

## Perspectives on condition monitoring techniques of wind turbines

Moeini, Rana; Entezami, Mani; RATKOVAC, MIRIJANA; Tricoli, Pietro; Hemida, Hassan; Hoffer, Rudiger; Baniotopoulos, Charalampos

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# Perspectives on Condition Monitoring Techniques of wind turbines

R Moeini<sup>1\*</sup>, M Entezami<sup>1</sup>, M Ratkovac<sup>2</sup>, P Tricoli<sup>1</sup>, H Hemida<sup>1</sup>, R Hoeffler<sup>2</sup>, C Baniotopoulos<sup>1</sup>

<sup>1</sup> School of Engineering, University of Birmingham, Birmingham, B15 2TT, UK

<sup>2</sup> Wind Engineering and Flow Mechanics, Ruhr-Universität Bochum, Bochum, Germany  
R.Moeini@bham.ac.uk

## ABSTRACT

The ever-increasing development of wind power plants has raised awareness that an appropriate condition monitoring system is required to achieve high reliability of wind turbines. In order to develop an efficient, accurate and reliable condition monitoring system, the operations of wind turbines need to be fully understood. This paper focuses on the on-line condition monitoring of electrical, mechanical and structural components of a wind turbine to diminish downtime due to maintenance. Failure mechanisms of the most vulnerable parts of wind turbines and their root causes are discussed. State of the art condition monitoring methods of the different parts of wind turbine such as generators, power converters, DC-links, bearings, gearboxes, brake systems and tower structure are reviewed. The paper addresses the existing problems in some areas of condition monitoring systems and provides a novel method to overcome these problems. In this paper a comparison between existing condition monitoring techniques is carried out and recommendations on appropriate methods are provided. In the analysis of the technical literature it is noted that the effect of wind speed variation is not considered for traditional condition monitoring schemes.

## 1. INTRODUCTION

Wind harvesting technology is one of the most popular alternative sources of renewable power generation [1]. This is due the higher efficiency of wind farms compared with photovoltaic power stations and tidal power. Compared with biomass and nuclear power plants wind is a pure and green source of energy. During 2016, 11 GW on-shore and 1.5 GW off-shore wind power farms were newly installed in European countries [2]. Growth of 20%-40% in off-shore wind farms has been reported; this may be due to higher wind energy capture and available planes [3]. However, the maintenance and unplanned downtime costs of wind turbines (WTs) have significantly adversely affected their growth in popularity [4]. Maintenance and unplanned downtime costs can be even worse in the case of off-shore wind turbines due to difficulty to access to site in different weather conditions as well as vessel and experts costs. Improving the availability of WTs has many advantages and can be achieved by reducing unplanned downtime. By distinguishing the most fragile parts of WTs and the root causes of the failure mechanisms of those parts, early failure can be anticipated and detected, thereby reducing unplanned downtimes. When a fault happens in a wind turbine subsystem, i.e. exceeding a critical threshold value measured from a sensor, the monitoring system logs the abnormal condition, which can be a fault, and in most known conditions it can also register the consequences of the fault. It then acts based on the type and severity of the indicated abnormality. If the fault is recognized as a serious fault then visual inspections for further detailed investigation are required [5]. Condition monitoring systems (CMSs) are applied to detect changes within the condition of a system [6]. Diagnosis is devoted to identification of the root cause of the different types of fault occurring in the system. Prognosis assesses the health level of each component and is used to predict incipient faults.

Different types of WTs are categorised and summarised in terms of their variety in drive systems in section 2. Faults in WTs can be mechanical (including hydraulic systems), structural and electrical related to a failure in power electronics. Results from a Swedish wind farm failure analysis, illustrated in Figure 1, show that the electrical subsystems, including electrical and control systems and generators, together have the highest failure rates [7].

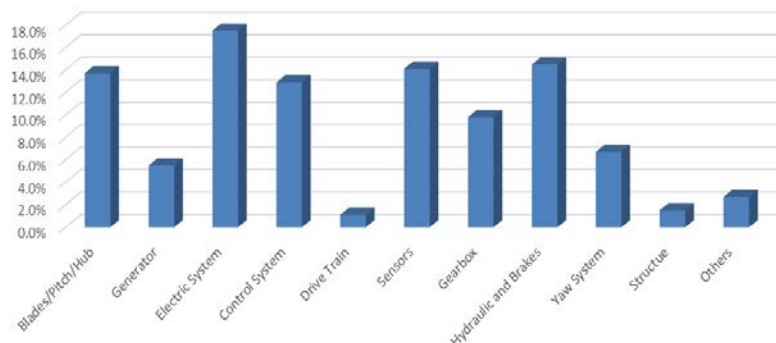


Figure 1: Subsystem failure rates in a Swedish wind farm [7]

In electrical drive train systems, generators and power electronics are the least reliable parts [8]. Different failure mechanisms of electrical drive systems and their root causes as well as Condition monitoring methods for the most critical parts are discussed in section 3. The CM methods are also compared to identify alternative approaches to traditional methods. Although a large number of studies have been published on the CM of electrical systems, most of the presented methods are either inaccurate when multiple faults occur simultaneously, or they are significantly complex to implement within the operation of converters. In this work, a novel approach of power electronic converters is also presented. This approach could simplify a non-linearity of non-linear relation between failure detectors and the actual ageing of insulated gate bipolar transistors (IGBTs) found in the converter.

Yaw systems, brake systems, bearings and gearboxes are the most vulnerable parts of the mechanical drive system in WTs. Their failure mechanisms and the root causes are discussed in section 4. This section also provides recommendations on the approaches which are introduced. The most common structural failure mechanisms of WTs are discussed in section 5. The root causes of failure mechanisms of the tower structures and different CMSs are discussed and evaluated. A promising approach is determined later in section 6.

