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A Survey on Wind Turbine Condition Monitoring and Fault Diagnosis–Part I: Components and Subsystems

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A Survey on Wind Turbine Condition Monitoring and Fault Diagnosis−Part I: Components and Subsystems

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***Abstract*--This paper provides a comprehensive survey on the state-of-the-art condition monitoring and fault diagnostic technologies for wind turbines. The Part I of this survey briefly reviews the existing literature surveys on the subject, discusses the common failure modes in the major wind turbine components and subsystems, briefly reviews the condition monitoring and fault diagnostic techniques for these components and subsystems, and specifically discusses the issues of condition monitoring and fault diagnosis for offshore wind turbines.**

***Index Terms*—Condition monitoring, fault diagnosis, survey, wind turbine (WT)**

I. Introduction

A. Background and Definitions

Compared to steam/hydro/gas turbines used in traditional power plants, wind turbines (WTs) are usually operated in harsher environment and, therefore, have relatively higher failure rates. The faults in WTs can be classified into two categories: wear-out failures and temporary random faults. Wear-out failures are long-term and permanent events. Repairing or replacing a failed component needs additional costs and results in a loss of energy production. If a failed component is not identified and repaired or replaced in time, it may cause consequent failures of other components and even the entire WT system. Temporary random faults are short-term, temporary events caused by factors such as wind speed fluctuation, thermal issue, grid disturbances, temporary wrong sensor readings, etc. Temporary random faults can usually be cleared by temporarily shutting down and restarting the components with faults or the WTs. Therefore, their impact is primarily a loss of energy production.

Condition monitoring is a process of monitoring the operating parameters of a physical system. From the change(s) in the parameter(s), possible failure(s) in the system can be diagnosed and prognosed. A WT condition monitoring system (CMS) provides diagnostic information on the health condition of various WT components and subsystems and, therefore, allows maintenance to be scheduled and taken before a failure or a critical malfunction occurs. The condition monitoring techniques fall into two broad categories: offline condition monitoring and online condition monitoring. Offline condition monitoring requires the WTs to be taken out of service to allow inspection by maintenance personnel. Online condition monitoring offers several advantages over offline condition monitoring. First, online condition monitoring is performed while the WTs are in service. This reduces the loss of energy production and the costs incurred during offline inspection for the WTs. Second, online condition monitoring provides a deeper insight into the conditions of WT components and subsystems during operation and can alert the maintenance personnel to both long-term trends and short-term events that may not be observed with an offline "spot check." Third, online condition monitoring can be integrated into the supervisory control and data acquisition (SCADA) system to automatically trigger appropriate alarms and alert maintenance personnel when a problem occurs. This feature is essential for unattended WT operation, especially in remote or inaccessible locations.

Using the information obtained from the condition monitoring process, fault diagnosis can be performed to detect, locate, and identify occurring faults and monitor the development of the faults from defects (i.e., incipient faults) into failures; and prognosis can be performed to predict the development of a defect into a failure, when the failure occurs, and the remaining useful life of the WT component with the defect. Fault diagnosis and prognosis are important extensions of condition monitoring. Based on the diagnostic and prognostic information, the appropriate (e.g., preventive and optimal) maintenance strategy can be taken to minimize the maintenance cost, reduce WT downtime, and improve WT reliability and lifespan.

The majority of the related literature and commercial WT CMSs have focused on WT condition monitoring and fault diagnosis (CMFD). Much less work has been reported on WT fault prognosis. Therefore, this survey focuses on WT CMFD, but also covers WT fault prognosis in various sections.

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B. Existing Literature Surveys

There have been several literature surveys on WT CMFD [1]-[5]. Verbruggen conducted a survey [1] on condition monitoring for WTs in Europe from the prospective of the signals used and WT components being monitored. However, the survey only investigated the WTs manufactured by Lagerwey and Enron and discussed neither failure modes of each WT component nor signal processing techniques for CMFD. Moreover, the survey was conducted in 2000. Since then the CMFD techniques have been greatly advanced.

Drewry and Georgiou's survey [2] focused on nondestructive testing (NDT) techniques for WTs. The NDT represents a group of techniques used in industries, such as ultrasonic scanning, infrared thermography, and X-ray inspection, to monitor the structures of materials, components or systems without causing damage to them. The survey mainly focused on the NDT techniques applicable to CMFD of WT blades, but did not discuss what blade failure modes or how they could be diagnosed by the NDT techniques.

