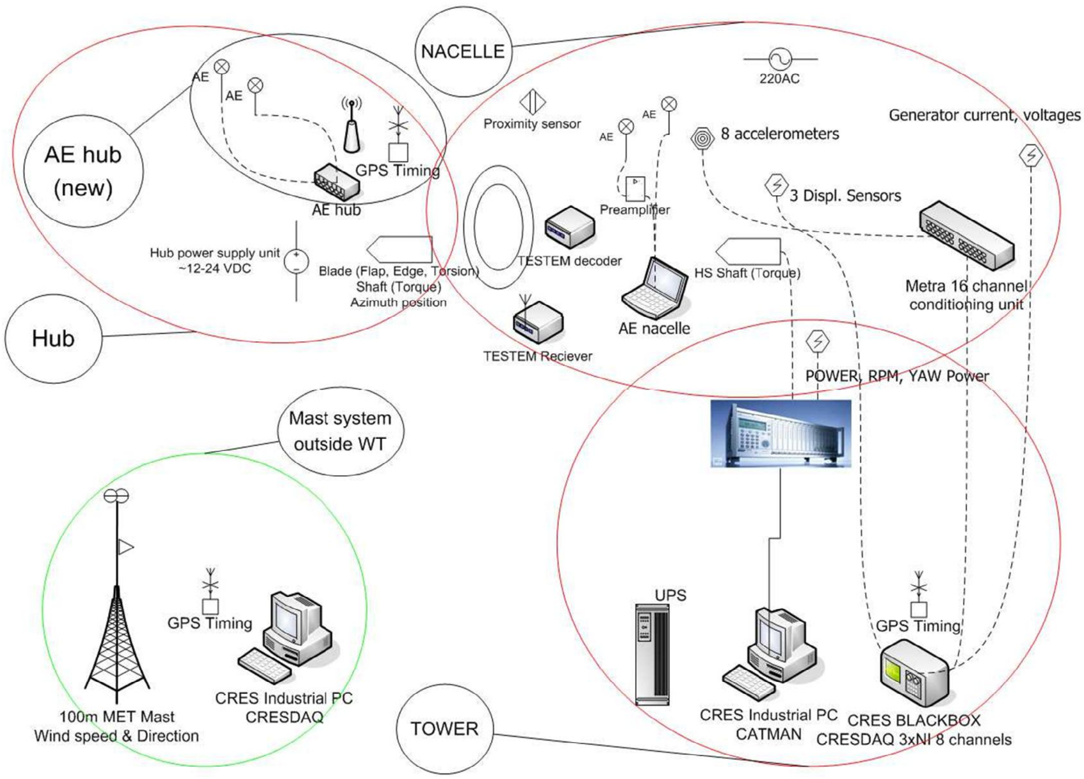


Figure 2 Overview of the information collection path

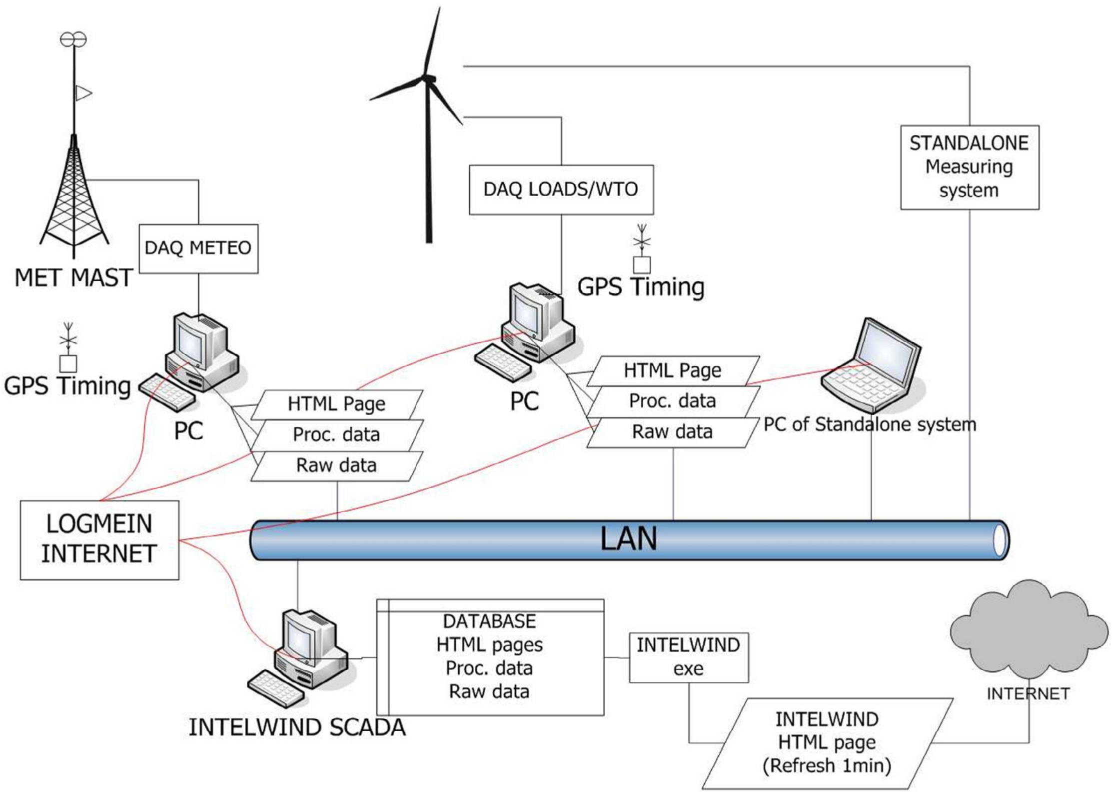
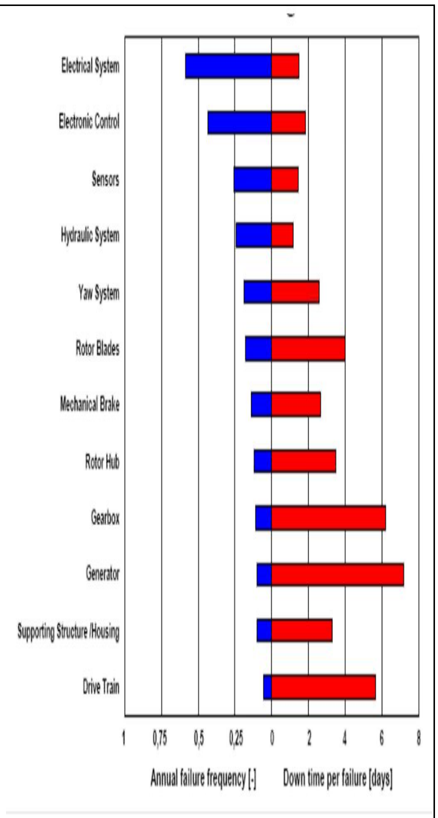


Figure 3 Remote logging and communication path ways

Table 1. **LHS:** Typical nacelle defects and common inspection/condition monitoring techniques employed by the wind energy industry for their detection and evaluation. **A:** Severity in case of occurrence (1=lowest, 5=highest), **B:** Interest in improving detection by the wind energy industry (1=lowest, 5=highest) **RHS:** Failure modes and typical downtime.