## 2. DIFFERENT TYPES OF WTS

WTs convert the kinetic energy of wind into electrical energy by first converting it to mechanical energy through the rotors and then to electrical energy by generators [9]. WTs are categorised into variable and fixed speed WTs in terms of electrical and mechanical drive systems. In fixed speed WTs, the generator is a squirrel-cage induction type and it is connected directly to the grid. However, this type of WT can produce power only when the wind speed is within a narrow range above the synchronous speed of the generator. In variable-speed WTs, a power converter has to be fitted to the electrical system [10]. Both doubly-fed induction generators (DFIG) and synchronous generators can be used for variable speed applications. Figure 2 summarises the different types of WTs, classified on the basis of the generator type [11].

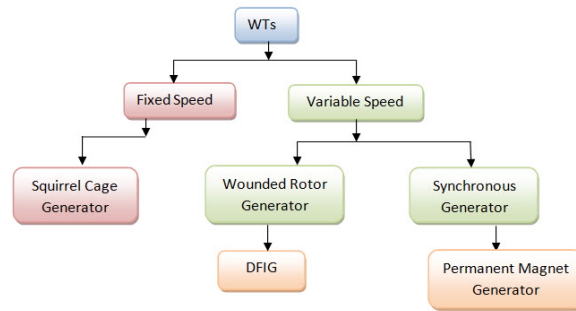


Figure 2: Classification of electrical generators for WTs [12]

### 2.1. FIXED SPEED WTS

Squirrel cage induction generators are used for fixed speed WTs and are directly connected to the grid [10], [13] as shown in Figure 3. The drive-train consists of a gearbox (in most WTs), a mechanical brake and the electrical generator. The generators are very cost-effective, especially for small and medium WTs. Due to the narrow range of operations and the requirements for reactive power, these generators are not preferred for large WTs. The fixed speed model is mainly used for small and medium WTs. The generator rotor speed has a constant value for all wind speeds. This means that the tip ratio can only be set by a variation in wind speed. However, the maximum efficiency of a WT is determined at a certain value of tip ratio. Therefore, fixed WTs cannot operate at maximum efficiency based on wind speeds [14].

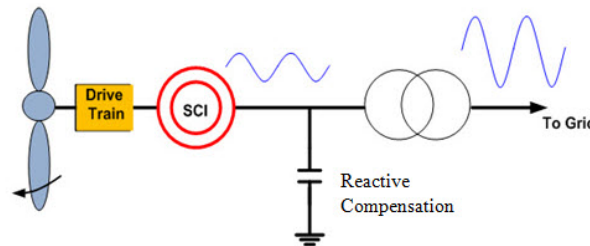


Figure 3: Diagram of a fixed-speed WT (squirrel cage generator)

### 2.2. VARIABLE SPEED WTS WITH DOUBLE FED INDUCTION GENERATOR (DFIG)

Variable speed WTs can generate the maximum efficiency at most wind speeds. The electrical system of a WT with a DFIG is shown in Figure 4. This type of system is used in large WTs. A DFIG has a stator winding, which is directly connected to the grid, while the rotor is supplied by a power converter [15]. For this reason, this type of generator is called doubly-fed, because both the stator and rotor windings are energised. A back-to-back power converter is used to rectify the grid voltage at grid frequency and then convert it into the desired three-phase ac voltage at slip frequency for rotor excitation. A DC-link capacitor is connected between the DC and AC sides of the

converter as an energy buffer [16]. A controller is used to regulate separately the real and reactive powers of the stator.

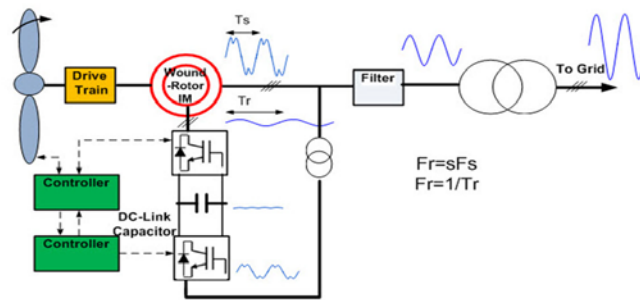


Figure 4: Diagram of a doubly-fed induction generator

### 2.3. VARIABLE SPEED WTS WITH SYNCHRONOUS GENERATOR TYPE

The electrical system of a WT with a permanent magnet synchronous generator (PMSG) is shown in Figure 5. The power converter is connected to the stator winding and the machine is excited by the rotor magnets. The converter has two stages with an intermediate DC-link to convert the variable frequency of the generator into the constant frequency of the grid [17]. The efficiency and the power density of permanent magnet generators are significantly higher than those of squirrel cage generators and DFIGs, because of the lack of excitation current [18]. However, they are more expensive because rare-earth magnets (e.g. NdFeB) are necessary for the rotor. In the case of permanent magnet generators, stator faults, bearings and converters must be monitored. These are the only types of generator that can be used without a gearbox, thereby improving the reliability of the WT, although at the premium of a higher cost of the machine [19].