Amirat et al.'s survey [3] focused on the CMFD techniques for some major components of the WTs equipped with doubly-fed induction generators (DFIGs), such as generator, blade, gear, and bearing. The survey also discussed the signals, such as vibration and electrical signals, used for CMFD of these components based on simple statistical analysis for the signals. However, it is not a comprehensive survey. Many important subsystems and components with high failure rates and/or downtime, such as sensors, control subsystem, and mechanical brake, were not discussed at all, and neither were the failure modes of the components discussed. In addition, there was little discussion on the signal processing techniques for WT CMFD.

The survey of Hameed et al. [4] first discussed the signals available for WT CMFD, and then reviewed the signal processing techniques for CMFD of various WT components. However, the survey did not compare different signal processing techniques or discuss their capabilities and limitations for WT CMFD. In addition, the survey did not sufficiently discuss the failure modes of different WT components. Furthermore, some important WT subsystems, e.g., hydraulic system, mechanical brake, control system, and sensors, were missing in the survey.

Lu et al. [5] briefly surveyed CMFD techniques for major subsystems in WTs reported from 2006 to 2009, including gearbox, bearing, generator, power electronics, electric control, rotor, blade, and hydraulic control. The survey briefly discussed advances and challenges of the CMFD techniques. However, it is not a comprehensive survey. For example, it did not discuss the failure modes of each WT subsystem. Moreover, the survey did not provide a complete review on the signals and signal processing techniques used for WT CMFD. For example, temperature monitoring is commonly used for CMFD of gearbox, but was not discussed in the survey.

C. Overview of the Survey

This paper provides a comprehensive survey on CMFD for horizontal-axis WTs, which are complex systems consisting of many components and subsystems. In order to design a WT CMFD system, it is important to have the knowledge of the failure modes in various WT components and subsystems and their characteristics. Therefore, the Part I of this survey will focus on failure modes and CMFD of major WT components and subsystems. Moreover, since the operation and maintenance (O&M) for offshore WTs is more difficult and expensive than their onshore counterparts, the issues of CMFD for offshore WTs will also be discussed in the Part I of this survey.

Compared to existing literature surveys, the contribution of this survey is that it provides the most comprehensive, up-to-date information on the most critical issues of WT CMFD. Specifically, the Part I of this survey discusses the failure modes and their characteristics in almost all WT subsystems; while this part was missing in almost all existing surveys. The Part II of this survey discusses almost all of the signals used for WT CMFD and compares the functions, capabilities and limitations of these signals as well as major signal processing methods that have been applied or studied for WT CMFD. None of the existing surveys has provided such a complete review and comparison on signals and signal processing methods for WT CMFD.

II. Wind Turbine Classification

Table I lists the configurations, operating and control principles, and gird connection methods of most existing medium- and large-size WTs. Based on a combination of these features, WTs are commonly classified into four different types, which require different CMFD and maintenance strategies. For example, for Type 1, Type 2 and Type 3 WTs, gearbox is an important component and much attention should be paid on CMFD of gearboxes. While for Type 4 WTs, CMFD of power electronics is highly important.

Based on the failure data collected in Germany and Denmark [6], it was found that direct-drive WTs (i.e., no gearbox) might achieve a higher availability than indirect-drive WTs (i.e., with a gearbox). However, direct-drive WTs do not have a lower failure rate than indirect-drive WTs. For

TABLE I
MEDIUM- AND LARGE-SIZE WT CLASSIFICATIONS BASED ON RESPECTIVE CONFIGURATIONS AND CHARACTERISTICS.

Type	Rotating Speed	Blade Control	Drivetrain	Generator	Grid Connection
Type 1	Fixed speed	Pitch or stall control	Using a gearbox	Squirrel-cage induction generator	Directly connected
Type 2	Partly variable speed	Pitch or stall control	Using a gearbox	Wound-rotor induction generator	Directly connected
Type 3	Variable speed	Pitch control	Using a gearbox	Wound-rotor induction generator	Through partial-load power converters
Type 4	Variable speed	Pitch control or fixed pitch	No gearbox	Synchronous generator	Through full-load power converters

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example, the total failure rate of the electronic components in direct-drive WTs is 33% higher than that of the gearboxes in indirect-drive WTs. However, based on the data provided by the wind industry, the mean time to repair of electronic subassemblies is about 250 hours per failure, which is shorter than that of gearboxes, which is about 350 hours per failure. Moreover, in large direct-drive WTs, the failure rate of generators is double of that in indirect-drive WTs. The cause of this disparity in failure rates is not known yet and, therefore, needs further investigation.

