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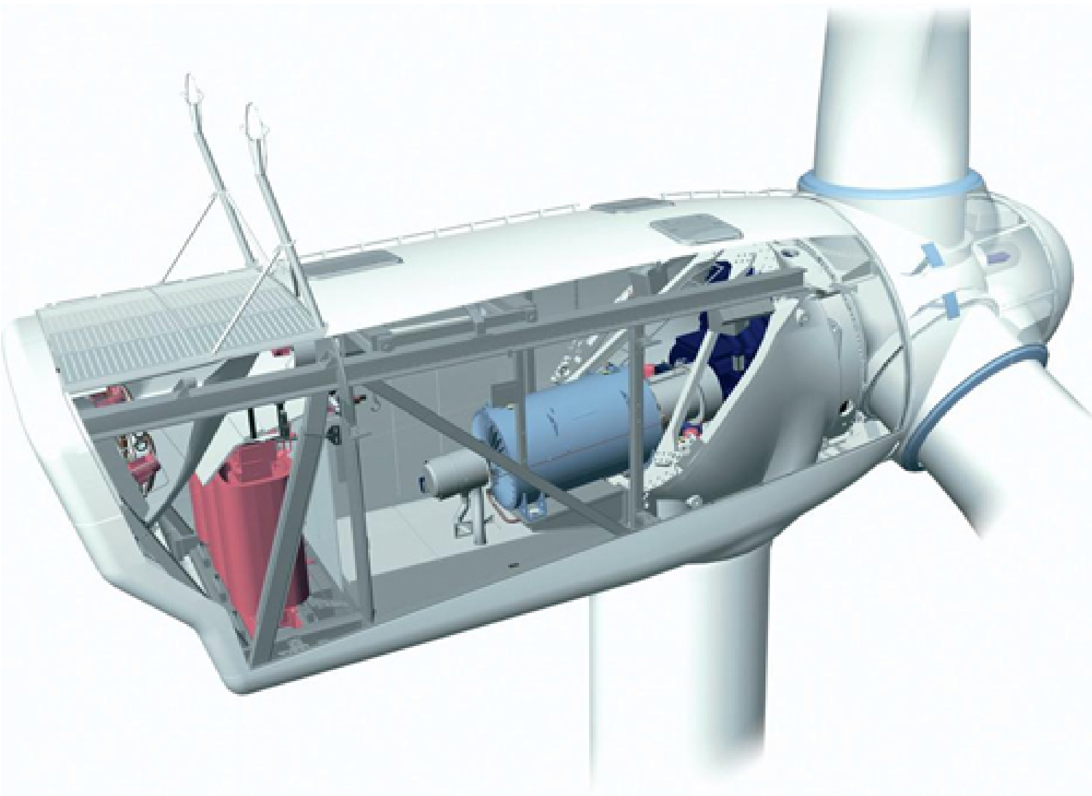
SESG - 6035 Advanced Sensors and Condition Monitoring

An offshore wind turbine condition monitoring system for the Vestas v90 3MW



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1. Introduction

The Vestas V90 is a pitch regulated wind turbine. It has a rotor diameter of 90 m and a 3 MW generator. This turbine can be used in offshore wind farms; a good example is the Belwind wind farm which is in the North Sea 49 km off the shore of Belgium. Belwind contains 55 Vestas V90 models and it has an overall capacity of 165 MW.

When it comes to condition monitoring, the elements which are most frequently subjected to failures and which can cause a total shutdown of the whole system should be prioritized for the monitoring of the system. In addition, the down-time time due to failure is another important factor to take into consideration.

To outline an appropriate condition monitoring system for Vestas V90, the likelihood and frequency of failure of different sub-systems will be considered as well as the cost of failure. The cost of maintenance and condition monitoring should be proportional with the impact of failure of a given subsystem.

In this report, a condition based maintenance strategy will be described for selected subsystems. The subsystems which will be considered for monitoring are the blades, gearbox, generator (with electrical system), tower and structure. Each subsystem will be discussed in detail to explain the most effective condition monitoring technique to be applied. Second, the data acquisition method will be described and finally a cost report will be presented.

2. Sub – Systems Breakdown

2.1 Blades

Blades are a large and expensive component of a wind turbine, which facilitate the conversion of kinetic energy into mechanical energy. Usually there are three blade of aerofoil shape which are bonded to the supporting beam [1]. For the V90-3.0 MV, the blades are 44m long and made of fibreglass reinforced epoxy and carbon fibres [2]. From a survey of 1500 wind turbines over 15 years, it was deduced that the failure of blades occupied 7% failures and the average failure rate is counted as 0.24 per turbine per year [4]. Regardless this low percentage, it is critical to apply appropriate condition monitoring techniques due to the high cost of the blades which accounts 15% - 20% of the total manufacturing cost, [3] but also due to the down-time of the system which is on average 11 days [4].

<u>Failures of blades</u>

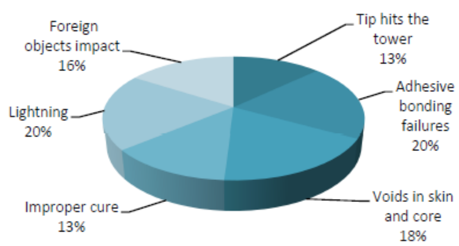

Figure 1: Distribution of rotor-blade failure modes [8]

During normal operation, the rotating speed of the blade is a function of the changing speed of wind. When gusts hit the wind turbine, the blades suffer from short and frequent loads, which will be transferred to the other components attached to the drive chain, and decrease the operating life of the whole wind turbine. Common failures that have been observed upon the blades are fracture, dislocation, bending as well as the fatigue failure, caused by the alternating wind load. In addition, the turbine blades are prone to erosion, freeze, damage from foreign objects and lighting [5]. Figure 1 portrays the likelihood of each different mode of failure.

<u>Monitoring methods</u>

Condition monitoring enables the monitoring and evaluation of the status of the blades with several different techniques as displayed in Table 1. Once the data is obtained from the transducers by applying analytical techniques, the problem and maintenance that needs to be scheduled can be determined.