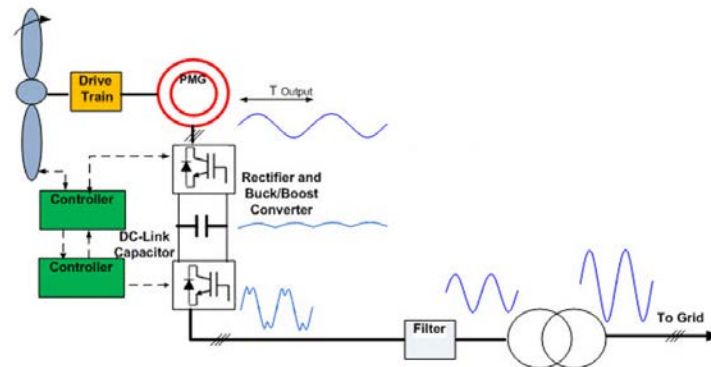


Figure 5: Diagram of a permanent magnet synchronous generator

## 3. CM OF THE ELECTRICAL DRIVE TRAIN COMPONENTS

### 3.1. CM OF GENERATORS

The main parts of the electrical drive system found in fixed speed WTs are the squirrel cage generator and gearbox, as shown in Figure 3. A common failure of the squirrel cage generator is cracking of the rotor bars. The health status of the rotor bars can be monitored by analysing the spectrum of the stator current, since any geometric and magnetic imbalance produces a harmonic having sideband frequencies with respect to the grid frequency [20]. Many harmonic detection techniques have been proposed to identify the presence of undesired harmonics in the spectrum of the stator current, using discrete Fourier transform (DFT) [21, 22]. DFT method is broader so it covers all those faults. Each fault can then be detected by their different signature in the spectrum.

The most common failure mechanism of the generator stator windings is degradation of windings insulation due to high temperature, electrical and mechanical stresses. Many CM methods have been proposed based on thermal monitoring, fault detection of winding turns and partial discharge [23, 24]. Electrical or mechanical faults have an impact on the magnetic field in squirrel cage generators (SCGs). This can be identified by measuring the stator current. By analysis of the variation of current signals, most mechanical and electrical generator faults can be detected. Generator current signature analysis (GCSA) is a non-invasive monitoring approach that is commonly used in fault detection of SCGs [27]. The key advantages of this approach are that physical access to the machinery is not required. Current transducers, usually in the form of a clamp, are used to avoid any interference with the system's original wiring. This method is capable of identifying faults, and it can be used to improve the maintenance regime and to prevent further damage and avoid long downtimes [27].

The robustness of SCGs is higher than that of DFIGs and PMGs which are used in variable speed WTs. This is because of the differences in structure of these generators. There are no brushes or slip-rings in SCGs, and there is also no limitation on the temperature of the magnet in comparison with synchronous generators. Hence, SCGs

have lower maintenance costs. However, the output efficiency of DFIGs and PMGs is much higher than that of SCGs [28]. Another main advantage of DFIGs and PMGs is that they capture the maximum power at different wind speeds.

Faults in the rotor winding can be detected by measuring the leakage flux and the shaft voltage, in the case of DFIGs [29]. In the leakage flux test, a detection coil is mounted near to the rotor, so that it can measure an induced electromotive force due to leakage flux. A decrease of the leakage flux due to a fault in one of the rotor coils can be detected by a decrease of the induced electromotive force. In the case of a fault of the insulation of the rotor winding, a leakage current flows through the shaft and causes a variation in voltage that can be applied as a failure detector.

Thermal monitoring is carried out by using temperature sensors locally or by thermographic cameras [30]. This can be used to identify faults that cause overheating, such as overloading, stall situations, and an unbalanced rotor. For example, it has been shown that fluctuations in stator winding insulation can thoroughly reduce the lifetime; an increase of about 5°C can reduce the life of the machine by around eight years [31]. The installation of temperature sensors in between rotor windings and stator windings is crucial. This makes the technique an invasive approach; to achieve the best performance, the sensors must be fitted during the manufacture of the motors. However, the use of thermal cameras to measure the temperature gradients can be advantageous in unsafe conditions [32]. The drawbacks of a perfect thermal camera are usually cost and difficulty of the analysis. Another downside is that using the rise in temperature to detect the fault is not fast enough to achieve an optimum fault detection procedure, as the fault has already developed [33]. The rotor winding's faults can be detected by measuring both the leakage flux and the shaft voltage [34]. In the leakage flux test, a detection coil is mounted near to the rotor, so that it can measure induced voltage. Any reduction of the leakage flux in one of the rotor coils can be detected via the decrease of the induced voltage. In the shaft voltage test, the shaft-to-ground voltage is monitored, so that any leakage current that flows through the shaft generates a voltage that can be detected by the CM system.

### **3.2. CM OF POWER ELECTRONIC CONVERTERS**

For variable-speed WTs, a power converter has to be added to the electrical system. The power converter has the function to harmonise the voltage output of the generator with the voltage of the grid, either in terms of magnitude or frequency or both. Statistically, insulation gate bipolar transistors (IGBTs) are the most fragile parts in converters accounting for 30% of failures, followed by DC-link capacitors and IGBT drivers at nearly 20% and 15%, respectively [35]. Both IGBT and DC-link capacitors should be accurately monitored during the WTs operation. IGBTs suffer from thermal stresses due to load variations (wind speed variations). Various types of failure mechanisms occur in semiconductor modules, such as bond wire fatigue [36], bond wire lift-off [37], bond wire heel cracking [38], aluminium metallization [39] and solder fatigue [40]. Almost all of them originate from thermal swings during converter operations and the different thermal expansion coefficient between different layers of the modules [41]. In fact, thermal stresses originate from both power and thermal cycling of power switching components. Power cycling losses are generated by load variations, while thermal cycling losses are generated by thermal variations [42].

The main challenge for the next generation of CM systems for power electronics is to track the temperature variation of the hottest point (junction terminal) as an early failure indicator. The problem is that the temperature of the junction terminal is not accessible for direct measurement. In other words, direct measurement of temperature requires amendment of IGBT module, which is destructive method. This method is not really applicable in not research based CM methods.