NACELLE DEFECTS, FAULTS, FAILURES	CURRENT INSPECTION	A	B
1. Main Bearings	Every 12 months, vibration analysis.	5	5
2. Gearbox			
Housing cracks	Every 6 monhs, standard preventive inspections.	5	3
Bearings	Every 6 months, standard preventive inspections (sound and/or debris). Videoscope inspections. Not scheduled. Every 12 months, vibration analysis.	4	5
Gears (Pitting, spalling, scuffing, cracks, corrosion...)	Every 6 months, standard preventive inspections (visual and/or debris). Videoscope inspections. Not scheduled. Every 12 months, vibration analysis.	5	5
Lubricant	Every 6 months, oil analysis	4	5
3. Coupling			
Misalignment	Every 12 months, vibration analysis. Alignment every 24 months.	3	5
4. Generator			
Bearings	Every 6 months, standard preventive inspection (sound) and global vibration measurement. Every 12 months, vibration analysis.	4	5
Unbalance	Every 12 months, vibration analysis	3	3
Other damages	Every 12 months, vibration analysis	3	5
5. Yaw System			
Yaw drive	Every 6 months, standard preventive inspections	2	4
Yaw gear	Every 6 months, standard preventive inspections	5	3
Yaw bearings		5	3
6. Blades bearings		5	5
7. Hydraulic Unit	Every 6 months, standard preventive inspections and oil analysis. Pressure sensors.	4	5



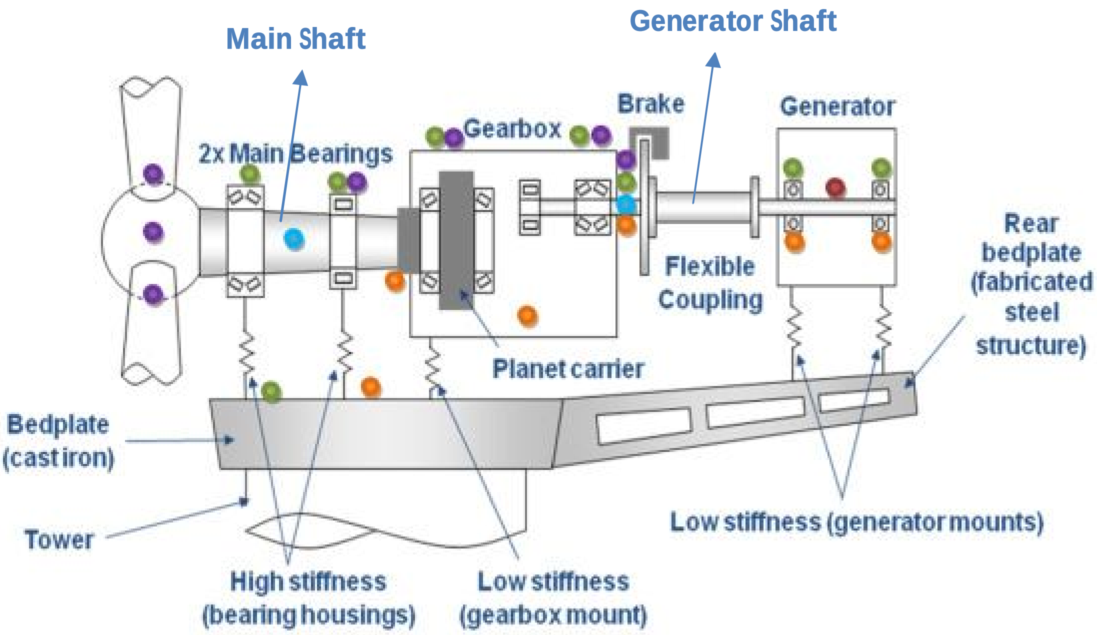


Figure 4 Location and Type of sensors in Nacelle, AE sensors are indicated in purple, vibration in green and temperature in orange

Figure 5 AE sensors (KH and Vallen) on main bearing (LHS), AE on high speed gearbox bearing (Middle) and AE on low speed gearbox bearing (Right)

Figure 6

Figure 7

Figure 6 Accelerometer acquiring from nacelle main bearing

Figure 7 Accelerometer acquiring from nacelle high speed outlet gear box bearing

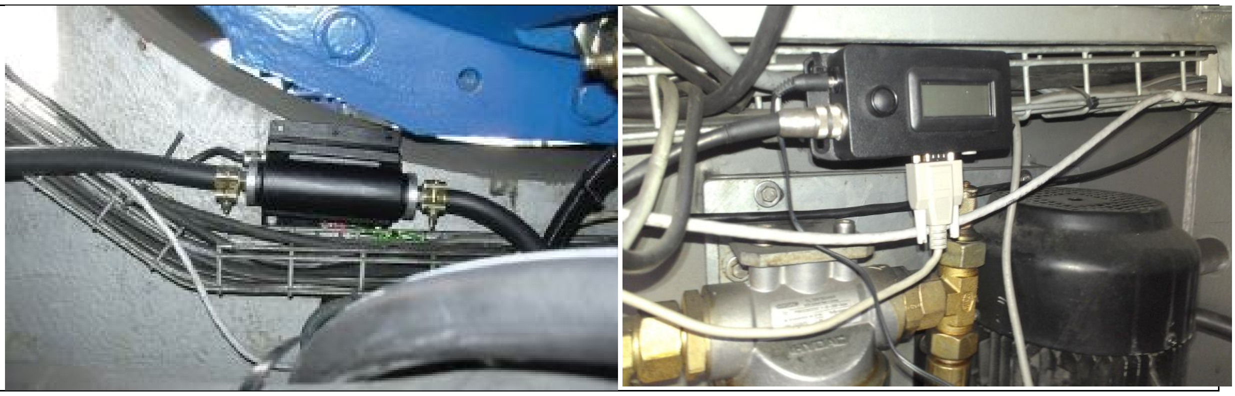


Figure 8 Oil sensor (left) and digital counter (right) installed on the NEG-MICON 750kW wind turbine at CRES's wind farm in Lavreotiki, Greece, the operational temperature range of the wear debris sensor is from -20°C to +65°C. The maximum permissible pressure of the oil is 10 bar

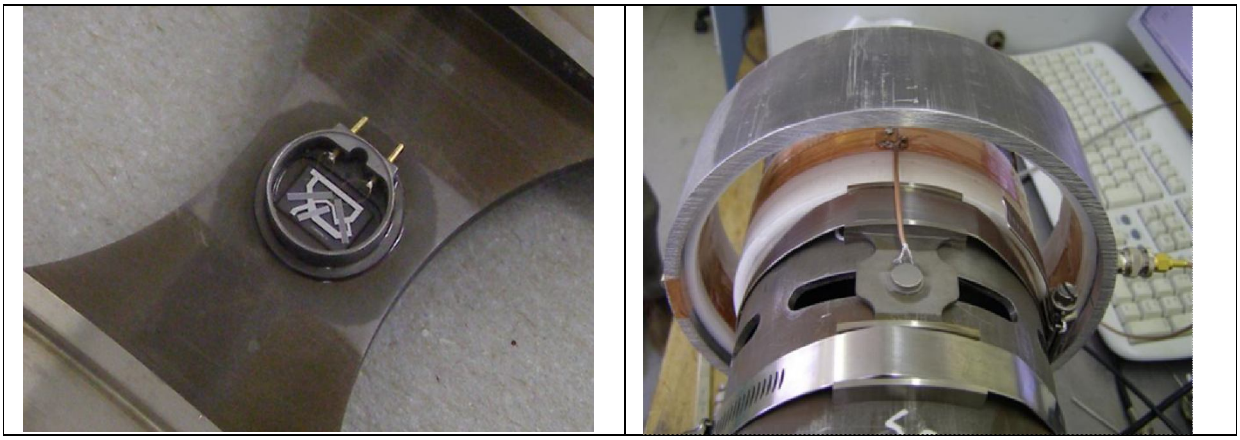


Figure 9 SAW torque sensor with an open lid (LHS), Large diameter RF Rotary Coupler and SAW torque transducer installed on the test shaft (RHS)