Failure	Parameters	Transducers	Techniques	Power-Type
Corrosion Fatigue	Load, bending moment	Fibre-optical strain gauges	Fibre optics method	Self-power
Cracking, Deformation, Deboning, Delamination, Impacts, Crushing	Stress release wave	Piezoelectric sensors	Acoustic emission methods (AE)	External power
Erosion, Freeze	Vibration	Accelerometers	Vibration analysis methods	External Power
Material irregularity or damage	Temperature	Infrared sensors or cameras	Thermal imaging method	External power
Delamination and cracks, in adhesive, impact damage	Ultrasonic wave	The transducer pair for AWI	Ultrasonic methods	External power

Table 1: Technology and parameters used for blade condition monitoring

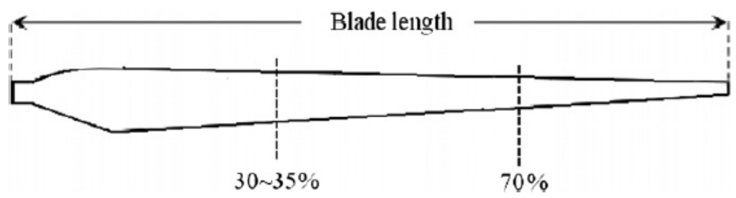

Figure 2: The span wise location of a blade that is likely to damage [3]

Reliable data regarding the impending failure or damage of certain components can only be acquired by optimally placing the sensors in the most appropriate locations [3]. The sensors should be placed in structure damage "hot spots" to reduce the number of sensors required and ultimately decrease the overall cost of the condition monitoring system. The locations where damage is most likely to occur are: (1) 30–35% and 70% in chord length from the blade root. (2) The root of the blade [3].

<u>Working strategies</u>

For the system, the fibre-optic strain method will be used to monitor and evaluate the condition of the blades. In total, 18 Fibre-optical strain gauges' sensors are utilized. For each blade 6 sensors will be places in the three "hot-spot" locations. For every hot spot location, the sensors are attached to both the windward and the leeward internal surfaces of the blade, on opposite symmetrical positions.

The strain sensors are usually mounted on the surface or embedded in the layers of a blade. The measured strain signals can be used to detect structural defects or damages in the blade, blade icing, mass unbalance, or lighting strikes. The measurements from fibre-optic strain sensors do not degrade with time or long transmitting distance making them ideal [6].

The measurement system collects the load cases every 10 minutes and pre-processes the raw data, including processing of transients, plausibility checks and diagnostic analysis. The results will then be stored in single mode files for further processing [7]. For the normal condition, the load on the blade at a typical frequency is similar, though different in different frequencies. When a failure occurs, the load at the blades changes. The signal acquired from the sensors at the same frequency, will be different compared with the normal condition. This implies that the amplitude will change from the base line. Based on this deviation, the operator can decide if and which maintenance action is required.

AS a demonstration, figure 3 shows the power spectra of the blade. The data comes from a test model under the wind tunnel. From the figure, it can be found that, the blade under the different frequency will got the different strain energy. Since the blade damage, which cause the mass of blade change, the strain of the blade will change.

The K-FS62 optical strain sensors will be used in the system.

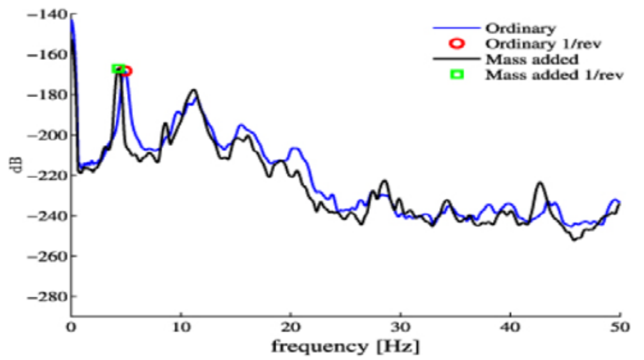

Figure 3: Comparison of mass-added blade power spectra with that of a baseline case [9]

2.2 Gearbox

The Vestas V90 gearbox consists of two planetary stages and one helical stage, as shown in figure 4

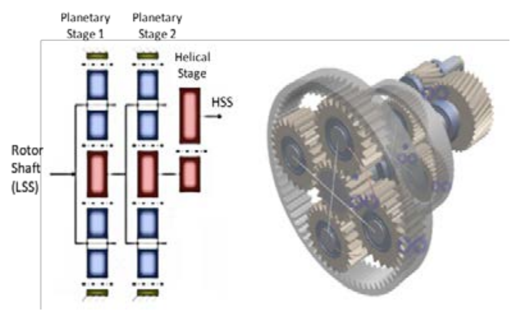

Figure 4: Layout of gearbox [10]

Planetary gearboxes allow higher load bearing capacity through load sharing between more meshes. [11][12][13][14]. Gearboxes are susceptible to faults which can eventually lead to failures. Vestas invested €40 million in gearbox replacement which indicates the importance of monitoring the status. Gearbox failures despite being limited, lead to long downtimes due to its complex design and the inaccessibility of various components [15][16].

The primary sources of gearbox failures are faults in the bearings and gears. In 2012, 15% of Vestas offshore wind turbines were affected by bearing failures where axial cracks were observed in the high-speed shaft bearings. Ruts also form along lines of contact of gears, due to fretting corrosion at the gear interfaces [16]. Gears are also subject to cracks and fractures due to fatigue loading.

The initiation and presence of the faults are most apparent through amplification of vibration modes and their harmonics [17]. Analysis of vibration responses of the gearbox is the most popular and cost-effective means for condition monitoring today. The frequencies of most significance are the gear meshing frequencies at each stage of the gearbox. Table 2 illustrates the gear mesh frequencies for the V90 gearbox expressed in terms of rotor shaft speed.

Stage	Gear Mesh Frequency (f_{in} = frequency of rotation of input shaft)
Planetary Stage 1	$104.91 \times f_{in}$
Planetary Stage 2	$681.98 \times f_{in}$
Helical Stage	$3447.76 \times f_{in}$

Table 2: Gear Mesh Frequencies at each stage of Vestas V90 gearbox

The Fourier transform and wavelet transform can be applied in conjunction with other signal processing and analysis methods. This is due to the nonstationary and nonlinear nature of the signals [12]. Thus, the adaptive technique proposed by Romero et al. would be ideal for condition monitoring of the gearbox. This technique uses unsupervised learning to actively define the healthy status of the machine based on loading conditions.

Using a tachometer rotor shafts speeds are determined. Vibration data from the accelerometers is stored with corresponding shaft speeds. Root mean square values are used to set the baseline for healthy operation of the gearbox. Whenever a deviation is registered, an intrinsic scale-down decomposition (ICD) is carried out on the signals [21]. The rotor shaft speed determines the gear mesh frequencies at all stages of the turbine and the forcing frequencies in the output signal. Thus, a match between detected faulty frequencies and the forcing frequencies is indicative of a fault which is registered in the system.