Estimation of temperature is an alternative method to track variation of temperature and also detect early failure mechanisms of IGBTs. This can be conducted through thermal sensitive electrical parameters (TSEPs) measurements [43, 44]. TSEPs is a promising approach to detect failure mechanisms of IGBTs, mainly due to the direct accessibility of the required terminals. Another advantage is that different TSEPs have shown altered sensitivity to different failure mechanisms. Therefore, the type of failure mechanism can be distinguished and correlated with other failure mechanisms [45, 46]. Some TSEPs are recognised as off-line methods and others as on-line methods for early failure detection.

In addition, another advantageous of TSEPs measurement instead of direct measurement of junction temperature is that temperature profile is affected in the presence of all mentioned failure mechanisms, as well as load variations [47, 48].

Threshold voltage is ensured for CM even at low switching frequency. However, it is not distinguished as an on-line CM method [49], since tracking of this electrical parameter is difficult due to the required high sampling rate and it is inaccurate while the system operates in different load conditions. In addition, gate-emitter voltage,  $V_{GE}$  is also considered as an off-line method, since it requires injection of external signals to the gate in order to make this electrical switching parameter measurable [50]. Measuring some parameters such as junction temperature  $T_j$ , or thermal impedance, or resistance thermal path,  $t_{on}$ ,  $t_{off}$  and  $V_{CE-on}$  can be applied for an on-line condition monitoring based method [51]. In order to provide valid online CM methods for WTs, it is essential to verify the variation of most appropriate electrical parameters based on the type of failure mechanism. Multi-fault indicators should also be cross-related to obtain accurate CM methods. To cross-relate multi-failure mechanisms, TSEPs can be chosen based on their sensitivity to the presence of each failure mechanism. Ghimire et al. [52] and Busca et al. [53] revealed that  $V_{CE,on}$  shows a significant sensitivity to the bond wire lift off (BWLO) compared to the other TSEPs. D. Xiang et al. [54] revealed that  $T_c$  changes noticeably in the presence of solder fatigue (SF). Zhou et al. [55] studied odd harmonics of converters and revealed that in the presence of BWLO the odd harmonic current output of the converter increases. However, the odd harmonic does not show a noticeable sensitivity to the SF. Considering  $V_{CE,on}$ ,  $T_c$  and the odd harmonic of the converter current as failure detectors can help to cancel the

adverse effect of multi-failure mechanisms. There is a lack of study in understanding the effects of wind speed variation on failure detectors of the electrical drive systems, i.e. DC-link, IGBTs and generators. In the application of WTs, the effect of wind condition on the operation of the electrical system should be studied in order to correlate wind speed variations to failure detectors.

Variable wind conditions cause variations of the electrical parameters and temperature swings. Due to the non-linear relations between the parameters and the ageing of components, a significant computational effort is expected and, hence, advanced monitoring algorithms based on artificial intelligence (AI) are necessary. Thanks to these algorithms, the detection of faults and the consequent decision-making can be reliably carried out even when there are multiple factors. Starting from an initial healthy condition, wind speed, electrical parameters and temperature swings are measured on-line and any variation is analysed by an AI to provide real-time information of the operation of the components. In other words, each component faces different fault mechanisms and root causes. For instance, for generators, electrical faults can originate from short circuits or electrical asymmetry or inductive imbalance. An early detection of faults based on the elaboration of information related to the fault's mechanism is beneficial to significantly enhance the accuracy of the CM system. The AI monitoring system can be based on a fuzzy controller. This type of controller is particularly suitable when the mathematical model of the system is unknown or too complex to be managed by deterministic controllers such as A proportional–integral–derivative (PID) controllers. In fact, a fuzzy controller is based on empirical rules and can be readily upgraded for a more complex system by simply increasing the number of fuzzy rules. For example, to monitor the health status of an IGBT, a fuzzy description can prepare the precise capability of analysis of the IGBT's health status by considering the variation in electrical parameters ( $V_{CE}$ ,  $V_{GE}$  and  $I_{GE}$ ) and  $T_j$ . Additionally, many other algorithms such as genetic algorithms (GA), bee colonies (BC) and neural networks (NN) will be investigated. The amount of variation of the electrical parameters ( $T_j$  and  $V_{CE,on}$ ) plays a key role in understanding the health status of the switching devices. For instance, a 3% increment of  $V_{CE,on}$  is the symptom of wear-out, whereas an increment between 5% and 10% can be considered an early fault, while a 20% increment can be considered as a critical failure. Similarly, a 5% increase of  $T_j$  indicates that wear-out has started, a 10% increment an early fault and a 20% increment a critical failure [56]. These variations can be introduced as fuzzy rules to estimate the health status of the IGBTs. The CM monitoring of power devices is complicated by the fact that some failure mechanisms are positively correlated with an electrical parameter, while other failure mechanisms are negatively correlated to the same electrical parameter. For instance, bond wire lift-off produces an increased trend of  $V_{CE,on}$ , while die degradation causes a decreased trend of the same parameter. Therefore it is essential to understand the correlation between all the parameters related to each fault mechanism to avoid error in the fault detection.

### **3.3. CM OF DC-LINK**

DC-Link capacitors are used in power electronic convertors in order to balance output power and input source of converter. Statistically, DC-link capacitors are also one of the most vulnerable parts in power electronic convertors. Open circuit, short circuit are the most failure mechanisms of DC-link capacitors [57]. Open circuit occurs due to increase in ambient temperature, current ripple, voltage stresses of capacitors and humidity, which is led to moisture corrosion and electrical vaporization. Short circuit causes due to sever vibration leading to failure of oxide layer, capacitor body and dielectric film of capacitors. Both two common failure mechanism, short circuit and open circuit, causes variations in capacitor electrical parameters, such as leakage current, equivalent series resistance (ESR) and equivalent series inductance (ESI). Tracking variation of those electrical parameters can help to detect failure mechanisms [58]. Proper failure detector of DC-Link capacitors are highly depends on size of capacitors [59]. Electrolyte vaporization is dominant for small capacitors due to limited available surface to temperature dissipation and higher ESR. Breakdown of oxide layer is the most dominant failure mechanisms of DC-link, causes increase in leakage current. A typical method used to monitor capacitors is based on the measurement of the equivalent series resistance, which is an index of their residual lifetime [60]. An alternative method is based on the measurement of the voltage ripple across the capacitor, which is related to current ripple [61, 62]. However, the effect of load variations on voltage ripple variations is not considered in this method. Furthermore, acoustic emissions are also utilized to distinguish the discharge of capacitor due to the aging process [63].