III. CMFD for WT Components and Subsystems

A WT is a complex electromechanical system consisting of hundreds of components and subsystems, including rotor hub, blades, bearings, shafts, gearbox, generator, power electronics, etc. Fig. 1 shows a typical Type 3 WT. Each component of the WT has its own failure modes and contribution to the downtime of the WT. Fig. 2 shows the annual failure frequencies of major WT subsystems and the average downtime caused by the failures of these subsystems based on two large surveys of onshore WTs in Europe over 13 years [7]. This section surveys the major failure modes in these critical WT subsystems and provides a brief overview on the CMFD techniques for these subsystems and their critical components. Some of the components, e.g., bearing, electric motor, and control system, are used in multiple WT subsystems, such as pitch and yaw subsystems. Thus, each type of these components is surveyed in a separate subsection for all of the subsystems using this type of components.

A. Rotor Hub and Blade

WT power production depends on the interaction between rotor and wind. The rotor of a WT consists of a hub and blades. Possible faults of a WT rotor include rotor asymmetries as well as fatigue, reduced stiffness, crack, increased surface roughness, and deformation of blades, etc. [8], [9]. A rotor asymmetry is usually caused by errors of blade pitch angle (i.e., aerodynamic asymmetry) or rotor (blade) mass imbalance [10], [11]. Fatigue is caused by material aging and varying wind loading experienced by the blades. Long-term fatigue can result in delamination of a blade's glass or carbon fiber-reinforced plastic structure, which will reduce the stiffness of the blade. Long-term fatigue can also cause cracks on the surface or in the internal structure of a blade. Increased surface roughness of a blade is usually caused by pollution, icing, blowholes, exfoliation, etc. Deformation of a blade is usually caused by long-term unbalanced loading and reduced stiffness of the blade.

Fatigue, reduced stiffness, crack, and increased surface roughness of a blade are all related to structure changes in the blade materials and, therefore, can be diagnosed by using signals acquired from acoustic emission (AE) sensors installed on the blade [13], [14]. If these defects develop to certain levels that cause abnormal vibrations of the blades, then they can be diagnosed by using signals acquired from vibration sensors installed on the blades. Moreover, crack, increased surface roughness and deformation of blades and rotor

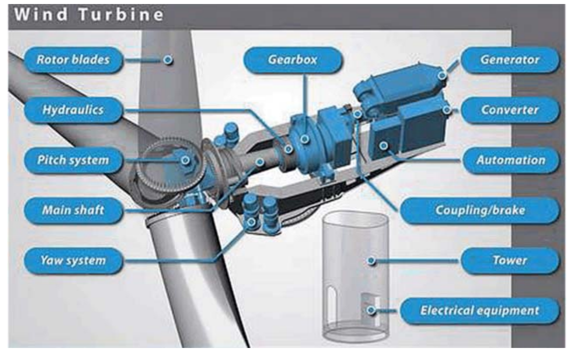

Fig. 1. A typical Type 3 WT with main subsystems shown [12].

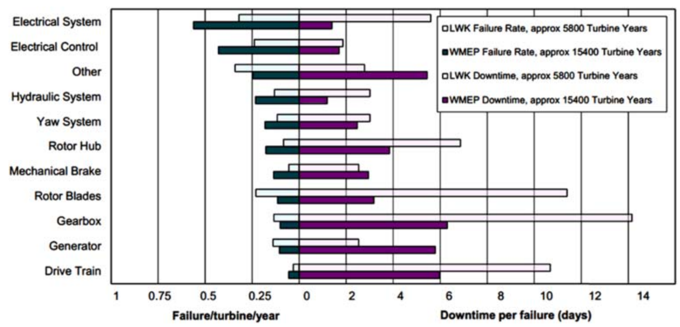

Fig. 2. Failure frequencies of major WT subsystems and downtime caused by failures of these subsystems [7].

asymmetries can excite characteristic frequencies in rotor rotating speed, which will induce vibrations of the main shaft. Such vibrations will modulate the electrical signals acquired from generator terminals owing to electromechanical coupling between the main shaft and the generator [8]. For examples, a rotor asymmetry will cause excitations at the 1P frequency of the power spectral density of the WT shaft rotating speed [8], [9], where 1P frequency stands for the rotating frequency of the WT rotor. Therefore, these faults can be diagnosed by frequency spectrum analysis of rotor rotating speed [9], vibration [8], [15], [16] and AE [16] signals collected from the WT drivetrain and electrical signals acquired from generator terminals [9]. In addition, the failure modes related to material structure changes can be diagnosed by using NDT techniques [2], [16].

B. Gearbox

Gearbox is considered the most troublesome subsystem in WTs as gearbox failures contribute to approximately 20% of the downtime of WTs [17]. The methods used for gearbox condition monitoring are mainly based on vibration monitoring. AE-, current-, and temperature-based condition monitoring techniques are becoming popular as well [18].