Table 2 Advantages and Disadvantages of sensors used in IntelWind with monitoring component

INTELWIND Sensor type	Monitored Component	Advantages	Disadvantages
Acoustic Emission (AE)	**Gearbox** Bearing at high speed and low speed ends **Main Bearing**	Able to detect faults at an early-stage fault Good for low-speed operation High signal-to-noise ratio Quick signal attenuation allows to pin-point defect location Frequency range far from load perturbation	Expensive High Sampling Rate required
Vibration	Gearbox Bearing Generator Bearings	Reliable	Limited performance for low speed rotation
Torque	Shaft	Direct measurement for rotor load Novel attachment developed	Expensive in the case of low volumes Requires a torque wrench for installation
Oil (Particle Analysis)	Gearbox	Direct characterisation of bearing/gearbox condition	Expensive for inline operation Limited to closed loop operation (offline not considered for IntelWind)
Moisture and Temperature	Gearbox	Reliable and sensitive	Limited scope for planned maintenance without the others (AE, Vibration, Oil etc)

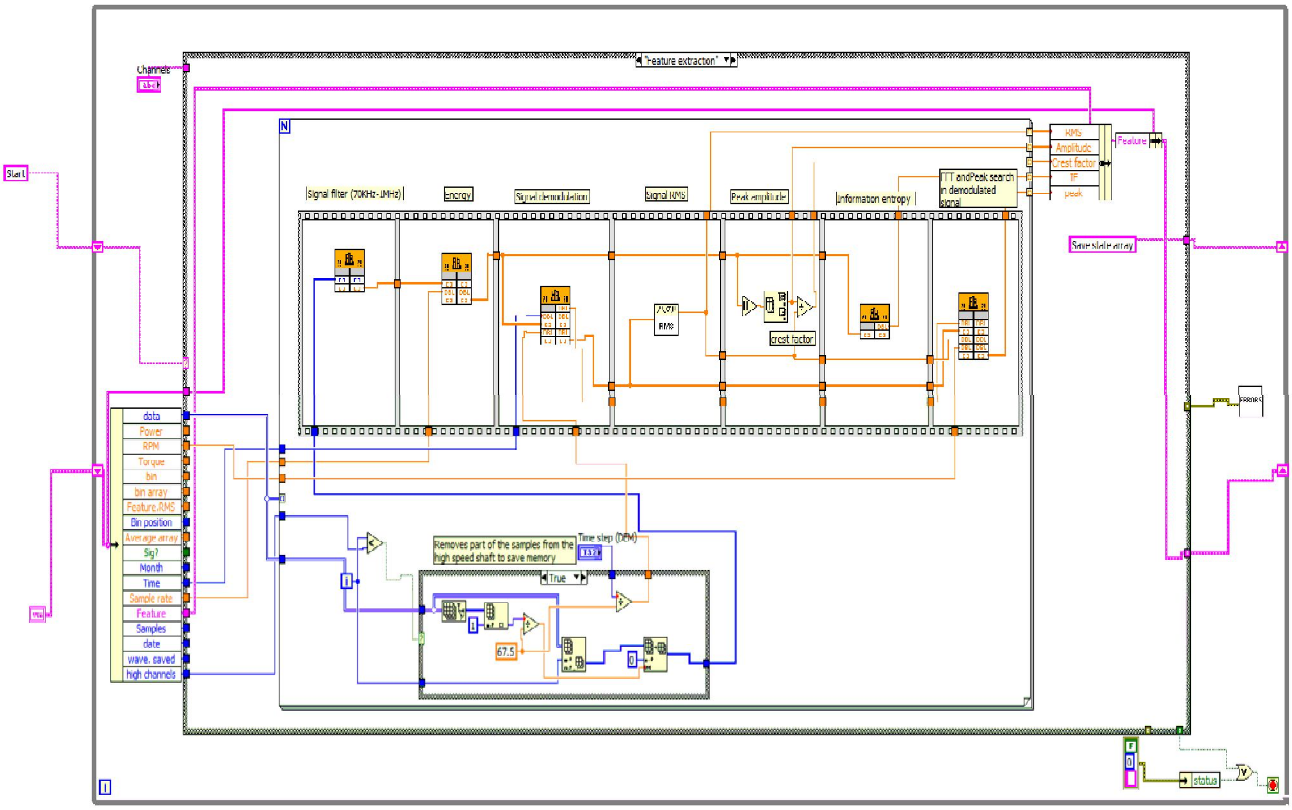


Figure 10 Snapshot of the AE software developed using LabView

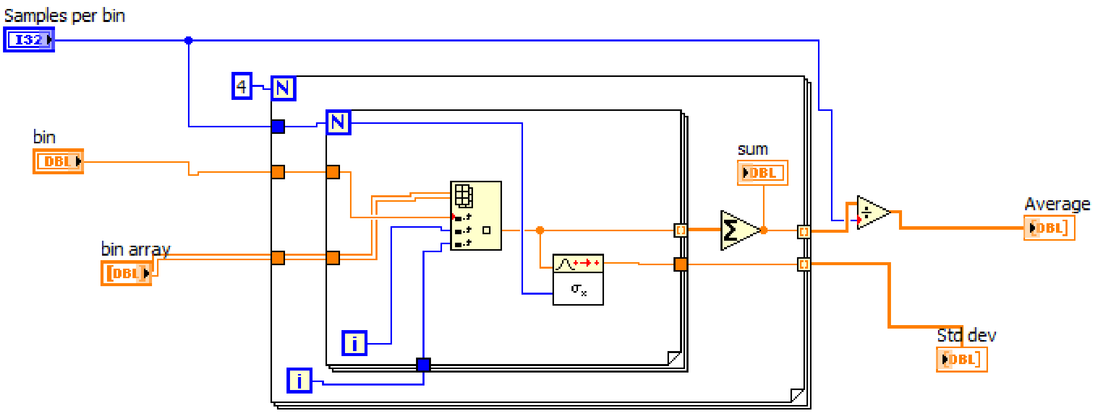


Figure 11 Code in LabView for average and standard deviation calculation

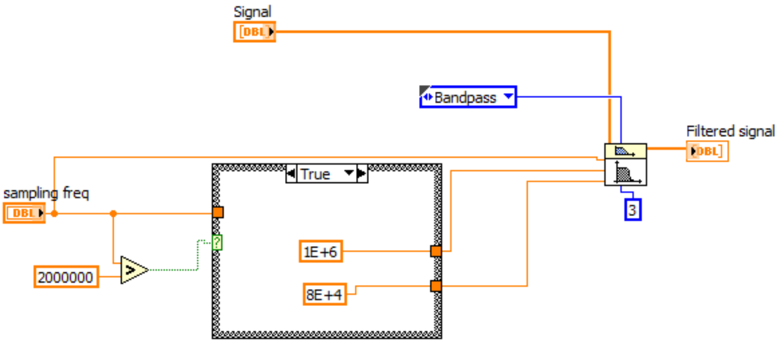


Figure 12 Code for signal filtering

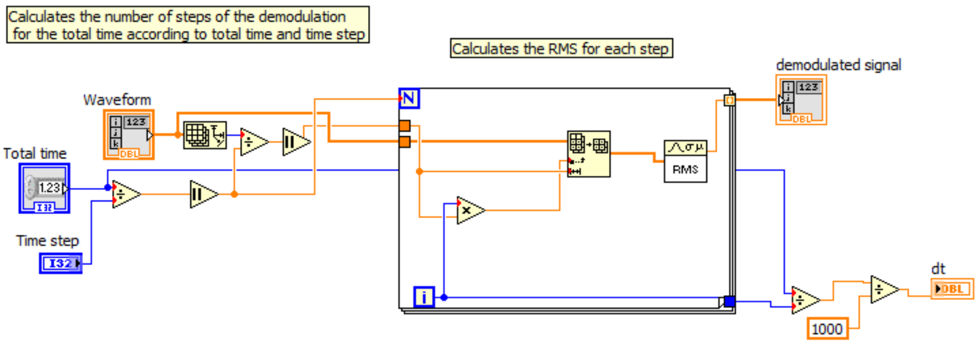


Figure 13 Snapshot of the demodulation process

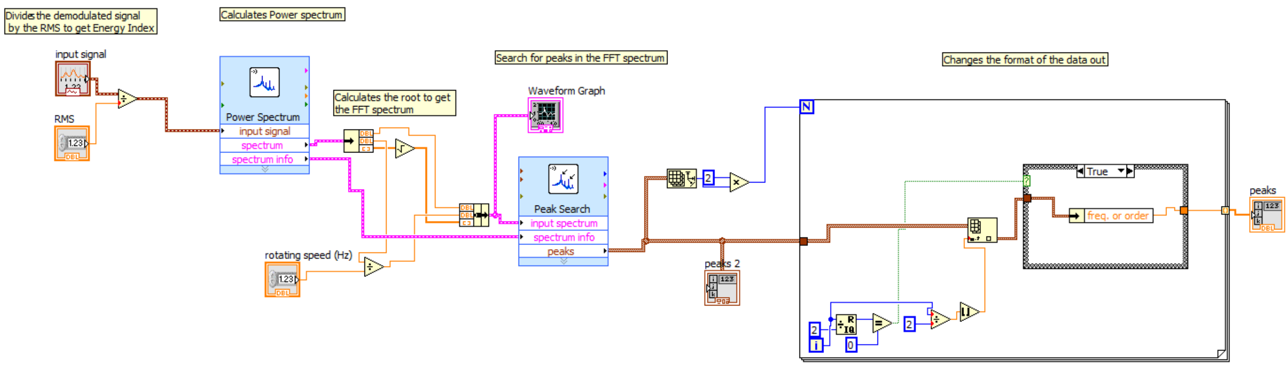


Figure 14 Snapshot of the peak search process

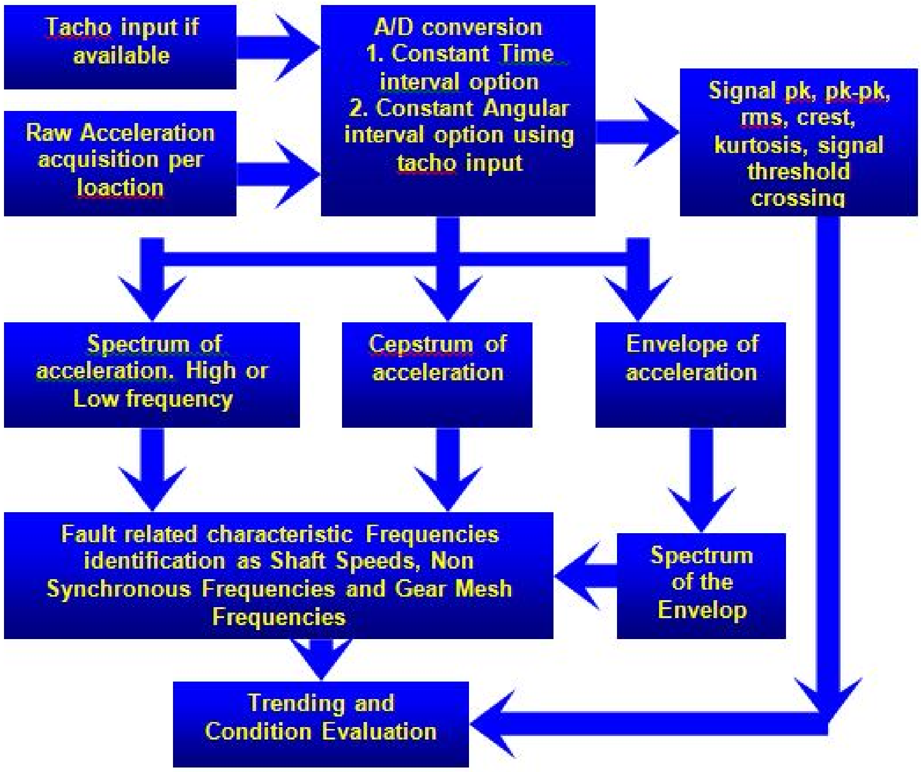