## **4. CM OF THE MECHANICAL DRIVE TRAIN COMPONENTS**

Vibration monitoring is the measurement of a machine motion due to internal and external forces, which can be mechanical, electrical or magnetic [64]. Normally, rotating machines vibrate at a specific level. To detect these vibrations, high sensitivity vibration sensors are used. Faults in bearings and gearboxes, and unbalanced rotors are common uses of this approach [65, 66]. A drawback of this method is that it requires high frequency sample rates (around 20-50 kHz), generating a large volume of data which can be difficult to store and process. Also, the cost of a vibration sensor can be expensive in comparison to the cost of the IMs. The main disadvantage of this technique is that it requires physical access to the machine so that The sensor needs to be physically attached, data can be transferred wirelessly. For example, to monitor the yaw motors, a journey to the nacelle by a specialist technician is required. Furthermore, any problem with the sensors adds an extra maintenance cost for the monitoring system

### **4.1. CM OF BEARINGS**

The main reason for bearing faults is torque variations due to variable power, which lead to surface and bending fatigue. Misalignment and improper lubrication are other important causes of bearing faults [67, 68]. Degraded bearings can lead to inefficient operation and even failures and associated downtime [69].

The performance of rolling element bearings is critical for the functioning of machinery. Thus it is important to monitor the condition of bearings continuously to avoid system failures. Early fault detection would also be advantageous for service and maintenance. A number of techniques are currently being used for the detection of defects in rolling element bearings. These include vibration, acoustic emission (AE) measurements and oil monitoring, using methods such as overall level of kurtosis, spectral analysis, high frequency resonance and spectrographic oil analysis. Techniques such as particle counting, ferrography and chip detection are also used in certain circumstances [70].

When there is damage the strike between the damaged area and the components such as races and rollers within the rolling element generates additional noise and vibrations. Rolling element bearing faults are categorized into four groups: roller damage, inner race defect, outer race defect and cage damage [71].

The vibration frequency varies depending on the type of fault. The following equations define the characteristic frequencies [72]:

FTF, Fundamental Train Frequency, fault on the cage or mechanical looseness

$$f = \frac{\omega_r}{2} (1 - \frac{RD}{PD} \cos \beta) \quad (1)$$

BPFO, Ball Passing Frequency Outer Race, local fault on outer race

$$f = \frac{n}{2} \omega_r (1 - \frac{RD}{PD} \cos \beta) \quad (2)$$

BPFI, Ball Passing Frequency Inner Race, local fault on inner race

$$f = \frac{n}{2} \omega_r (1 + \frac{RD}{PD} \cos \beta) \quad (3)$$

BFF, Ball Fault Frequency = 2 \* RSF, Roller Spin Frequency, local fault on rolling element

$$f = \frac{PD}{2RD} \omega_r (1 - (\frac{RD}{PD} \cos \beta)^2) \quad (4)$$

where  $f$  is the frequency of the item [Hz];  $\omega_r$  is the shaft rotation rate [Hz];  $RD$  is the roller diameter [m];  $PD$  is the mean roller race diameter [m];  $\beta$  is the contact angle [rad]; and  $n$  the number of rolling elements (balls) [72].

High frequency resonance technique (HFRT), also known as Envelope Analysis, extracts fault-related high frequency components of a signal, which are compared to known bearing fault characteristic frequencies [73].

However, one of the drawbacks of the vibration and acoustic emission (AE) techniques is that they require direct access to the bearing within the machinery. In some conditions, due to health and safety or for practical reasons, the system cannot be accessed, and direct mounting of the sensors is therefore problematic. Faults in a bearing within a mechanical system that operates by an induction motor cause changes in flux and therefore the current spectrum can be used to identify the changes [74, 75, 76].

Tendon et al have performed a number of experiments to evaluate the performance of vibration, acoustic emission and MCSA techniques to detect bearing faults. It was concluded that all the techniques can successfully detect simulated defects in the test bearings. AE was shown to be the most advanced technique, capable of detecting micro-size defects [77]. However, stator current monitoring is the most cost-effective technique [76].

## 4.2. CM OF GEARBOX

In wind turbines a gearbox increases the speed of the low-speed shaft to a suitable value that is required in the electricity generators. It is stated that gearboxes cause the longest downtime due to their failures [78].

Most gearbox failures in wind turbines start in the bearings, even though they usually have high quality bearings [79]. Gear tooth damage, high speed and low speed shaft faults are also failures in the wind turbine gearbox. Vibration measurement and spectrum analysis are usually chosen for gearbox monitoring. Vibration methods might not be able to detect faults at early stages due to slow rotation of the main shaft, therefore, acoustic emission (AE) is often used, as this method can detect stress on the surface that has been caused by a rubbing action in faulty components [80].

Time synchronous averaging (TSA) is a well-known vibration monitoring method to reduce signal components that are not synchronous with the shaft rate of rotation, which include electrical and environmental noise, bearing vibrations, and vibrations related to other machinery [81, 82].

