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Chapter 9

Reliability Analysis of Wind Turbines

Caichao Zhu and Yao Li

Additional information is available at the end of the chapter

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Abstract

With the rapid development of wind power industry, the reliability of wind turbines has become a hotspot in wind power research. The failure modes and research progress of wind turbine reliability both at home and abroad are analyzed. The failure modes, failure causes and detection methods of some key components in the wind turbines are summarized. Also, the frequently used methods of reliability analysis and research status of wind turbine reliability are analyzed. Following this, research focuses, methods and measures to improve wind turbine reliability are presented. We also shed light on the condition monitoring and assessment process with condition monitoring system and supervisory control and data acquisition. It is of great significance to reduce the cost of operation and maintenance and to improve the safety of wind turbines.

Keywords: wind turbines, failure modes, reliability analysis, condition monitoring, assessment

1. Introduction

Fossil fuels are nonrenewable and their associated prices are fluctuating sharply. Meanwhile, the increasing environmental and climatic concerns of the current times have moved the research focus from conventional electricity resources to renewable resources [1, 2]. Renewable energy resources, such as wind, solar and geothermal power, are clean alternatives to fossil fuels. Among them, wind energy is one of the most promising renewable energy resources in the world today. The main attractions of wind energy are a large resource and low environmental impact. In this condition, wind energy is developing rapidly. For example, over 51.2 GW of capacity was installed in 2014 [3].

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In recent years, wind power industry has been flourishing all over the world, and in some countries, the focus has been gradually shifted from land-based to offshore wind farms [4]. On a global basis, the size of the annual market grew 42% year-over-year in 2014 compared to a 20% fall in 2013 [3]. By the end of 2014, the cumulative installed capacity climbed to 372 GW [5, 6], which is shown in **Figure 1**. Policy-driven accelerations play a very important role in market growth, especially in China, Germany and the United States. In these three countries, China is the world's largest wind power market with 23.2 GW of new wind power installed in 2014. The development of wind power in China is shown in **Figure 2**. **Figure 3** shows the top 10 countries of newly installed capacity from January to December in 2014 [6]. The total installed capacity is up to 51,473 MW, and the share of China is 45.1%. With more

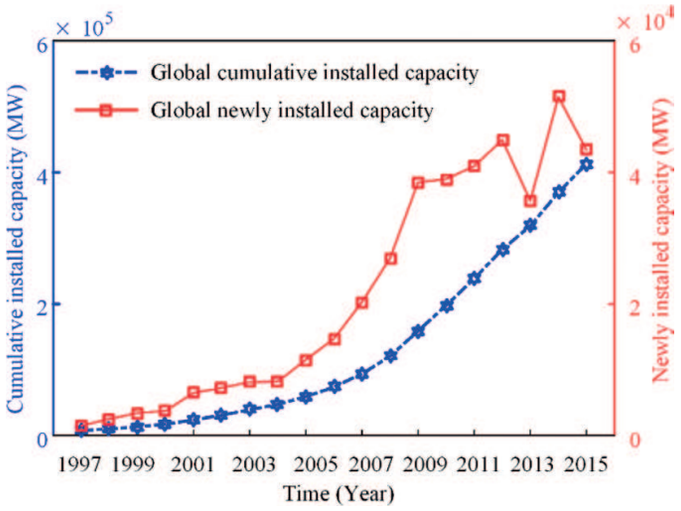


Figure 1. The global wind power capacity.