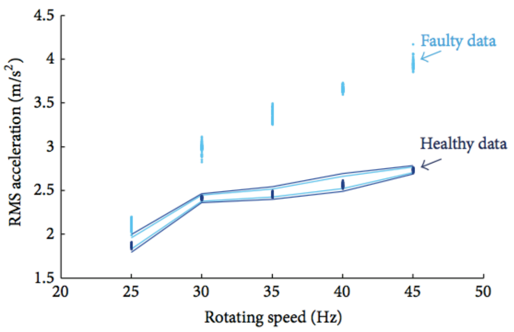

Figure 5: Proposed condition monitoring method implemented on a laboratory test rig showing the baseline for healthy operation and faults detected over various operating speeds [20]

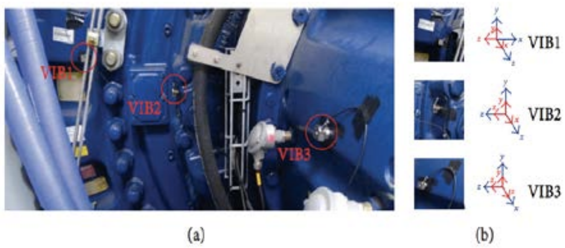

Figure 6: a) Position of the sensors on the gearbox b) Orientation of the sensors axes (shown in blue) with respect to gearbox global axes (shown in red) [20].

Due to diverse loading conditions and the range of frequencies to be monitored, a piezoelectric accelerometer such as the Metra KS943B100 can be used [18]. The KS943B100 is a tri-axial transducer with a sensitivity of 100 mV/g [19]. The KS943B100s are sold with magnetic attachments which are used to mount an accelerometer on the outside of the ring gear and the outside of the high-speed shaft bearing as shown in Figure 6.

Possible alternatives for future implementations

Considering the complexity involved in the signal processing and analysis techniques, it is worth considering sensor positioning which would make simpler time domain methods for fault detection more viable. Schütz et al proposed mounting wireless accelerometers on the planet carrier of each planetary stage of the gearbox [22]. This mitigates modulation caused by nonstationary meshing positions [22][11]. Schütz et al. found that motion of the accelerometers results in superposition and other signal modulations. However, these parasitic effects are easier to understand and can be mitigated with additional research.

Lubrication

The Vestas V90 gearbox uses a forced feed lubrication system. Oil from the gearbox is pumped through a filter to a heat exchanger. Following this it is pumped back into the gearbox [23]. Due to the inaccessibility of the parts, optimal oil quality and flow is essential to prevent the occurrence of wear induced faults.

Wear debris sensors are part of the Vestas V90 lubrication system. Metalscan online oil debris sensors are mounted on the pump discharges as shown in Figure 7 [24]. It detects both ferrous and non-ferrous particles of sizes ≥ 100 µm and is more relevant to monitoring the gearbox health than the oil quality.

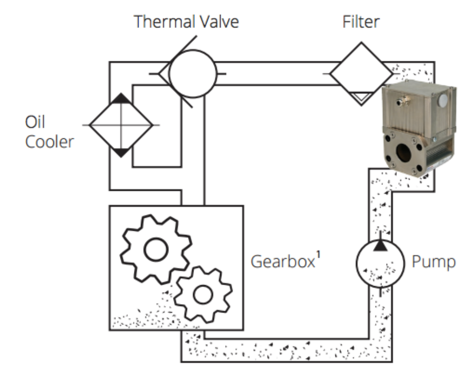

Figure 7: Position of Metalscan sensor Vestas V90 gearbox [24]

Oil contamination by smaller particles (size < 100µm) is detrimental to lubricant performance and promotes wear [26][27]. Such particles can be detected by using particle concentration sensors which quantify particles according to the ISO 4406:99 standards. Martechnic manufactures particle sensors can be mounted parallel to the supply lines from the oil tank to the gearbox [28].

A lubricant's dielectric constant exhibits a direct correlation with its moisture content. Water catalyses oil oxidation which in turn reduces bearing life and promotes wear [29]. Hydrocarbon oils typically used for lubrication in wind turbine gearboxes have dielectric constants in the range of 2.1 to 2.4 [30]. Fluid property sensors manufactured by TE connectivity measure the dielectric constant, temperature, and viscosity of the oil. They are placed in-line before oil is passed into the gearbox. Temperature fluctuations can affect the sensor output and impair lubricant performance [31].

2.3 Generator

The generator of an offshore wind turbine is an integral component in production of electrical power in the wind turbine. Should it fail, the turbine would cease to function. The generator is connected to the gearbox through the high-speed drive shaft, and outputs electrical power to the transformer. The Vestas v90 uses a 4-pole asynchronous generator that contains a wound rotor. It is rated at 3.0 MW and 60 Hz. As demonstrated in Figure 8 generator failures are not the most common failures observed in wind turbines, however they can result in long down times – up to 9 days for on shore wind turbines. [32] More common faults occur in the electrical and control systems however these cause less significant down times.

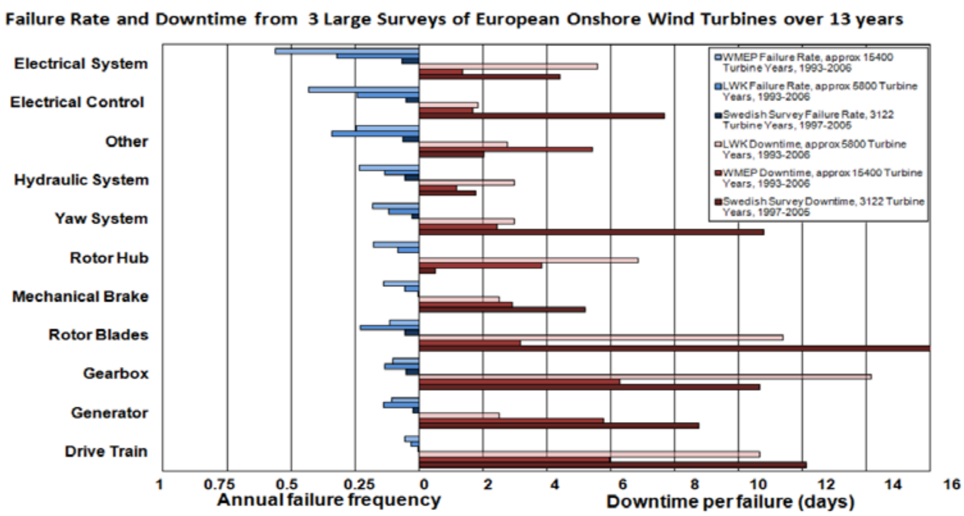

Figure 8: Common modes of failures and average down time for a range of European wind farms [32]

The generator and transformer converts mechanical power to useable electrical power for the grid, thus, faults in the mechanical or electrical systems could affect efficiency. The main systems in a generator include; the high-speed drive shaft, bearings on the drive shaft, magnets on the rotor, coils in the stator, and the electrical power output system including the transformer.

A potential fault in a generator is short circuits occurring in the wound coils. Short circuits can occur because of mechanical damage to the system, water damage in the system, or damage to insulation. Shorts lead to inconsistent current generation or increased resistance, reducing the efficiency of power generation. By logging the electrical output of the generator using voltmeters and ammeters the electrical response of the system can be determined, as shown in Figure 9. This information can be used to perform online condition monitoring. Discrepancies in the electrical output directly correspond to faults in the coil windings, and therefore are a good indication of the status of the coils in the system [33]. Additionally, the current measured can be used to determine the presence of a mechanical fault in the drive system. This could complement vibrational monitoring on the mechanical systems.