TSA extracts periodic waveforms from noise. It is appropriate to use TSA in analysis of gearbox data, as it separate the vibration signature from other sources of noise in the gearbox, which are not synchronous with that main shaft speed [82]. Vibration signals related to the gears repeat every rotation. Averaging every single one of these individuals enhances the rotational components of the gear and reduces the amplitude of the other components. This will amplify the gear mesh frequency and its harmonics. This technique requires a constant speed, therefore variable speed case re-sampling and interpolation are necessary [82].

The main tooth mesh frequency created by the gears can be used for spectrum analysis and monitoring the gears' condition. In the same load and speed, if the peaks rise, this could be an indication of a fault. The gear mesh frequency can be calculated using:

$$f_m = N \cdot f_r \quad (5)$$

where,  $f_m$  is the mesh frequency (Hz),  $N$  is the number of teeth and  $f_r$  is the shaft rotational speed (Hz).

Frequency analysis is shown to be able to detect faults in a gearbox; however, it has some weaknesses. One drawback is that frequency-domain analysis is effective to identify faults but it is less efficient for on-line condition monitoring systems due to the overheads caused by the complexity of processing and required parameters. Moreover, most frequency domain analysis, e.g. the Fourier transformation, assumes that the system is linear and stationary. Thus, the time factor is not used in the frequency-domain. Therefore a combination of a time-domain and a frequency-domain technique can improve the efficiency of the detection algorithms [83].



Oil debris monitoring using particle count devices has also been shown to be effective. The existence of particles larger than 200  $\mu\text{m}$  in the gearbox oil can indicate bearing spall or gear pitting at an early stage [84]. The main disadvantages of this method are cost and installation of the sensor, which is intrusive. To install such a sensor the WT must shut down so that the sensor can be placed within the oil pipe between the gearbox and the cooling system.

#### 4.3. CM OF BRAKE SYSTEM

It is vital that wind turbines stop their operation when a failure of a critical component occurs or at wind speeds greater than their rated limits [85, 5]. There are three main types of braking system: aerodynamic, mechanical and electrical. Aerodynamic braking, feathering or blade tips, and electrical braking (using the generator) if available, are mainly applied to reduce the speed, and then the mechanical brake is used to stop the turbine [86]. Entezami M. et al. [5] introduced a new technique to monitor the turbine blade tips using speed measurements of the high-speed shaft. Entezami. et al. also states that the wear of the discs can be monitored by measuring the speed of the shaft when the brakes are applied. In wind turbines, a hydraulic power unit provides an active hydraulic pressure to keep the wind turbine brakes disengaged [85].

The active hydraulic pressure is maintained by a hydraulic system that is driven by a three-phase induction motor. Induction motors can be monitored using different techniques such as MCSA and vibration. In addition to this, the hydraulic pressure can also be monitored. However, this is an intrusive technique and similar results can be achieved using the other methods.

Mechanical braking is performed using friction between the pads and the disc. This is a large force which is applied on both sides and the temperature of this friction can rise up to 700  $^{\circ}\text{C}$  [85, 87]. Temperature sensors can be used to prevent overheating of the pads and disc by disengaging and engaging the callipers when the temperatures exceed the threshold [88, 89].

#### 4.4. CM OF YAW SYSTEM

A yaw system turns the nacelle so that the rotors face the wind. This allows the WT to achieve the highest amount of energy by facing the direction of the wind. The yaw system consists of yaw drives, yaw brakes and a yaw bearing. The yaw drive has an electric motor, gears and a shaft pinion engaged with a ring gear on the yaw bearing. The yaw brakes are mounted between the nacelle flange and the yaw bearing [90]. According to the authors' knowledge there is no existing condition monitoring system for the yaw.

### 5. CONDITION MONITORING OF A WT STRUCTURE

In recent years, due to the higher demand for clean energy and developments in the wind turbine industry, wind turbine structures have been getting bigger and are often exposed to more challenging environments with higher wind loads. This increases the chances of possible failures happening and makes monitoring of the structure a more challenging task due to the increased heights and rough locations such as mountainous or distant sea regions. After the installation of the wind turbine structures, it is necessary to ensure their functionality and safety during operation. Condition monitoring of the structural components of WTs, known as structural health monitoring, presumes different sets of measurements for successful maintenance of the blades, tower and foundation in the operational phase. Traditionally, defects on the structure can be detected using various methods such as visual inspections, acoustic, ultrasonic and many other non-destructive methods. However, all of these methods require planned site visits and allow only local inspection. More disadvantages include the amount of time needed for the inspection of the whole structure and difficulties in approaching the structural components. For this reason, current structural health monitoring (SHM) systems that allow more efficient and economic preventive maintenance are predominantly vibration based. Sensors such as accelerometers, displacement transducers, strain-gauges, inclinometers, temperature sensors and anemometers are used to capture the data regarding both the dynamic responses of the structure and the environmental effects.

SHM systems typically consist of system state definition, data acquisition, data filtration, feature extraction, data reduction, pattern recognition and decision making [91]. An example of an implemented SHM system at the wind turbine located in Dortmund, Germany is shown in Figure 6 [92].