Figure 15 IntelWind Vibration Signal Processing block diagram

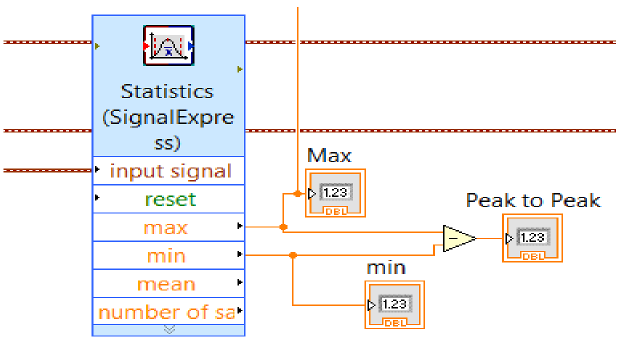


Figure 16 Coding for Peak and Peak-Peak Amplitude

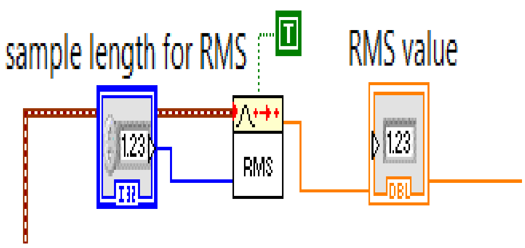


Figure 17 Coding for RMS calculation

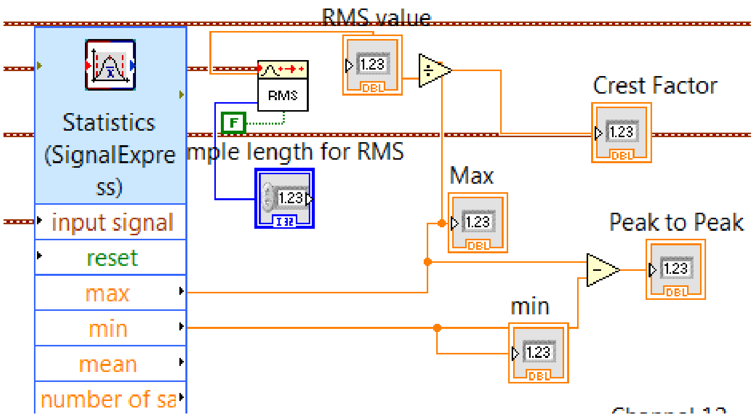


Figure 18 Coding for Crest Factor calculation

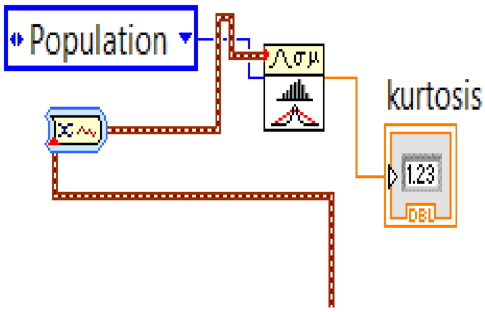


Figure 19 Coding for Kurtosis

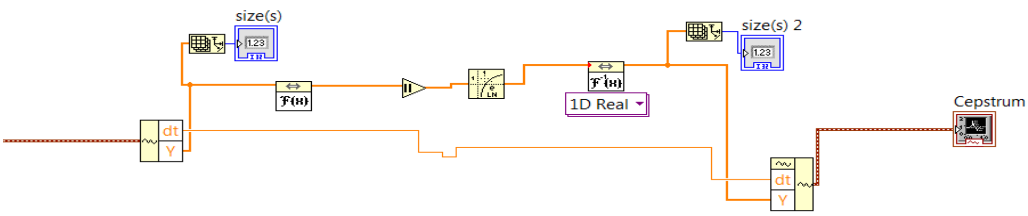


Figure 20 Coding for Power Cepstrum

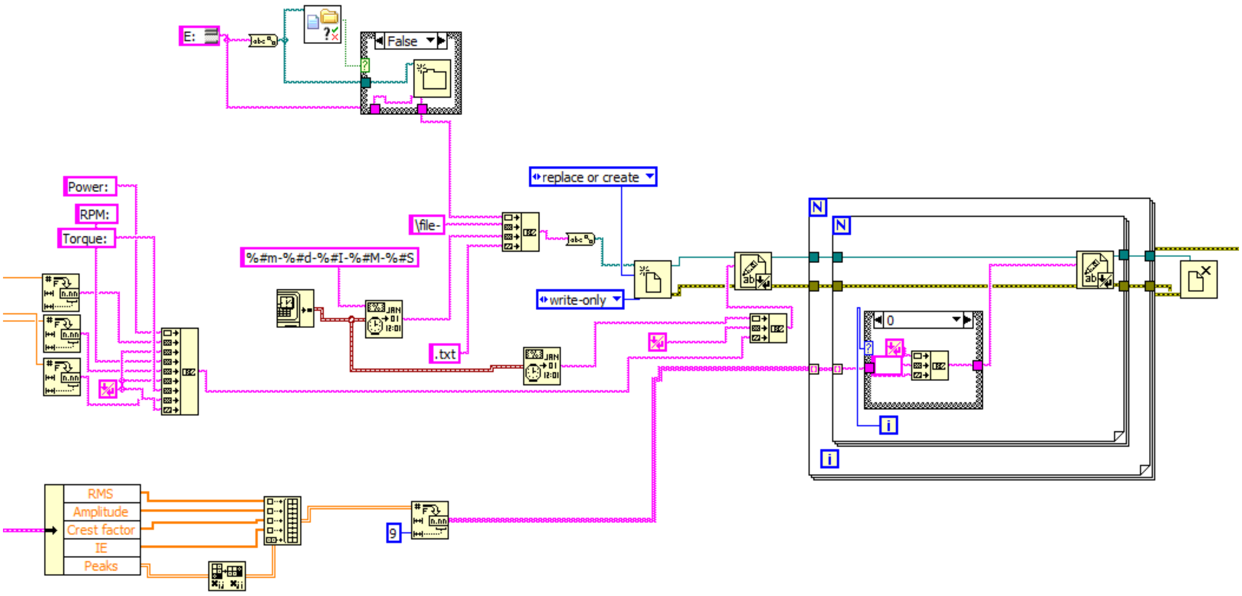
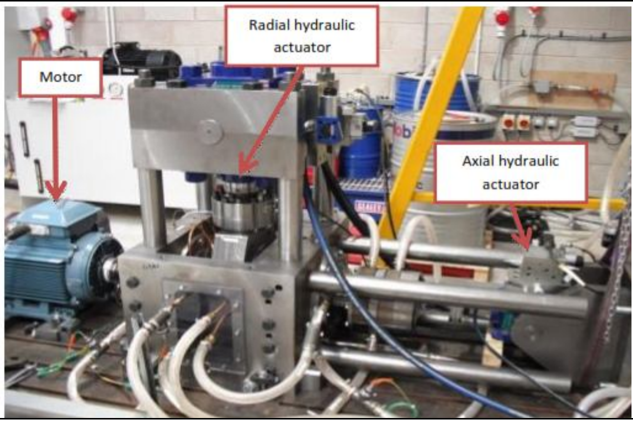


Figure 21 Code in LabView for the HTML File creation



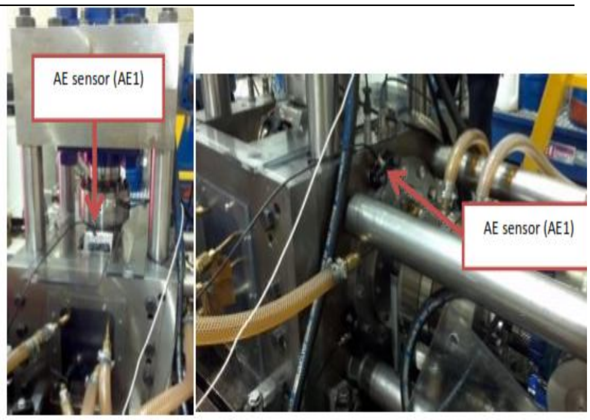


Figure 22 Test rig used for the laboratory trials (LHS) Figure 23 AE (2of4) mounting positions are shown (RHS)