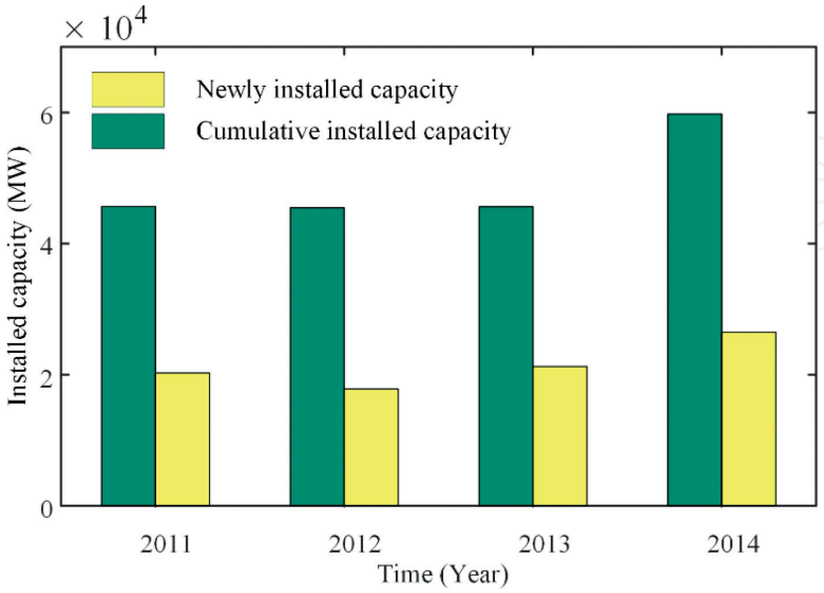


Figure 2. Development of wind power in China.

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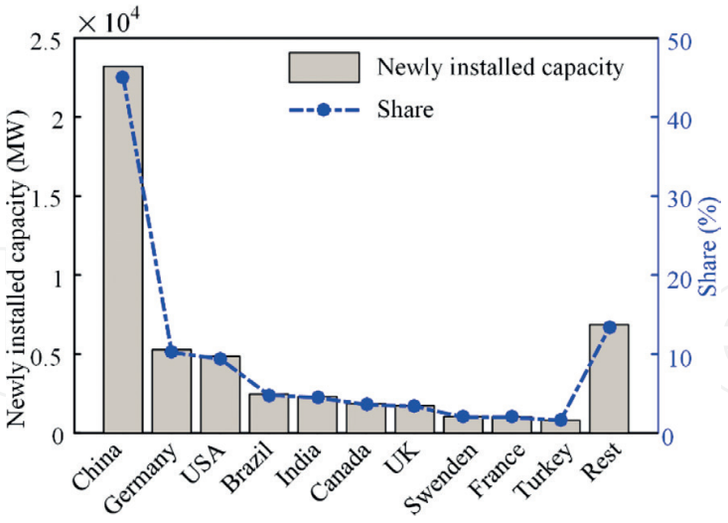


Figure 3. Top 10 newly installed capacity Jan.–Dec. 2014.

and more wind turbines being installed, lots of potential problems still need to be solved, such as fatigue, failures, condition monitoring, operation and maintenance, which are especially true in the current circumstances where the tower height, rotor diameter and overall turbine weights have almost quadrupled in size and capacity [7]. Hence, the reliability of wind turbines is becoming more important now than ever before.

2. Developments and challenges

In the late 1970s, in response to the oil price increasing around that time, a number of government programs were initiated with the objective of developing suitable wind turbines. To reduce the dependence on conventional electricity sources, the related countries carried out many programs and focused on the development of wind turbines, rating up to 4 MW and diameters up to 100 m. Some examples are included in **Table 1**. Furthermore, wind energy has witnessed rapid development in few decades, making it one of the fastest growing sources of electricity in the world today. But it is thought that wind energy is still immature these days. Due to technological advancements, policy initiatives and economic drivers, wind energy is now able to make a cost-competitive contribution to our growing energy needs. For example, over 240,000 commercial-sized wind turbines were operating in the world by 2014, producing 4% of the world's electricity [8, 9]. Wind power showed the potential for replacing natural gas in electricity generation on the cost basis. Technological innovations continue to drive new developments in the application of wind power. Until now, the cumulative installed capacity has been more than 400 GW.

With the growing number of the wind turbines, the industry still needs to face numerous challenges. A number of wind turbine components are prone to failure, and it is difficult and expensive to repair or replace them. For example, bearings, inverters and gearboxes raise the maintenance issues. Still, wind energy challenges still exist due to: (1) poor performance and

Location	Name	Rating (MW)	Diameter (m)	Blades	Date	Features
Canada	Eole	3.6	64	2	1987	Vertical axis, direct drive
Denmark	Tjaereborg	2	61	3	1988	
Germany	Growian	3	100	2	1981	
Germany	Monopteros	0.64	50	1	1989	
Italy	Gamma 60	1.5	60	2	1991	Variable speed, Power control by yaw
Netherlands	Newecs 45	1	45	2	1985	
Spain	AWEC-60	1.2	60	3	1989	Variable speed
Sweden	WTS-3	3	78	2	1982	
UK	LS1	3	60	2	1987	Partial span pitch control
USA	WTS-4	4	78	2	1982	Similar to WTS3 (Sweden)
USA	MOD-5B	3.2	99	2	1987	Variable speed

Table 1. Some of the early prototype machines, mostly funded by governments.

reliability and (2) rising costs driven by transportation, maintenance, and so on. To achieve a longer life of wind turbines and to reduce the cost of maintenance, the development of technologies for improving the reliability of wind turbines is an important consideration for future development, especially for offshore wind turbines. Hence, measures must be taken to improve the reliability of wind turbines.