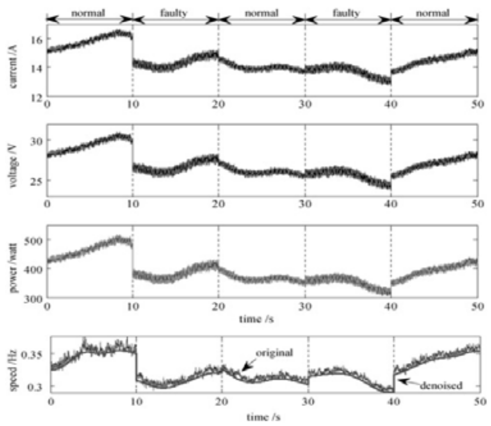

Figure 9: Demonstration of the changing electrical response due to a short circuit in the coils [2]

To improve the robustness of large off shore wind turbines the transformer can be placed in the nacelle. The Vestas V90 uses a 2-winding, 3-phase transformer isolated in in a room with surge arresters on the high voltage output [34]. Measurements on the low-voltage output of the transformer can be made to acquire the necessary data for analysis and operation. The following types of analysis determine power quality: peak power output, reactive power, voltage fluctuations, and harmonics.

In addition, mechanical properties can be measured to improve the condition monitoring. The temperature of the coils in a generator is expected to rise during operation. The Vestas v90 uses air-to-air cooling to control the temperature of the generator and systems during operation. Normal operating temperatures for wind turbines can be predicted and range between -20 °C and 40 °C [35]. Significant fluctuations in temperature can cause damage to the electrical systems in wind turbines, it is a common mode of failure for the electrical system [36]. The Vestas V90 uses PT 100 resistive temperature devices (RTD) to monitor the temperature during operation. RTDs are platinum devices that vary resistance as temperature changes [37]. They are rated for -200°C and 850 °C, therefore appropriate for wind turbine applications. Online fault detection can be done during operation by comparing the measured temperatures to the expected using nonlinear state estimation techniques (NSET) to differentiate high temperatures due to faults and normal operation [38].

Faults can also occur in the mechanical systems which could result in loos of function in the drive shaft. These faults include damage to the bearings such as cracking and contamination of associated lubrication as described in the gearbox section above. Additionally, the high speed drive shaft could be misaligned or cracked. Due to the design of the power transmission the majority of the mechanical load is observed in the gearbox, as a result failure due to high load is less likely to occur in the generator [39]. The generator contains the high speed shaft; therefore, the bearing and shaft are more likely to fail due to wear. Radial accelerometers with sensitivity of <1.8mm/s can be placed on the bearings and outer case of the generator [35, 39] to determine the presence of mechanical failures.

2.4 Tower

The tower and foundation cost above 40% of the overall cost of the wind turbine. Therefore, a monitoring strategy should be implemented to ensure that a failure is reported at early stages [50]. The foundation support of an offshore wind turbine is another important element since it supports the entire weight of the turbine. The most commonly used foundation structure for Vestas v90 turbines in the monopiles support foundation [51]. The tower is connected to the foundation through a transition piece. The medium of connection (grout) between those two is subject to failures, therefore, a grout monitoring will be investigated [52].

2.4.1 Strain and dynamic measurement:

A predictive method will be implemented for strain measurement. This method relies on the usage of accelerometers and optical fibre sensors. This technique consists of predicting the behaviour of the wind turbine under normal operating condition using finite element analysis. Afterward, a prediction of the acceleration and strain values of the sensors is obtained by using limited numbers of sensors. For quality control, a correlation value between the predicted and measured valued will be calculated. A high correlation would indicate good working conditions whereas a low correlation would be an indication of potential failures [53] [54].

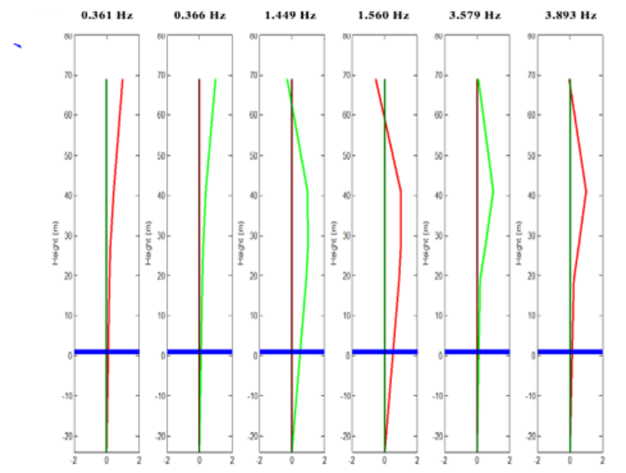

Figure 10: 6 fundamentals foundation modes with corresponding resonance frequency. From left to right (FA1, SS1, FA2, SS2, FA3, SS3) [54]

An estimation of the strain at any point on the tower can be achieved using a dynamic modal decomposition approach. The different modals considered in this case are the 6 fundamentals foundations modes which are represented in figure 10. [53]

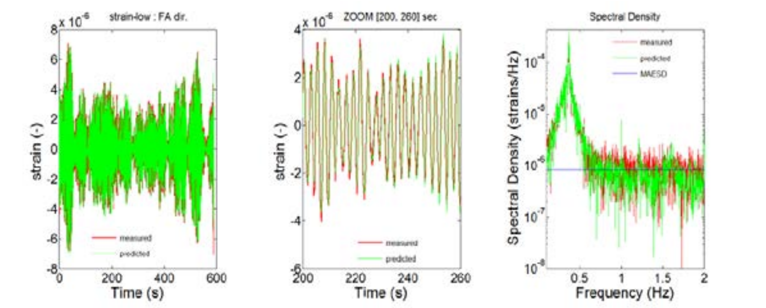

Figure 21: Predicted and measured values of strain in time and frequency domain for Vestas V90 turbine in Belwind farm [54]

By finding the predicted and measured values of acceleration and strain, a quality measure can be found to assess the condition of the turbine structure. An example from a study by Iliopoulos et al [54] has been conducted where turbine in Belwind farm has been investigated using the dynamic modal decomposition modal approach. The Strain and acceleration has been assessed at different heights of the tower. The measured results are presented with the predicted result and a mean correlation value was found as shown in figures 11, 12 and 13