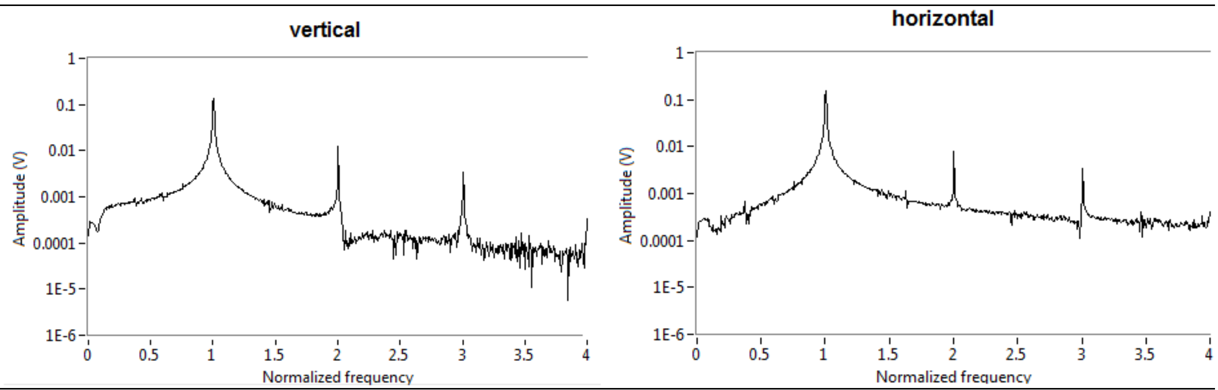
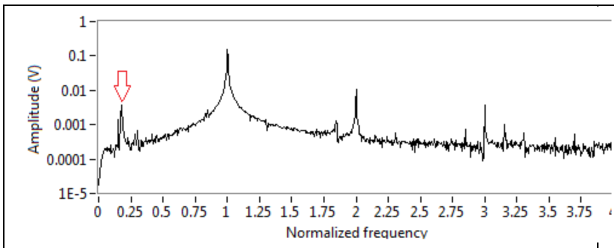


Figure 24 FFT spectrum of the proximity signal in the horizontal and vertical directions, peak 1X is dominant but 2X and 3X are clearly evident too



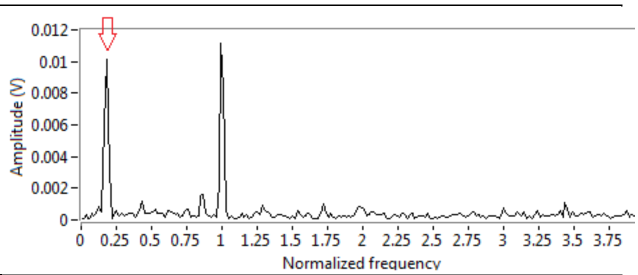


Figure 25 FFT spectrum of vertical proximity sensor (LHS) Figure 26 FFT of Enveloped AE signal (Condition 6)

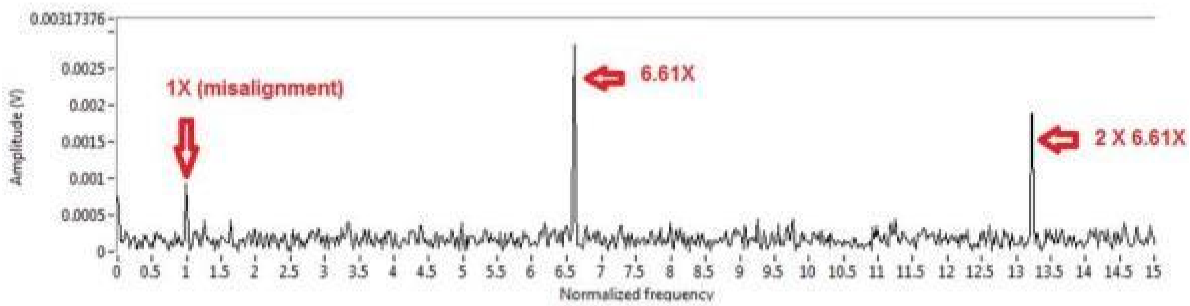


Figure 27 FFT of the Enveloped AE signal

Figure 28 Two halves of the RF rotor coupler (left) and its installation on the test shaft (right)

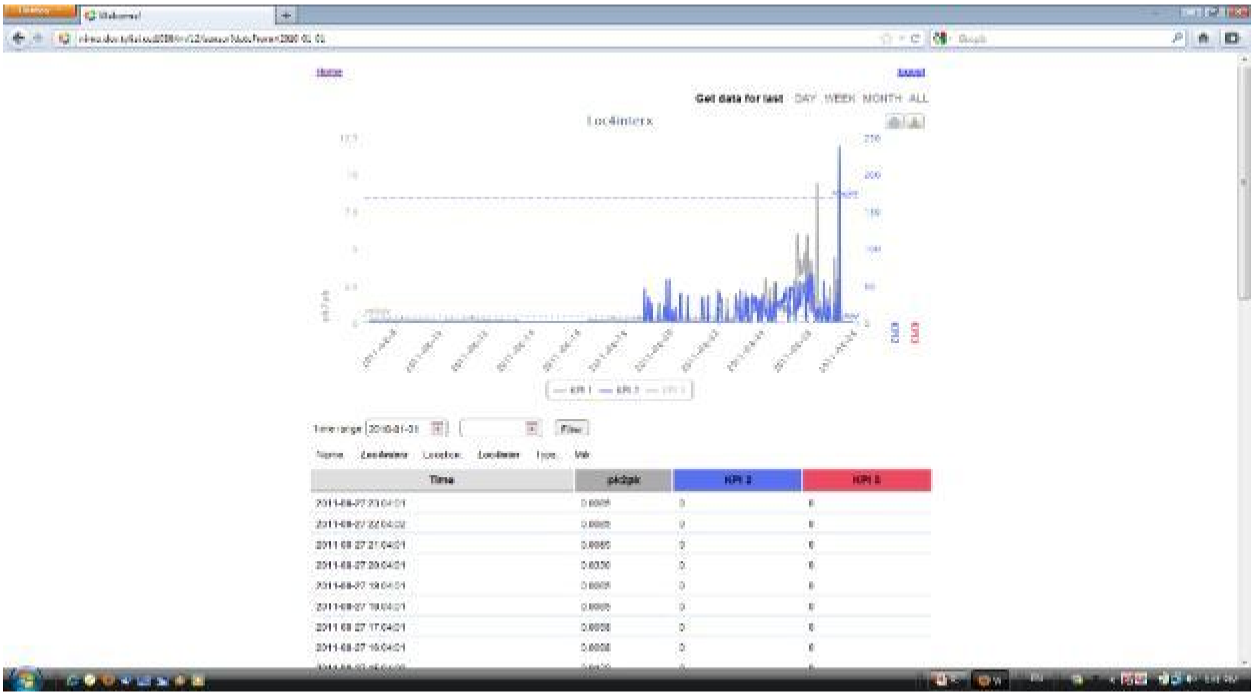


Figure 29 Trending (Combined KPI's)