Gear and bearing are two main components in a gearbox. Most gearbox failures are caused by gear and bearing failures. Various factors, such as design and material defects, manufacturing and installing errors, misalignment, torque overloads, surface wear, and fatigue, contribute to WT gearbox faults. Most gearbox failures start from bearing faults [19]. The debris produced by a bearing failure will cause the abrasion of other components, such as gears, of the gearbox. Gear failures may also occur independently of bearing

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failures, although not common. The most common gear failures identified by the industry include tooth abrasion due to poor lubrication (commonly seen in planetary gears due to their low rpm) and surface fatigue initiated by the debris generated from bearing failures [19]. Other more severe gear failures include gear or tooth crack, breakage and fracturing.

A gear fault in a WT gearbox usually induces vibrations of the gearbox at certain characteristic frequencies f_{gb}, which will appear in the vibration signals acquired from the vibration sensors installed on the gearbox [20]-[23].

$$f_{gb} = \left\{ f \middle| f = \sum_{i=1}^{I} l_i f_{sh,i} \pm \sum_{j=1}^{J} m_j f_{m,j} \, ; \; l_i, m_j = 0, 1, 2, \cdots \right\} \tag{1}$$

where $f_{sh,i}$ is the rotating frequency of the ith shaft in the gearbox; $f_{m,j}$ is the jth gear meshing frequency; and I and J are the numbers of the shafts and gear pairs in the gearbox, respectively. Similar characteristic frequencies of the fault can be found in AE signals measured by AE sensors installed on the gearbox [24]. In electrical signals, such as current signals measured from the terminals of the generator connected to the gearbox, the characteristic frequencies f_{cc} of the fault are the results of frequency and amplitude modulations of the current signals by the vibrations, given by

$$f_{cc} = \left\{ f \middle| f = k f_s \pm \sum_{i=1}^{I} p_i f_{sh,i} \pm \sum_{j=1}^{J} q_j f_{m,j} \, ; p_i, q_j = 0, 1, 2, \cdots \right\} \tag{2}$$

where f_s is the fundamental frequency and k is a positive integer representing the fundamental and possible harmonics of the current.

Therefore, the methods used for gearbox CMFD are mainly based on vibration monitoring [25]-[27]. AE- [24], [28], and current-based [13], [20]-[23], [29]-[32] condition monitoring techniques are becoming popular as well. All of the effort on diagnosis of gearbox faults was to find the excitations at the characteristic frequencies of the faults in the signals using appropriate frequency analysis methods [18]. A challenge in frequency analysis-based gearbox CMFD is that a healthy gearbox also has many characteristic frequency components in the signals. A fault may induce new characteristic frequencies in the signals or may only change the amplitudes of the existing characteristic frequency components [20]-[23]. The latter cannot be detected by solely using frequency analysis methods and will require additional statistical analysis for the characteristic frequency components [20], [21].

Some gearbox faults cause abnormal temperatures in the gearboxes. For example, a bearing fault may cause an abnormal increase of the bearing temperature and the lubrication oil temperature. Therefore, the temperatures measured from bearings, lubrication oil, etc. in WT gearboxes have also been used for gearbox CMFD [33]. Moreover, the gearbox faults which generate debris may cause changes of some parameters (e.g., viscosity, particle counting, etc.) of the lubrication oil used in the gearbox. These faults can be diagnosed by monitoring the oil parameters. It was also reported using statistical analysis of the temperature trend and lubrication oil parameters for diagnosis of gear faults [34].

C. Bearing

Bearings are used in various WT components and subsystems, e.g., rotor, main shaft, gearbox, generator, pitch system, and yaw system. The most commonly used bearings in WTs are ball bearings. However, the trend is moving toward roller bearings [18].

Bearing faults usually appear as wear or surface roughness of certain parts initially, which then develop into some major failure modes, such as fatigue, crack, or breakage of the outer race, inner race, ball, or cage. These faults induce different characteristic vibration frequencies of the bearings, which are one group of the primary vibration frequencies in faulty WTs [35], [36] given by [31]:

$$f_o = 0.5 \cdot N \cdot f_r \cdot \left(1 - \frac{D_b \cdot cos\theta}{D_p}\right) \tag{3}$$

$$f_i = 0.5 \cdot N \cdot f_r \cdot \left(1 + \frac{D_b \cdot cos\theta}{D_p}\right) \tag{4}$$

$$f_b = 0.5 \cdot \frac{D_p}{D_b} \cdot f_r \cdot \left[1 - \left(\frac{D_b \cdot cos\theta}{D_p}\right)^2\right] \tag{5}$$

$$f_c = 0.5 \cdot f_r \cdot \left(1 - \frac{D_b \cdot cos\theta}{D_p}\right) \tag{6}$$

where f_o, f_i, f_b and f_c are the characteristic frequencies of the outer race, inner race, ball and cage faults, respectively; f_r is the rotational frequency of the bearing; N is the number of balls; D_b and D_p are the ball diameter and ball pitch diameter, respectively; and θ is the ball contact angle with the races.