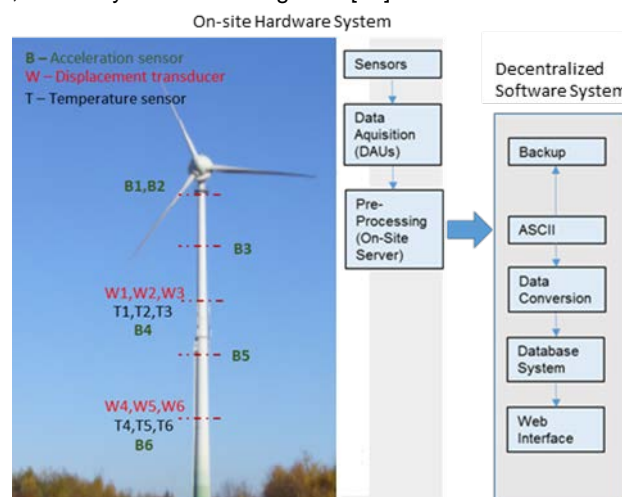




Figure 6: Scheme of SHM system

Generally, there are two main types of monitoring strategies, which are prescriptive based inspection (PBI) and risk based inspection (RBI) [93]. In the first case, inspection is done according to a predetermined schedule. All the structural points that are considered to be hot spots, where faults and deteriorations are most likely to occur, are investigated. Advantages of this strategy include reliability and planned maintenance where all the components of interest are investigated. The disadvantages include possible unnecessary inspection of certain structural components, which can cause unnecessary costs and can be overly time consuming. Additionally, serious damage can occur between inspection appointments, which leads to unnecessary costs and repairs.

On the other hand, a risk based monitoring strategy is based on the prediction of possible deterioration and faults occurring by means of risk and structural reliability analysis, as shown in Figure 7 [94]. The faults are usually predicted by tracking the changes in vibration responses, modal parameters of the structure and by setting alarms for when thresholds for predetermined parameters are crossed.

The main advantage of this method is that the inspection and the repair are done only if required, which classifies this approach as a low cost maintenance strategy. This is especially beneficial for off-shore wind farms, where a site visit requires much more time and resources. The drawback of this method is the possibility of sudden unpredicted events (unexpected scenarios that are not taken into account during the analysis) or even technical failures in the SHM system. More information on these strategies can be found in [93, 94].

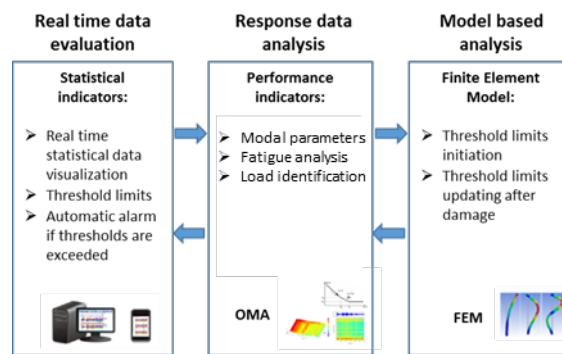


Figure 7: RBI data evaluation strategy after [94]

### 5.1. HOT SPOTS AND DAMAGE SCENARIOS

Damage of different structural components, rotor blades, tower or foundations can occur, depending on the circumstances, but a report that summarises the wind turbine accident data to 30 Sept 2017 [95] shows that the most common type of failure is blade related failure, followed by fire and structural failure. structural failure does not only include the complete collapse of the structure or the structural components, but it also consists of all the changes in the system, such as cracks, bolts loosening, scouring etc. these changes are more likely to lead to variations in the boundary conditions, resulting in changes in the expected behaviour of the structure.

The locations on the structure where the damage is most likely to occur are referred to as hot spots. These locations are the most suitable for optimum sensor placement in order to catch the change and damage at an early phase. For the rotor blades, these locations are considered to be at 30–35% and 70% along the length of the blade from the root section [91].

Tower structures, made out of steel or concrete, are transported in smaller sections to ease the installation demands, and are assembled from parts, which are connected over welded flanges with pre-tensioned bolts. Hot spots on the tower include the sections with stress accumulation such as openings and most importantly sections near the connections between tower substructures, where loosening of the pre-tensioned bolted connections along the flanges can occur, along with failure of the welds.

In the case of off-shore wind turbines, hot spots also include the transition piece, such as grouted connections between tower and foundation structure. Another failure scenario is change in the foundation of the structure due to scouring of the sea bed, which leads to changes in boundary conditions and can influence the natural frequencies and overall behaviour of the structure [94].

### 5.2. OPTIMUM SENSOR PLACEMENT

Strategic placement of sensors, along with the application of a global structural health monitoring strategy based on a risk based inspection approach, can significantly reduce maintenance costs and the number of unnecessary site inspections. As previously mentioned, the best positions for sensor placement are the hot spots where damage is most likely to occur, but for the future developments in SHM it is desirable to position sensors in such way that accurate extrapolation of modal parameters, such as natural frequencies and mode shapes is possible. Many new strategies rely on tracking the changes in dynamic structural parameters, based on which different damage scenarios are developed using numerical simulation software and later recognized in case of their occurrence. The most commonly used sensors for SHM are accelerometers, displacement transducers, strain gauges, temperature sensors, and in the case of offshore wind turbines, inclinometers.

Accelerometers measure the vibrations of the structure and are used for modal investigation in output-only or ambient techniques, such as operational modal analysis. They are used to obtain natural frequencies, mode shapes and damping. Tracking the changes in modal parameters, such as lower natural frequency or higher

damping indicates the existing damage in the structure. Accelerometers must be combined with temperature sensors for the temperature effect compensation.

Displacement transducers and strain gauges measure relative displacements of the tower based on the local referent system, and are used to monitor the strain history. This information can be used for stress and fatigue analysis and residual life time estimation. Figure 8 shows displacement time histories from displacement transducers (W1-W6) placed at two sections at a wind turbine in Dortmund, Germany. They are accompanied by temperature sensors (T1-T6) for temperature effect compensation.

In order to develop more advanced structural fatigue and lifetime assessments of WECs, authors would like to propose additional load identification, since the wind force is generally not being measured. A new wind load identification model is currently being developed by the authors, which is based on the response analysis for the inverse wind load reconstruction.