Date	Time	AgilentSN	Slot	Channel	Location	Type	Duration	SR	F1	F2	LowBand	HighBand	Points	Normalise	T1	T2	KPI1	KPI2	KPI3	KPI4
11-Apr-12	15:00:05	TW50063501	1	0	ae1mb	AE	12	500000	0.2	2000	0.2	2000	62	yes	0.5	6	0.34791	337.352	5.4006	0.01035
11-Apr-12	15:00:54	TW50063501	1	1	ae2planet	AE	12	500000	0.2	2000	0.2	2000	62	yes	0.5	6	0.32349	355.1942	5.9566	0.012565
11-Apr-12	15:01:34	TW50063501	1	2	ae3outlet	AE	12	500000	4	2000	4	2000	62	yes	0.001	0.2	0.5066	9.7765	7.5192	3.219
11-Apr-12	15:02:14	TW50063501	1	3	ae4intermid	AE	12	500000	2	2000	2	2000	62	yes	0.02	0.2	0.57374	21.8807	8.8296	0.2731
11-Apr-12	15:02:54	TW50063512	2	0	ae5gen	AE	12	500000	4	2000	4	2000	62	yes	0.001	0.2	0.49073	10.6091	5.3512	3.0795
11-Apr-12	15:03:33	TW50063512	2	1	v1mb	Vib	24	25000	0.2	2000	0.2	2000	62	yes	0.5	6	0.15869	3374.5529	2.7096	0.11767
11-Apr-12	15:04:02	TW50063512	2	2	v2planet	Vib	24	25000	0.2	2000	0.2	2000	62	yes	0.5	6	0.1062	2124.355	10.1965	0.083353
11-Apr-12	15:04:31	TW50063512	2	3	v9zplanet	Vib	24	25000	0.2	2000	0.2	2000	62	yes	0.5	6	0.25025	116.6158	44.6224	0.32792
11-Apr-12	15:05:00	TW50063502	3	0	v7low	Vib	24	25000	0.2	2000	0.2	2000	62	yes	0.5	6	0.12451	4130.5925	4.2903	0.092263
11-Apr-12	15:05:29	TW50063502	3	1	v4intermid	Vib	24	25000	2	2000	2	2000	62	yes	0.02	0.2	0.06714	3274.2443	4.4892	0.96536
11-Apr-12	15:05:58	TW50063502	3	2	v8high	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.06836	4144.9511	2.1105	7.8839
11-Apr-12	15:06:26	TW50063502	3	3	v10zoutlet	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.36378	4537.5195	3.131	17.0016
11-Apr-12	15:06:55	TW51043507	4	0	v3outlet	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.053712	3004.3139	6.2081	12.5195
11-Apr-12	15:07:24	TW51043507	4	1	v5gencoupl	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.091554	5139.1073	1.9891	9.1762
11-Apr-12	15:07:54	TW51043507	4	2	v6genother	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.1709	3234.3319	3.6118	10.0023
11-Apr-12	15:08:23	TW51043507	4	3	none	Vib	24	25000	1	2000	1	2000	62	yes	0.2	1	0.0085451	324.5593	3.7074	0.12547
11-Apr-12	18:00:04	TW50063501	1	0	ae1mb	AE	12	500000	0.2	2000	0.2	2000	62	yes	0.5	6	3.9063	16.8576	56.6019	0.010262
11-Apr-12	18:00:48	TW50063501	1	1	ae2planet	AE	12	500000	0.2	2000	0.2	2000	62	yes	0.5	6	19.9991	159.7827	3.5861	0.012715
11-Apr-12	18:01:29	TW50063501	1	2	ae3outlet	AE	12	500000	4	2000	4	2000	62	yes	0.001	0.2	19.9991	89.408	5.5722	3.731
11-Apr-12	18:02:09	TW50063501	1	3	ae4intermid	AE	12	500000	2	2000	2	2000	62	yes	0.02	0.2	19.9991	162.8944	2.9072	0.36685
11-Apr-12	18:02:51	TW50063512	2	0	ae5gen	AE	12	500000	4	2000	4	2000	62	yes	0.001	0.2	1.0791	36.037	12.1399	2.8217
11-Apr-12	18:03:29	TW50063512	2	1	v1mb	Vib	24	25000	0.2	2000	0.2	2000	62	yes	0.5	6	0.5359	3093.4896	8.6443	0.20852
11-Apr-12	18:03:58	TW50063512	2	2	v2planet	Vib	24	25000	0.2	2000	0.2	2000	62	yes	0.5	6	0.19898	558.3727	7.3879	0.067893
11-Apr-12	18:04:27	TW50063512	2	3	v9zplanet	Vib	24	25000	0.2	2000	0.2	2000	62	yes	0.5	6	0.78737	638.7472	14.0355	0.063837
11-Apr-12	18:04:56	TW50063502	3	0	v7low	Vib	24	25000	0.2	2000	0.2	2000	62	yes	0.5	6	0.38819	625.0503	7.6125	0.080639
11-Apr-12	18:05:25	TW50063502	3	1	v4intermid	Vib	24	25000	2	2000	2	2000	62	yes	0.02	0.2	0.60426	759.2099	10.7382	1.4287
11-Apr-12	18:05:54	TW50063502	3	2	v8high	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	1.0193	564.3226	11.0709	13.7262
11-Apr-12	18:06:23	TW50063502	3	3	v10zoutlet	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.56153	3665.563	3.1501	26.2075
11-Apr-12	18:06:52	TW51043507	4	0	v3outlet	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.26123	488.477	8.2027	14.8548
11-Apr-12	18:07:21	TW51043507	4	1	v5gencoupl	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.29664	1187.1567	3.7833	84.125
11-Apr-12	18:07:50	TW51043507	4	2	v6genother	Vib	24	25000	4	2000	4	2000	62	yes	0.001	0.2	0.21241	1569.8731	3.5102	16.0801
11-Apr-12	18:08:19	TW51043507	4	3	none	Vib	24	25000	1	2000	1	2000	62	yes	0.2	1	0.0085451	425.7987	3.9206	0.14554
11-Apr-12	21:00:04	TW50063501	1	0	ae1mb	AE	12	500000	0.2	2000	0.2	2000	62	yes	0.5	6	0.43458	295.4428	6.6525	0.011207
11-Apr-12	21:00:48	TW50063501	1	1	ae2planet	AE	12	500000	0.2	2000	0.2	2000	62	yes	0.5	6	19.9991	242.3461	1.571	0.011175
11-Apr-12	21:01:41	TW50063501	1	2	ae3outlet	AE	12	500000	4	2000	4	2000	62	yes	0.001	0.2	19.9991	117.2441	3.6318	4.7972
11-Apr-12	21:02:21	TW50063501	1	3	ae4intermid	AE	12	500000	2	2000	2	2000	62	yes	0.02	0.2	19.9991	97.8185	1.8438	0.20244
11-Apr-12	21:03:05	TW50063512	2	0	ae5gen	AE	12	500000	4	2000	4	2000	62	yes	0.001	0.2	0.80201	63.2443	5.4693	2.6865

Figure 30 An example of Combined AE and Vibration KPI's evaluated from specific sensor location and with a time stamp