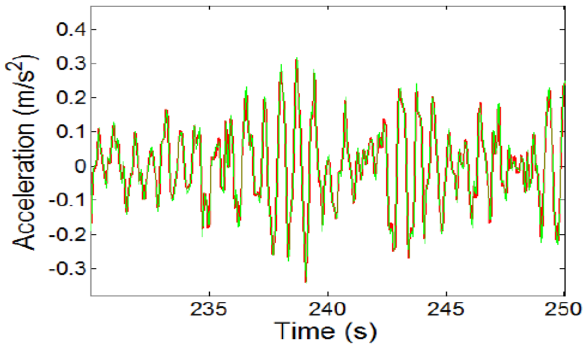

Figure 12: Predicted values (in green) and measured values (in red) for acceleration values in time domain at a height of 19 m above sea level [54]

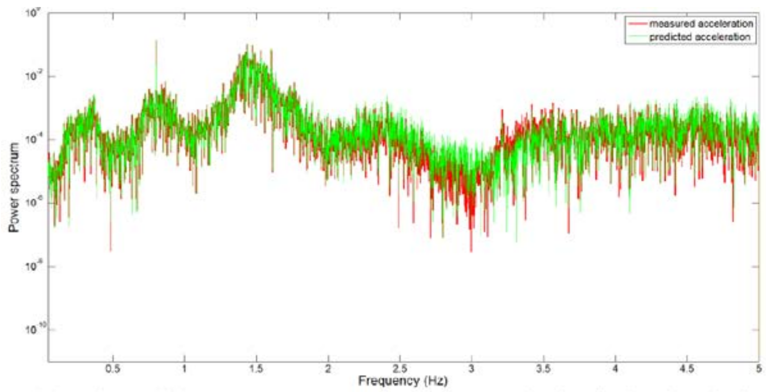

Figure 13: Predicted values (in green) and measured values (in red) for acceleration values in frequency domain at a height of 19 m above sea level [54]

<u>Working condition and fault analysis:</u>

The Working condition can be identified from the correlation value. A correlation value above 0.95 would show good working condition. A correlation between 0.90 and 0.95 is alarm level. Any correlation value below 0.90 would indicate potential failure and would require complete system shutdown. Therefore, figure 11, 12 and 13 shows good working conditions since the correlation between the predicted and measured values are high (>0.99) for time and frequency response. A low correlation would indicate an unusual strain which can be caused by corrosion, cracks or fatigue. In the case of low correlation, onsite inspection should be performed to analyse the damage.

The accelerometers selected should be low cost and responsive to low frequency since the resonance frequency of the tower range from 0.4 to 4 Hz. Therefore, the accelerometer selected is the Dytran 3166B1. There will be 10 accelerometers attached at 4 levels; 19m, 27 ,41m and 69m. In addition, 6 K-FS62 optical strain sensors will be placed as follows; four at 19m latitude and two at 41m latitude [55].

2.4.2 Grout failure:

Grout failure can potentially happen in the foundation support of wind turbines. This can make the structure vulnerable to external load and can cause slippage, displacement, and cracks

For a Vestas v90, monitoring of grout condition can be achieved by installing 6 load sensors on the bearing used to prevent the slippage of the transition piece. The bearing addressed are elastomeric bearings which are used to give the foundation higher loading capacity. A grout failure will impose more stress on the bearing. Therefore, grout damage can be spotted by monitoring the strain on all the elastomeric bearings.

Different modes of grout failure:

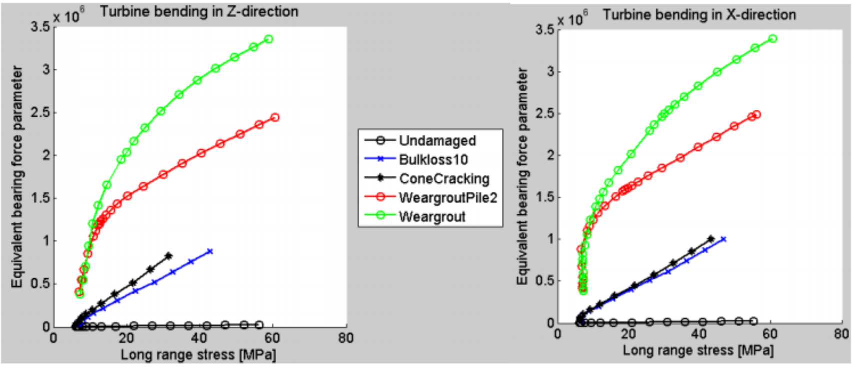

Figure 14: Bearing Force variation due to Long range stress [56]

To measure the strain in the grout, the strains in the bearing are measured using FPG sensors. A geometric average of all the strains measured is an indication of the type of grout failure manifested inside the grout. The force measured by the strain sensors would vary with the total external load manifested on the wind turbine. The equivalent bearing force parameter is a normalized value of all the load measured on the bearings. The long strange stress is an indication of the load imposed on the overall structure as shown in Figure 14.

3. Condition Monitoring System

The offshore wind turbine under investigation is a complex system in which several different components need be monitored to assure normal operation and early detection of faults. This implies that a reliable, high performance data acquisition system needs to be put in place. In addition, scalability needs to be taken into consideration but also potential increase in the number of sensors in the system. For this reason, National Instrument's (NI) PXIe platform in combination with NI software can be used to interface with all the sensors to perform the required signal analysis, storage, and data visualization. PXI systems offer high performance, processing, high channel counts, solid state hard drives for offline store data, communication with industrial buses (Ethernet, Modbus, CAN etc) but also offer sample rates at more than 200kS/s per channel. This section will discuss the proposed hardware, software as well as cost of sensors needed to implement the condition monitoring system under discussion.

3.1 Data Acquisition Hardware, Sensors, and Costs

The PXI system can be broken into three parts; the chassis, the controller and different modules mounted to interface with the transducers. The PXIe-8880 is suitable since it offers 8 cores together with a real-time operating system to allow deterministic analysis at very high rates. An extra 8GB of RAM has been included because several

System Configuration				
	Model	Description	Quantity	Price
Controller	NI PXIe-8880	NI PXIe-8880, Xeon 8-Core Controller, Win 7 (64-bit)	1	£5,337
	8 GB	8 GB Upgrade/Replacement RAM for PXIe-8880	2	£499.50
	Add Dual Boot - LabVIEW RT	LabVIEW RT Deployment License for NI PXI Controllers (ETS RTOS)	1	£123.75
Modules	NI PXI-8513/2	NI PXI-8513/2, CAN Interface, Software-Selectable/FD, 2 Port	1	£1,521
	NI PXI-6514	NI PXI-6514 Industrial 32 DI, 32 Source DO Isolated DIO & NI-DAQ	1	£432
	NI PXIe-4300	NI PXIe-4300 8-Ch 300V Isolated Analog Input	1	£1,773
	NI PXI-4496	NI PXI-4496, 24-bit, 204.8 kS/s, 16 Input, 2 Gain,TEDS,AC-Coupled	1	£7,191
	NI PXIe-4357	NI PXIe-4357 RTD Input Module	1	£2,151
	TB-4357	NI TB-4357 Terminal Block Accessory for PXIe-4357	1	£283.50
	NI PXIe-4844	NI PXIe-4844 4 Ch. Optical Sensor Interrogator	1	£10,620
Chassis	NI PXIe-1082	PXIe-1082, 8-Slot 3U PXI Express Chassis	1	£2,691
		Total:		£32,623

Table 3: Cost breakdown of Data Acquisition hardware

different channels will be sampled simultaneously at very high rates (up to 22kHz) thus producing a significant amount of data [40]. The PXIe-8880 controller also offers USB ports which can be used to connect external storage disks to store data in case communication is lost between the wind turbine and the server. In the extreme case were the wind turbine will experience a failure and all power is lost, a secondary power unit of backup batteries is proposed to allow further monitoring until maintenance is carried out.