Similar to gearbox faults, bearing faults were commonly diagnosed using vibration signals [30], [31], [35], [37], [38]. AE signals have also been used for CMFD of bearings [39]. Recently, electrical signal-based CMFD methods are gaining more attention [15], [29]-[31], [38], [40]. Different from gear faults, bearing faults induce new characteristic frequencies in the signals and, therefore, can be diagnosed by appropriate frequency analysis methods applied to the signals [29]-[31], [39], [40]. Bearing faults may lead to catastrophic failures of other components in a WT subsystem. For example, most gearbox failures start from bearing faults [19]. Therefore, it is always valuable to detect a bearing fault at an early stage. However, a major challenge for diagnosis of incipient bearing faults is that they may not have any characteristic frequencies [41] or have low SNRs in the signals. Advanced signal processing is required to solve this challenge. In addition, if a bearing is lubricated with oil, bearing faults can also be diagnosed by monitoring some oil parameters [42].

D. Main Shaft

The failure modes of the main shaft in a WT include corrosion, crack, misalignment [43], [44], coupling failure, etc. The faults will affect the rotation of the shaft and other rotating subsystems connected to the shaft. This will affect the torque transmitted in the drivetrain and may excite vibrations in the rotor, gearbox and generator at certain characteristic

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frequencies [37], [45]. For example, a shaft misalignment fault was found to affect the magnitude of the fundamental frequency of the vibration of the rotor, gearbox, and generator [37], [45]. Thus, shaft faults can be detected by analyzing torque, vibration and electrical signals [43] using frequency analysis techniques, such as fast Fourier transform (FFT).

E. Hydraulic System

A hydraulic system is widely used in the WT blade pitch, yaw, and mechanical brake subsystems to delivery hydraulic power to the drive motors to adjust the blade pitch angle [46] and the yaw position to maximize wind power generation and to control the mechanical brake to ensure WT safety [47], respectively. The hydraulic system suffers various faults, such as oil leakage and sliding valve blockage [48]. These faults can be diagnosed by using signals acquired from pressure and level sensors. If the values of the signals are abnormal, it indicates a fault in the hydraulic system.

F. Mechanical Brake

A mechanical brake is usually mounted on the high-speed shaft of a WT to prevent over-speed of the rotor and stop the WT in the case of failures of critical components. A mechanical brake is also used in the WT yaw subsystem to stabilize the yaw bearing. A mechanical brake typically consists of three main sections: a disc and calipers, a hydraulic mechanism to drive the calipers, and a three-phase AC motor to power the hydraulic mechanism, as illustrated in Fig. 3 [49]. Since the brake usually experiences extreme mechanical stresses, the disc is subject to cracks and failures caused by overheating, while both the disc and the calipers suffer from over-wearing. These faults can be diagnosed by vibration and temperature monitoring. However, little work has been reported on CMFD of disc or calipers. Other failures related to the hydraulic section and the AC motor are discussed in other subsections. The electrical signals, such as voltage and current, acquired from the AC motor terminals could also be used for fault diagnosis of the hydraulic section and the motor itself [49]. Faults in the mechanical brake are of particularly concern because they can result in a catastrophic failure of the WT. Therefore, more research is needed on CMFD for mechanical brakes.

G. Tower

The faults in the tower of a WT are mainly related to structure damages, such as corrosion and crack. These faults can be caused by factors such as a poor quality control during the manufacturing process, improper installation, loading, harsh environment (e.g., lighting and storm), and fire. Analyzing the vibration of a tower in the time [50] and frequency [51] domains can reveal its health condition.

H. Electric Machine (Generator and Motor)

The generators used in WTs can be classified into several types, as listed in Table I. Moreover, electric motors are used in pitch, yaw, and mechanical brake subsystems. The failure modes in electric generators and motors can be classified as electrical faults (e.g., stator or rotor insulation damage or open circuit and electrical imbalance) and mechanical faults (e.g., broken rotor bar, bearing failure, bent shaft, air gap eccentricity, and rotor mass imbalance). Several papers [38], [52]-[55] have surveyed the CMFD techniques for electric generators and motors used in various industries. Many of the existing techniques can be adopted for CMFD of the electric machines in WTs [3], although little work has been reported specifically on CMFD of the electric machines used in WTs.