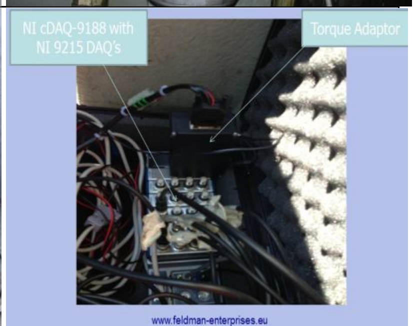












Left to Right, Top Row and Bottom Row
Figure 31 Inductive proximity sensor for measurement of generator speed
Figure 32 Sensors to measure nacelle's yaw position
Figure 33 Vibration Accelerometers place on the high speed bearing of gear box (measuring vertical)
Figure 34 Vallen and KH AE sensors on main bearing
Figure 35 Vallen AE on high speed gearbox bearing
Figure 36 Vallen AE on low speed gearbox
Figure 37 Vibration accelerometers mounted on main bearing, gearbox inlet, planet casing and low speed internal axel
Figure 38 Oil sensor
Figure 39 Oil Sensor and moisture condition monitoring unit
Figure 40 Saw (Torque) sensor on the high speed shaft
Figure 41 Sensor conditioning and data acquisition equipment for AE
Figure 42 Data Acqusition system for vibration and torque

Table 3 *Dissemination of new developments (Foreground) during project phase*

WindForce 2013, Bremerhaven, Germany, 4-6 June 2013. **"From Laboratory to field measurements for wind turbine condition monitoring".** Participants: CRES.
2013 06 : CM2013 / MFPT2013 CONFERENCE Poland **Shaft Angular Misalignment Detection using Acoustic Emmission** (http://www.bindt.org/Events/CM_Conferences_&_Seminars/CM_2013_and_MFPT_2013) Juan Luis Ferrando Chacon, Estefania Artigao Andicoberry, Vassilios Kappatos, Georgios Asfis, Tat-Hean Gan and Wamadeva Balachandran Brunel Innovation Centre, Granta Park, Great Abington, Cambridge CB21 6AL Contact: Juan.ferrandochacon@brunel.ac.uk (+44 (0) 1223 899186)
2013 06 CM-MFPT-0076-2013 Krakow,Bindt S. Kerkyras, V. Karakassidis and M. Papaelias, **Condition monitoring of wind turbine gearboxes using acoustic emission**
2013 07 : IEEE Int. Frequency Control Symposium, Prague **Resonant SAW Torque Sensor for Wind Turbines** V. Kalinin, A. Leigh, A. Stopps (Transense Technologies plc, Bicester, Oxfordshire, UK) Estefania Artigao (Brunel Innovation Centre, Brunel University, UK)
Shaft Angular Misalignment Detection Using Acoustic Emission Technique – Submitted to Applied Acoustics Journal, Oct 2013, Awaiting feedback from Journal.
An approach based on wavelet packet and autocorrelation function for incipient defect detection in rolling bearings using acoustic emission - not yet submitted

Table 4 Post Review Actions to make IntelWind modules/software and CM System ready for marketing

Stage	Description	Lead partner	Duration
1	Secure additional funding for the system optimisation	Innotecuk	Q1-Q2 2014
2	System design optimisation and integration with existing CMS	CoServices	Q2-Q3 2014
3	Field installation for the demonstration phase	Romax/Transence/BIC/Cres/EDPR	Q3-Q4 2014

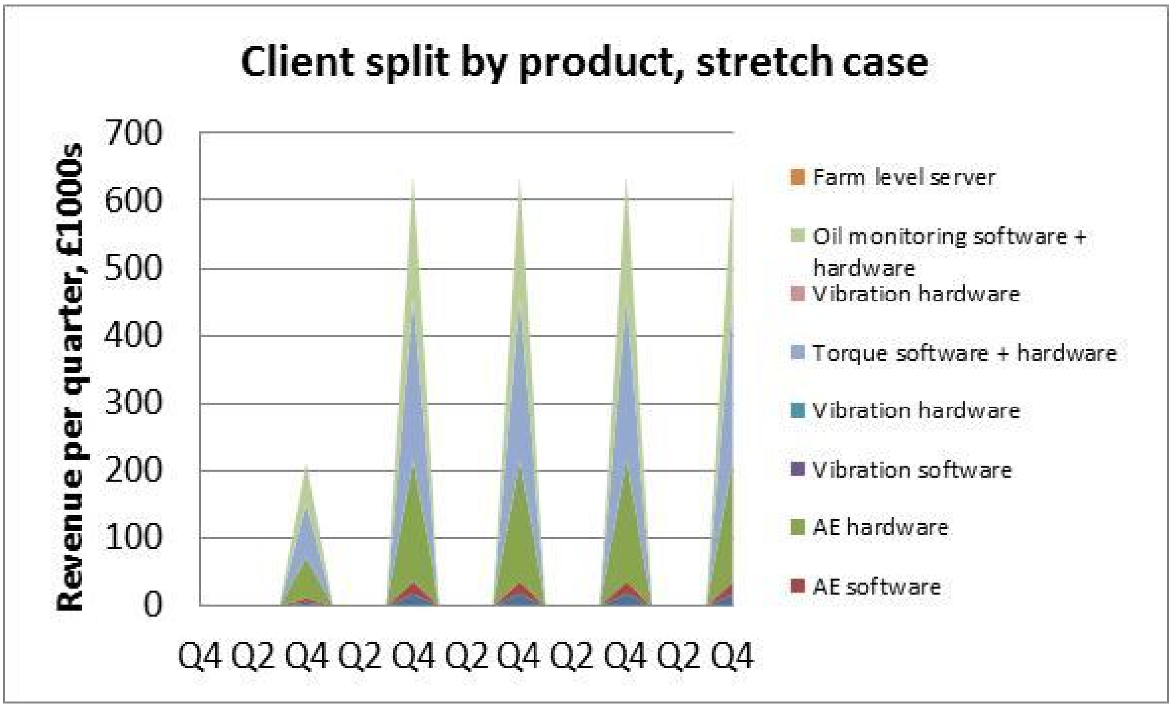


Figure 43 revenue cycle for a European onshore operator/utility

Cost Justification of Wind Turbine CM

- Experience at Schenck [3]

Operator / Owner	# of Turbines Duration of Service	Costs CMS plus Service in €	Detected Damages	Costs unplanned Replacement Costs planned Repair in €	Total Savings in €
enviaM	15 WTG's 5 years	150,000	3 x Gearbox	405,000 101,250	303,750 In 5 years
e.disnatur	130 WTG's 5 years	1,300,000	12 x Gearbox 40 x Generator bearing	4,620,000 1,155,000	3,465,000 In 5 years
juwi Management	59 WTG's 3 years	472,000	20 x Gearbox 1 x Generator bearing 1 x Main bearing	2,811,000 702,750	2,108,250 In 3 years

- Based on 1.5 MW wind turbine with replacement costs of about €150,000 for gearbox, €38,000 for a generator and €25,000 for a main bearing (DEWI)
- Costs for planned repair < 30% for unplanned replacement (DEWI)
- Cost per CM system approximately €5,000 plus €1,000 per year per wind turbine (service)
- Above cost savings do not include loss of production

Return on Investment for all three cases less than 3 years

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Table 5 Illustration of Cost Justification for CM System (Ref: Kewitsch, R. "Optimizing Life Cycle Costs (LCC) for Wind Turbines by Implementing Remote Condition Monitoring Service," presented at the AWEA Project Performance and Reliability Workshop, January 12– 13, 2011, San Diego, CA)