Each sensor provides a different output signal but can also interface using a different bus. For example, the OPCom MMPM and FPS2800B12C4 transfer data via CAN communication, hence the selection of the PXI-8513 which provides 2 CAN ports [41]. The FPG sensors that are used both for the health monitoring of the blades and the structure will be interfaced using the PXIe-4844 Optical Sensor Interrogator [42]. Each optical channel has an 80nm wavelength range which can typically scan up to 20 FBG sensors per channel thus making it suitable for the system. A potential increase in the use of FBG sensors would not require a different or additional module. The PXI-6514 card will be used to acquire the square wave output signal from the in-built wear debris sensors of the turbine whilst also providing the other sensors with their respective excitation voltage [43]. Because there are many temperature sensors the high channel count PXIe-4357 together with the TB-4357 Terminal block can be used to enable fast and easy installation of the RTDs [45]. To interface with the accelerometers a module was needed which can do simultaneous sampling at very high rates whist also providing a good ADC bit resolution with a high dynamic range to provide a clean signal. For this reason, the PXI-4496 was selected [44].

Sensors	Model	Price	Quantity	Price
Temperature (RTD)	ProSense™ Bolt-On Ring RTD	£45	10	£445
Acceleration (tower)	Dytran 3166B1	£238	10	£2,380
Acceleration (gearbox)	KS943B100	£1,489	3	£4,467
Wear Derbis	-	£0	0	£0
Particle Concentration	OPCom MM PM	£2,435	1	£2,435
Fluid Property	FPS2800B12C4	£513	1	£513
FPG Optical Strain Transducers	K-FS 62	£88	30	£2,651
Total Price:				£12,891

Table 4. Cost of sensors

Since the generator produces very high voltages and amperage the following method of measurement is proposed. The voltage from the generator output will be scaled down to an acceptable level by placing a transformer in between the DAQ card (PXI-4300) and the generator [46]. Similarly, current clamps or current sensors that can convert high amperage into proportionally low-voltage outputs need to be used to measure the output current.

The total cost of the proposed condition monitoring system is £45,514. This price does not include costs for connector blocks, cabling and further accessories.

3.2 Software

To accelerate software development and avoid long term costs of software maintenance, National Instruments software has been selected. In addition, there are toolkits available such as the NI Sound and Vibration Measurement which will simplify the analysis of the signals. Post analysis, it is important to be able to view the data but also to send notifications to the base station in case a fault is detected. For that reason, the NI InsightCM software module has been selected [47].

The NI InsightCM Enterprise is a software solution specifically designed for online condition monitoring applications. It allows for the acquisition, management and analysis of sensor data, whilst providing options to visualize both raw data and results. In addition, it integrates easily with common IT infrastructures such as SCADA or CMMS Systems.

4. Conclusions

In this report, a potential condition monitoring system has been investigated to be implemented on large scale offshore wind turbine. The report has examined the Vestas v90 3MW turbine but the information may be relevant elsewhere. For each major subcomponent of the wind turbine the potential faults have examined and suitable condition monitoring techniques suggested. Additionally, suitable signal analysis and processing techniques have been investigated.

The research has demonstrated that the cost for a wind turbine condition monitoring system can be about £45,500. Which can be significantly less than the costs associated with replacement and maintenance of off shore wind turbines. Suggesting that condition based maintenance is suitable for this application.

5. Appendix A– Distribution of workload

During the course of the project the workload was divided as evenly as possible. During the initial stages of the project all 5 group members did generic research on the condition monitoring of offshore wind turbines to familiarize themselves with the concepts. Once the project was fully understood and an example system was selected the group identified the most important sub components and split up. Each member was assigned a specific sub component based on interests and expertise in the area, for each component the respective group member did extensive research, identified the likely faults, what damage they would incur, and identified parameters to measure that could identify these faults. The subgroups we identified were: blades of the turbine, gearbox with bearings, generator and transformer, support structure and nacelle casing, and data acquisition and processing.

The blades of the turbine were investigated by Ning Wang. They did extensive research on the modes of failures and potential damage to turbine blades. The corresponding section of the report was written by Ning Wang. They also found very technical information on the chosen example system.

Gearbox and Bearings were covered by Roshan Pasupathy who found in depth information on the monitoring of oil quality in the gearbox and bearings. Additionally, they investigated numerous methods of using vibration to monitor the status of the gearbox. They also wrote the corresponding section of the extensive report, and provided detailed information on the relevant sensors.

Generator and transformer were looked at by Jelmer van den Dries. They investigated a number of existing condition monitoring techniques for wind turbine generators, and evaluated the potential for additional monitoring techniques to distinguish normal operating conditions from faults. They also wrote their corresponding section, Appendix B, and organised meetings in the intermediate stages of the project.

The support structure and nacelle were researched by Ahmed Khafaga. They identified the most relevant parameters to measure and determined effective ways to monitor the condition of the structure. In addition to the relevant section in the report they also wrote the introduction and provided information on costing and down times.

Lastly, Georgios Alexopoulos identified the appropriate Data acquisition modules, and processing required for effective condition monitoring of the individual sections. Where relevant they added specific information on the sensors to be used. They took sole responsibility for compiling the whole report and ensuring it fits together well. Additionally, they organised meetings in the early stages of the project.

Overall each individual team member worked effectively and completed their assigned work.

6. References

[1] Besnard, François and Lina Bertling. (2010) "*An Approach for Condition-Based Maintenance Optimization Applied to Wind Turbine Blades*". *IEEE Transactions on Sustainable Energy* 1.2): 77-83. [On line]. Available at: *Ieeexplore.ieee.org*. Assessed on: 26 Nov. 2016.