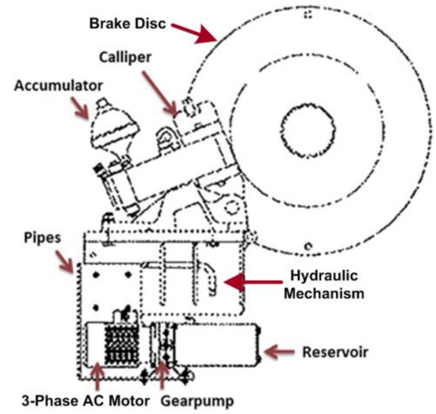

Fig. 3. Configuration of a typical WT mechanical brake [49].

Winding faults, such as short circuits of coils and inter-turn faults, are one of the most common failure modes in the induction machines used in WTs [56]. Asymmetry is usually present in the magnetic field during a winding fault [28]. In this case, the faults can be diagnosed by monitoring their characteristic frequencies f_w described by (7) in the electrical signals acquired from the electric machine terminals using appropriate frequency and time-frequency analysis techniques.

$$f_w = \left\{ f \middle| f = \frac{\left[k \pm \frac{n(1-s)}{p}\right]}{f_s};\ k = 1, 3;\ n = 1, 2, \ldots, (2p-1) \right\} \quad (7)$$

where p is the number of pole pairs; f_s is the fundamental frequency; and s is the slip. The faults can also be detected by using torque measurements, shaft displacement, and gearbox or electric machine vibration. Winding faults will also cause an increase in the winding temperature [57]. Stator open-circuit faults will change the spectra of stator line currents and instantaneous power. Experimental results showed that the spectrum of the instantaneous power carried more fault-related information than the stator line currents [58].

Electrical imbalance is another major failure mode in electric machines. Rotor electrical imbalance will cause shaft vibration. Thus, shaft displacement can be an indicator of the fault [45]. Similarly, stator electrical imbalance will cause changes in the current and power output of the electric machine [56]. Stator electrical imbalance can be detected from the variations of the harmonic contents of electrical signals. Usually the fault-related information is contained in rotor and stator line currents.

The broken rotor bar fault is considered critical in squire-cage induction machines as it is hardly to be repaired. The current practice of detecting a broken rotor bar fault is to use

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spectrum analysis of machine stator current signals. In the spectrum analysis, the sideband components f_b around the fundamental frequency of a stator current are considered the characteristic frequencies of the fault, as described by (8).

$$f_b = \{f | f = (1 \pm 2ks) f_s\ ;\ k = 1, 2, 3, \cdots\} \tag{8}$$

Other mechanical faults in electric machines can also be detected by using electrical signals. For example, similar to electrical imbalance, rotor mass imbalance also exhibited characteristic frequencies in electrical signals. Moreover, it was reported that bearing failures in electric machines would change the amplitude and phase spectra of the power output [15], [37] and rise the winding temperature of the generator [28]. In addition, it is also common to use vibration monitoring to diagnose mechanical faults.

I. Power Electronic Converter

As the power rating of the WT increases, the reliability of the power electronic subsystem becomes more critical. According to the statistical data in [45], the most frequent faults in WTs are failures of the electronic subsystem, which account for 25% of total failures in WTs. It was reported [6] that the power converters in larger-capacity WTs would have a higher failure frequency. The downtime caused by failures of the electronic subsystem constitutes approximately 14% of the total WT downtime [18]. Research revealed that the proportion of the maintenance cost for power electronics is high, especially for offshore WTs, where the operational environment is harsher than that of onshore WTs.

The failure rate distribution of different components in power converters is shown in Fig. 4 [59], where capacitors, printed circuit boards (PCBs), and power semiconductors (e.g., insulated-gate bipolar transistor (IGBT) modules) are the three main reliability-critical components. The failures in power electronic converters are directly or indirectly caused by three major factors, i.e., temperature, vibration and humidity, where temperature is the most dominant stressor [60]. The failure modes of capacitors include excessive leakage and shorts, dielectric breakdown, electrode materials migrating across the dielectric forming conductive paths, leads separated from a capacitor, increased dissipation factor, etc. The failure modes of PCBs include broken buried metal lines, defect of vias, corrosion or crack of traces, board delamination, component misalignment, electrical leaks, cold-solder joints, etc. The failure modes of IGBT modules include chip-related failures (e.g., short circuit and gate misfiring), packing-related failures (e.g., bond wire liftoff and solder fatigue and crack), and gate driver open-circuit fault [61], [62]. The most frequently observed failure modes in IGBT modules are packing-related failures caused by thermomechanical fatigue stresses experienced by the packaging materials.