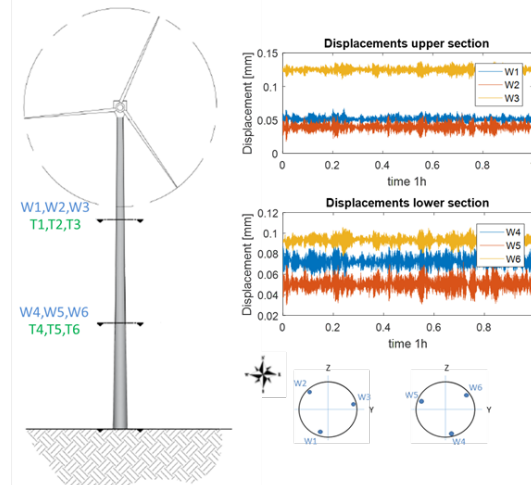


Figure 8: Time histories of displacements

Nowadays, due to the costs and risk factors of corrective maintenance, structural health monitoring systems are regularly being implemented. A detailed overview of condition monitoring and structural health monitoring strategies can be found in [96]. The trend in recent years has seen a transition from scheduled maintenance to risk based global monitoring of the structure, which is based on monitoring of dynamic structural characteristics and real time evaluation of measured data. The objectives and benefits of risk based SHM include:

- Early identification of structural damage and reduced maintenance cost
- More accurate life time prediction
- Planning of maintenance measures
- Continuous monitoring and database update
- Reduced down time of the structure
- Improving the design phase

The disadvantages of risk based SHM include the risk of sudden unexpected events happening and the existence of uncertainties in parametric structural investigation, which can lead to unpredicted damage. Nevertheless, a well-studied structural model with good knowledge on possible damage scenarios and structural dynamics and can benefit the global monitoring systems and lower the unwanted uncertainties.

## 6. COMPARISON AND SUMMARY

Fault diagnosis and failure detection are critical to develop an effective CM method for WTs, are crucial. Each type of WT has the potential to encounter different failure mechanisms, as shown in Figure 9, each of which requires specific monitoring techniques.

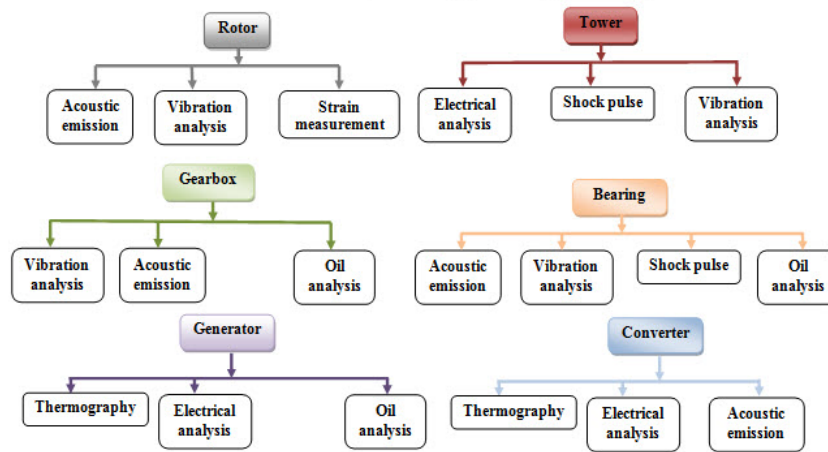


Figure 9: CM methods for WTs

Table 1 shows different failure mechanisms as reported in [97]. Electrical drive systems are categorised to three main parts, i.e. generator, DC-link and power electronic converters. Statistically, most failure mechanisms of generators are bar cracking and damage of the winding; these failures are mainly caused by thermal stress. Temperature stress is also distinguished as the main failure mechanism of power electronic converters. The mechanical drive train consists of gearbox, bearings, yaw systems and brake systems. Most root causes of failure mechanisms in mechanical parts are vibrations and thermal stress.

Table 1. Potential failures of WTs

Drive Train			Electrical system			Generator
Main shaft bearing	Mechanical brake	Gearbox	Control system	Power electronics	DC-link	
Wearing, Vibration	Locking position	Wearing, fatigue	Short circuit,	Short circuit, Bond wire lift-off, Solder fatigue, Thermal grease, Aging, Thermal and Electrical over-stresses	Electrolyte solution evaporation, Thermal and Electrical over-stresses	Wearing, Electrical problems, Bar cracking, Over speed, Overheating, Rotor asymmetries, Winding damage,

## 7. CONCLUSIONS AND FUTURE WORK

The main topologies of the electrical drive systems of wind turbines, including condition monitoring systems proposed in the technical literature, were reviewed in this paper. Most of the methods for the condition monitoring of electrical and mechanical components are based on the real-time evaluation of electrical parameters. Although the variation of wind speed and wind turbulence may have a significant effect on the health of these components literature suggests that this topic have received little attention and through investigation is needed. Accounting for wind fluctuation can be achieved by using an artificial intelligence based condition monitoring system. Artificial intelligence can provide a suitable method to discover not only the relations between different causes of faults but also to evaluate the health status of the components themselves. Due to the complexity of the phenomena involved, an artificial intelligence based control algorithm needs to be developed to infer the data from the sensors with sufficient accuracy and reliability. The authors believe that a dedicated fuzzy controller can also provide a definition of the health status for the electrical drive train components during the operation of wind turbines. A variety of techniques were introduced for the CM of rotary parts such as bearings and gearboxes. It was shown that AE techniques can provide accurate results, but vibration and MSCA can also be sufficient for the same tasks. An appropriate method can, therefore, be used according to the cost and the importance of the asset. Additionally, the transition from scheduled maintenance to risk based global monitoring of the structure was discussed. The proposed strategy relies on the risk and structural reliability analysis.

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