[2] Vestas Wind Systems (2004) "*General Specification V90 – 3.0 MW*" [on line] Available at: http://www.gov.pe.ca/photos/sites/envengfor/file/950010R1_V90-GeneralSpecification.pdf. Assessed on 26 Nov.2016

[3] Ciang.C, Jung.R L and Hyung-Joon.B (2008)"Structural Health Monitoring for A Wind Turbine System: A Review of Damage Detection Methods". Measurement Science and Technology. N.p., 2016. [Online]. Available at: http://iopscience.iop.org/article/10.1088/0957-0233/19/12/122001/pdf. Assessed on: 26 Nov. 2016

[4] Qiao, D. and Lu, D. (2015)." A Survey on Wind Turbine Condition Monitoring and Fault Diagnosis–Part I: Components and Subsystems" [online]. Available at: http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1302&context=electricalengineeringfacpub [Accessed 27 Nov. 2016].

[5] P. Tchakoua, R. Wamkeue, M. Ouhrouce, F. Slaoui-Hasnaoui, T. A. Tameghe and G. Ekemb, (2014). "*Wind Turbine Condition Monitoring: State-of-the-Art Review, New Trends and Future Challenges*" Energies, vol. 7, no. 4, pp. 2595-2630.

[6] Qiao, W and Lu, D (2015)" A Survey on Wind Turbine Condition Monitoring and Fault Diagnosis—Part II: Signals and Signal Processing Methods" IEEE Xplore. [online] Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7084650 [Accessed 28 Nov. 2016].

[7] ECN (Energy research Center for the Netherlands), "Fibre Optic Load Monitoring of Wind Turbines," (2012).

[8] Diego, C and Katharina, F (2015)" *Condition Monitoring of Wind Turbines: State of The Art, User experience and recommendations*" Fraunhofer Iwes Northwest

[9] Arsenault, T., Achuthan, A., Marzocca, P., Grappasonni, C. and Coppotelli, G. (2013). Development of a FBG based distributed strain sensor system for wind turbine structural health monitoring. *Smart Materials and Structures*, 22(7), p.075027.

[10] "Power Transmission World." *Power Transmission World* -. N.p., n.d. Web. 08 Nov. 2016.

[11] Vicunl̀a, Cristial̀n Molina. Contributions to the Analysis of Vibrations and Acoustic Emissions for the Condition Monitoring of Epicyclic Gearboxes. Aachen: Zillekens, 2010.

[12] Yaguo Lei, Jing Lin, Ming J. Zuo, and Zhengjia He. "Condition Monitoring and Fault Diagnosis of Planetary Gearboxes: A Review." Elsevier, 21 Nov. 2013. Web. 08 Nov. 2016.

[13] M., Adam, and Magdi Ragheb. "Wind Turbine Gearbox Technologies." *Fundamental and Advanced Topics in Wind Power* (2011)

[14] Bortolani, Luca. "Planetary Gearboxes Help Alternative Energy." *Planetary Gearboxes Help Alternative Energy*. N.p., n.d. Web. 01 Dec. 2016.

[15] *[Wind Stats] Wind Stats Newsletter, 2003–2009, Vol. 16, No. 1 to Vol. 22, No. 4, Haymarket Business Media, London, UK.*

[16] NREL, Shuangwen (Shawn) Sheng:. "Report on Wind Turbine Subsystem Reliability – A Survey of Various Databases." Report on Wind Turbine Subsystem Reliability - A Survey of Various Databases (Presentation) (n.d.): n. pag. National Renewable Energy Laboratory, June 2013. Web. 15 Nov. 2016.

[17] Sparis, Panagiotis, and George Vachtsevanos. *Automatic Diagnostic Feature Generation via the Fast Fourier Transform* (n.d.): n. pag. Web. 25 Nov. 2016.

[18] "Triaxial Accelerometers." *Triaxial Accelerometers*. MMF, n.d. Web. 08 Dec. 2016. <http://www.mmf.de/triaxial_accelerometers.htm>.

[19] "Triaxial Equipment." *Triaxial Testing of Soils* (2016): 99-143. Web. <http://www.mmf.de/pdf/1-8.pdf>.

[20] Romero, A., Y. Lage, S. Soua, B. Wang, and T-.H. Gan. "Vestas V90-3MW Wind Turbine Gearbox Health Assessment Using a Vibration-Based Condition Monitoring System." *Research Article* 12.6 (2003): 761-63. Web. <http://bura.brunel.ac.uk/bitstream/2438/13468/3/Fulltext.pdf>.

[21] Y. Li, M. Xu, Y. Wei, and W. Huang, "Rotating machine fault diagnosis based on intrinsic characteristic-scale decomposition," Mechanism and Machine Theory, vol. 94, pp. 9–27, 2015.

[22] Shultz, Hilbert Marc, Markus Boos, Domenic Bernet, Christian Baltes, and Raph Nienhaus Aachen. "Results on Built-in Vibration Sensors inside Planetary Gears." *Results on Built-in Vibration Sensors inside Planetary Gears* (2014): n. pag. Web. 19 Nov. 2016. <http://www.ewea.org/events/workshops/wp-content/uploads/2014/11/Tech14a-PO-A003.pdf>.

[23] "General Specification V90 – 3.0 MW 60 Hz Variable Speed Turbine." (2004): n. pag. *GOV*. Vestas Wind Systems. Web. <http://www.gov.pe.ca/photos/sites/envengfor/file/950010R1_V90-GeneralSpecification.pdf>.

[24] "VESTAS V90-3MW Metal Scan." (n.d.): n. pag. Gastops. Web. <http://www.gastops.com/wp-content/uploads/2016/06/Vestas-V90-3MW_5-Application-Guide.pdf>.

[25] Toms, Allison. "Oil Debris Monitoring: Part of an Effective Gearbox Monitoring Strategy." GasTops Inc, n.d. Web. <http://www.stle.org/AsiCommon/Controls/BSA/Downloader.aspx?iDocumentStorageKey=21916a65-95b2-455b-a89b-55b368c986d6&iFileTypeCode=PDF&iFileName=Oil%20Debris%20Monitoring%20-%20Part%20of%20an%20Effective%20Gearbox%20Monitoring%20Strategy>.

[26] Ukonsaari, Jan, and Hans Møller. "Oil Cleanliness in Wind Power Gearboxes." Elforsk, n.d. Web. <http://elforsk.se/Rapporter/?download=report&rid=12_52_>.

[27] Oil, Clean. "The Roadmap to Effective Contamination Control in Wind Turbines." Clean Oil Bright Ideas, 2009. Web. <http://wind.nrel.gov/public/Wind_Turbine_Condition_Monitoring_Workshop_2009/4.3.Stover.The_Roadmap_to_Effective_Contamination_Control_in_Wind_Turbines.pdf>.

[28] "Particle Sensor." *Martechnic® | Products Sensors*. Martechnic, n.d. Web. 08 Nov. 2016. <http://www.martechnic.com/products_sensors.php?product=particle_sensor&lan=en>.