It has been proposed to use thermo-sensitive electrical parameters, such as the collector-emitter saturation voltage $V_{CE(sat)}$, on-state resistance, gate-emitter threshold voltage, and internal thermal resistance R_{th}, to monitor the degradation of IGBT modules [61]. For example, a commonly used criterion to indicate the failure of an IGBT module is 20% increase in

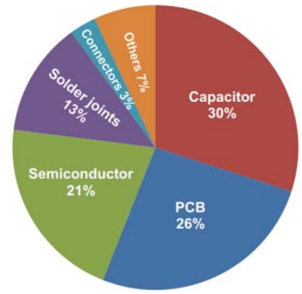

Fig. 4. Failure rate distribution of different components in power electronic converters [59].

$V_{CE(sat)}$ or R_{th}. However, it is difficult or not cost-effective to measure these parameters accurately in real time for online CMFD of IGBTs. In current WT CMSs, some operating parameters, such as terminal voltages and currents, ambient and coolant temperatures, etc., of power electronic converters are monitored. A fault in a power converter was identified mainly through the comparison of the reference and actual measured values of these parameters or using model-based techniques [63]-[65]. However, it is difficult to use these signals and techniques to locate the faults or identify the failure modes, because different failure modes may lead to similar patterns in the signals and model output. Moreover, since many faults can only be detected when they have developed to certain levels of severity, it is challenge to detect incipient faults or monitor the development of the faults in power converters.

J. Sensors

A variety of sensors, such as anemometers, accelerometers, encoders or resolvers, particle counters, temperature sensors, AE sensors, oil level, voltage, current and torque transducers, and humidity sensors, are installed in WTs for condition monitoring and control of the WTs. Sensors are subject to various faults, such as malfunction or physical failure of a sensor, the data processing hardware, or the communication link, or malfunction of the data processing or communication software, etc. According to statistical data reported in [17], sensor failures constitute more than 14% of failures in WTs. A sensor failure may further cause performance degradation of the WT, failure of WT control, mechanical and electrical subsystems, or even shutdown of the WT.

Sensor faults could be diagnosed by a variety of methods [65]-[68], e.g., comparison between the measured signal and the signal estimated using data acquired from other sensors, anomaly analysis on the time series of the measured signal, and model-based methods. For example, in [69], the rotor position of a DFIG was measured by using a position sensor and estimated from the rotor currents of the DFIG. The measured and estimated rotor positions were used by an observer (i.e., a model) to estimate the rotor speed. If the rotor speed obtained from the measured position deviates from that obtained from the estimated position and the latter speed has no sudden change, it indicates a fault in the rotor position sensor. In [70], the mean and standard deviation of the rotor speed signal measured by an encoder in an induction motor drive was used to detect encoder faults. That work showed

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that a drastic change in the average rotor speed over a period much shorter than the mechanical time constant of the system would indicate a mechanical or electronic breakdown of the encoder; while a substantial change in the moving average standard deviation of the rotor speed were caused by missing encoder pulses. Two methods were proposed in [71] for encoder fault detection of permanent magnet synchronous machines. One method was designed based on the correlation between rotor position and stator current to detect encoder faults from abrupt changes in a stator current signal processed by using the wavelet transform. The other method detected encoder faults according to the residuals of the measured rotor position and speed generated by parity equations. The encoder is healthy if the residuals are zero; otherwise, a fault occurs in the encoder. In [11], encoder faults were detected by a model-based classification method and a model-based residual analysis method.

When a sensor fault occurs, it is often difficult to identify the mode and the cause of the fault. Another challenge is that when there is fault in the sensor readings, it is often difficult to identify whether it is the sensor failure or failure of some other WT component being monitored by the sensor.

K. Control Subsystem

The control subsystem plays a vital role in controlling the operations of other critical WT subsystems, such as rotor blades, gearbox, yaw subsystem, mechanical brake, generator, power converter. The failures in the control subsystem can be classified into two categories: hardware failures and software failures. As shown in Fig. 5, the hardware failure modes include sensor faults, actuator faults, failure of controllers (control board) and communication links, etc. Hardware failures can be diagnosed by analyzing the signals used by the control subsystem or by using model-based methods. The software failure modes include buffer overflow, out of memory, resource leaks, race condition, etc., which usually lead to performance degradation or malfunction of the software and are diagnosed by the diagnosing codes in the software. Many software faults are temporary faults and can be removed by restart the software.

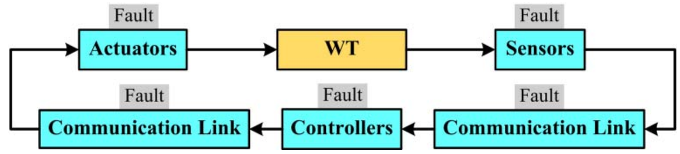

Fig. 5. Hardware failure modes in the control subsystem of a WT.

IV. CMFD FOR OFFSHORE WTS

Based on the installation locations, WTs fall into two categories: onshore and offshore. While the number of onshore WTs has grown dramatically over the last decade, the total available offshore wind power resources are vast and will be able to supply a significant proportion of the electricity demand in an economic manner [72]. Compared to their onshore counterparts, the increased turbine size, improved wind conditions (higher wind speed and lower turbulence), reduced visual and noise intrusion, and locations close to load centers, are the major advantages of offshore WTs [73]. However, the access to offshore WTs is more difficult. In particular, the attendance for maintenance of offshore WTs will be extremely limited during bad weather conditions, e.g., storms, high tides, etc. [74] Possible inaccessibility in certain periods of a year can prevent any maintenance and repair actions for a long time, e.g., several weeks. Therefore, the O&M for offshore WTs is inevitably more difficult and expensive than their onshore counterparts [15], [72]. It was reported by [1], [75] and [76] that the O&M costs for onshore and offshore WTs are in the order of 10-15% and 20-35%, respectively, of the total costs of the generated electricity, where approximately 25-35% is related to preventive maintenance and 65-75% to corrective maintenance. The offshore wind energy industry faces enormous challenges when dealing with O&M.

Despite substantial improvement in recent years, the reliability of current WTs is still inadequate for the harsher offshore environment [74]. The reduced accessibility will dramatically decrease energy harvest in the case of a severe failure. Moreover, the costs of special maintenance personnel and equipment are substantially high. Henderson et al. [72] reviewed the state-of-the-art offshore WT technologies in the last decade and compared the advantages and disadvantages of these technologies. The issue of availability can be addressed through and unplanned maintenance can be reduced by the improvement in offshore WT reliability, from overall system design to individual component design.

Onsite inspection and scheduled maintenance are the current practice in WT O&M. Traditional onsite inspection will become more problematic and cost intensive for offshore WTs [8]. Thus, condition-based maintenance (CBM) is essential to achieve the cost-effective availability targets [45]. Compared to onshore WTs, the economic benefits of CMSs are more substantial for offshore WTs [75]. The need for effective condition monitoring with more precise information about a particular failure mode and an accurate prediction of the mean time to failure becomes even more acute in the offshore environment [15]. CMSs can contribute significantly to reducing the total life cycle costs of offshore WTs. Such a cost reduction is expected to be more significant when WTs are placed in deeper water and harsher environment. A CMS of offshore WTs should provide the following functions [77]: 1) detecting critical changes in WT conditions in time, 2) predicting failure development and when a severe damage will occur, 3) identifying failure modes and locations and analyzing the root causes of failures, and 4) having clear and measurable criteria to determine when maintenance will be needed.

V. SUMMARY AND DISCUSSION

A WT is a complex system consisting of many components and subsystems. This paper has surveyed the common failure modes of the major components and subsystems in WTs and has provided a brief review of the CMFD techniques for these WT components and subsystems. The issues of CMFD for

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offshore WTs have been specifically discussed.

Based on the diagnostic and prognostic information, appropriate condition-based O&M strategies can be developed for WTs. For example, if a fault in a WT is diagnosed at an early stage, the appropriate fault tolerant control action can be taken to minimize the impact of the fault on the operation of the WT. Additionally, if the development of an incipient fault into a failure is predicted via prognostics, the appropriate predictive maintenance strategy can be optimally determined based on the risk and pre-posterior Bayesian decision theory to minimize the maintenance cost and downtime of the WT. Moreover, the reliability-centered maintenance is preferable in the wind industry. Such maintenance is built upon the concept of CBM, but is enhanced by reliability analysis [78], and is commonly called CBM plus (CBM+). Currently, the research on CBM+ has mainly focused on air vehicles [79], ground vehicles [80], and ships [81] in military systems. To the best knowledge of the authors, no work on CBM+ of WTs has been reported yet. Therefore, there is a need of developing CBM+ technologies for the wind industry to further explore and exploit the benefits of CMFD and prognosis.

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