[29]https://www.vgb.org/vgbmultimedia/383_Final+report-p-9786.pdf

[30] "The Dielectric Constant and Oil Analysis." *Machinery Lubrication Magazine*. N.p., n.d. Web. 08 Nov. 2016. <http://www.machinerylubrication.com/Read/226/dielectric-constant-oil-analysis>.

[31] "FLUID PROPERTY SENSOR." *Fluid Property Sensor - FPS2800 | TE Connectivity*. N.p., n.d. Web. 08 Dec. 2016. <http://www.te.com/usa-en/product-CAT-FPS0009.html>.

[32] C. J. Crabtree, D. Zappala and P. J. Tavner, "Survey of Commercially Available Condition Monitoring Systems for Wind Turbines," 2014.

[33] W. Yang, P. J. Tavner and M. R. Wilkinson, "Condition monitoring and fault diagnosis of a wind turbine synchronous generator drive train," IET Renewable Power Generation, 2008.

[34] Siemens AG, The standard for offshore wind, Hamburg: Siemens AG 2016, 2016.

[35] Vestas Wind Systems A/S, General Specifications v90-1.8/2.0 MW 50 Hz VCS, Randers, Denmark: Vestas, 2010.

[36] F. Robert and P. E. Weir, "Heat and Power Problems are the Greatest Risks To Telecom Equipment," Munich RE, 2016. [Online]. Available: https://www.hsb.com/TheLocomotive/HeatAndPowerProblemsAreTheGreatestRisksToTelecomEquipment.aspx. [Accessed 7 December 2016].

[37] Bastronic, "PT100 and J and K typeThermocouples," Bastronic, 18 August 2011. [Online]. Available: http://www.bastronic.com/articles/27_pt100-and-j-or-k-typethermocouples. [Accessed 7 December 2016].

[38] P. Guo, D. Infield and X. Yang, "Wind Turbine Generator Condition Monitoring Using Temperature Trend Analysis," IEEE Transactions on Sustainable Energy, vol. 3, 2012.

[39] D. Coronado and K. Fischer, "Condition Monitoring of Wind Turbines: State of the art, user experience and recommendations," Fraunhofer Institute for Wind Energy and Energy System Technology, Bremerhaven, 2015.

[40] "PXIe-8880 Intel Xeon Eight-Core PXI Express Controller, 24 GB/s." *PXIe-8880 - National Instruments*. N.p., n.d. Web. 1 Dec. 2016.<http://sine.ni.com/nips/cds/view/p/lang/en/nid/212872>

[41] "NI PXI-8513 1-Port Software-Selectable/FD NI-XNET CAN Interface, PXI." *NI PXI-8513 - National Instruments*. National Instruments, n.d. Web. 1 Dec. 2016. <http://sine.ni.com/nips/cds/view/p/lang/en/nid/207321>.

[42] "PXIe-4844 Optical Sensor Interrogator for Fiber Bragg Gratings." *PXIe-4844 - National Instruments*. N.p., n.d. Web. 1 Dec. 2016. <http://sine.ni.com/nips/cds/view/p/lang/en/nid/209012>.

[43] "NI PXI-6514 (32 Inputs, 32 Source Outputs) Low-Cost Industrial Digital L/O -- 32 Source/Sink Input, 32 Source Output." *NI PXI-6514 (32 Inputs, 32 Source Outputs) - National Instruments*. National Instruments, n.d. Web. 1 Dec. 2016. <http://sine.ni.com/nips/cds/view/p/lang/en/nid/13576>.

[44]"NI PXI-4496 24-Bit, 204.8 KS/s, 16 Inputs." *NI PXI-4496 - National Instruments*. National Instruments, n.d. Web. 1 Dec. 2016. <http://sine.ni.com/nips/cds/view/p/lang/en/nid/203803>.

[45]"NI PXIe-4357 20 Ch, 24-Bit, RTD Input Module." *NI PXIe-4357 - National Instruments*. National Instruments, n.d. Web. 1 Dec. 2016. <http://sine.ni.com/nips/cds/view/p/lang/en/nid/210596>.

[46] "NI PXIe-4300 8 Ch, 250 KS/s, 300 V Ch-Ch Isolated Analog Input Module." *National Instruments*. N.p., n.d. Web. 1 Dec. 2016. <http://sine.ni.com/nips/cds/view/p/lang/en/nid/208288>.

[47] "NI InsightCM™ Enterprise for Condition Monitoring." *NI InsightCM™ Enterprise for Condition Monitoring - National Instruments*. N.p., n.d. Web. 1 Dec. 2016. <http://www.ni.com/insightcm/>.

[48]"PXIe-1082 8-Slot 3U PXI Express Chassis With AC - Up to 8 GB/s." *PXIe-1082 - National Instruments*. N.p., n.d. Web. 1 Dec. 2016. <http://sine.ni.com/nips/cds/view/p/lang/en/nid/207346>.

[49] Mcfadden, P. D., and J. D. Smith. "An Explanation for the Asymmetry of the Modulation Sidebands about the Tooth Meshing Frequency in Epicyclic Gear Vibration." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 199.1 (1985): 65-70. Web.

[50] Ciang, C.C., Lee, J.R. and Bang, H.J., 2008. Structural health monitoring for a wind turbine system: a review of damage detection methods. *Measurement Science and Technology*, *19*(12), p.122001.

[51] Anonymous . (2013). Monopile support structures. Available: http://www.4coffshore.com/windfarms/monopiles-support-structures-aid4.html. Last accessed 8th Dec 2016.

[52] Price, T. (2012). Grouting still a major issue for offshore wind.Available: http://www.renewableenergymagazine.com/wind/grouting-still-a-major-issue-for-offshore. Last accessed 27th Nov 2016.

[53] Iliopoulos, A.N., Weijtjens, W., Van Hemelrijck, D. and Devriendt, C., 2015. Prediction of dynamic strains on a monopile offshore wind turbine using virtual sensors. In Journal of Physics: Conference Series (Vol. 628, No. 1, p. 012108). IOP Publishing.

[54] Iliopoulos, A., Devriendt, C., Guillaume, P. and Van Hemelrijck, D., 2014, July. Continuous fatigue assessment of an offshore wind turbine using a limited number of vibration sensors. In EWSHM-7th European Workshop on Structural Health Monitoring.

[55] Devriendt, C., Elkafafy, M., De Sitter, G. and Guillaume, P., 2012. Continuous dynamic monitoring of an offshore wind turbine on a monopile foundation. In Int. Conf. on Noise and Vibration Engineering, ISMA.

[56] Gupta, S et al. (2015). Condition monitoring of offshore wind turbine with monopile foundation. SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World. Accessible at: http://www.seced.org.uk/images/newsletters/GUPTA,%20STODDART,%20SANDERSON,%20MORRISON.pdf