3. Wind turbine failure modes

Nowadays, the development of wind turbines tends toward larger and heavier structures, which increases the failure frequency. In reality, the failure rates are also very different between onshore and offshore wind turbine systems for the same type. **Figure 4** shows failure rates of wind turbine systems and components [10]. The results in **Figure 4** show that some key components have higher failure rates than that of other components, and the same components working offshore have much higher failure rates than those working onshore.

For a wind turbine transmission system, key components like the generator, gearbox and blades have the highest failure rates. The gearbox failures are mainly caused by gears and bearings; the generator failures are mainly caused by bearings. **Table 2** shows the failure modes, failure causes and detection methods of wind turbine key components and subassemblies.

3.1. Gearbox failure modes

Any key components fail in the gearbox, it may result in high cost of maintenance and high production loss and may take longer time to repair, especially for offshore wind turbines. The

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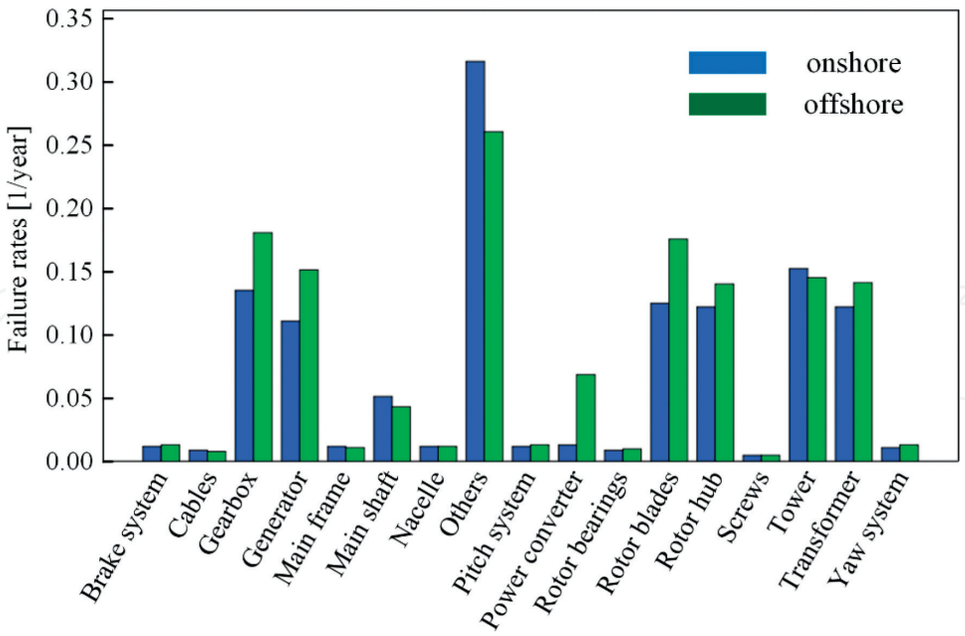


Figure 4. Failure rates for wind turbine subassemblies working onshore and offshore.

regular failure modes of gearbox are bearing failures, gear fatigue, wear, fracture, insufficient lubrication, and so on. **Figure 5** shows three common failure modes of gearbox, in which fatigue failures are the most common. The bolts connecting the front box, ring and middle box sometimes fail because of the strong and unbalanced axial forces acting on the bolts. The bolt failure is shown in **Figure 6**. The result in **Figure 5** shows that the section is smooth, so the failure is caused by fatigue fracture. However, the experiments show that a relief notch, a proper taper of thread and a thread root radius can increase its carrying capacity and reliability.

3.2. Generator failure modes

The generator is one of the most key components with high failure rates since it connects to the high-speed shaft of the wind turbine gearbox with time-varying mechanical torques. Four failure root causes are: design issues, operations issues, maintenance practices and environmental conditions. The failure rates of wind turbine generators have a close relationship with their power rating, working environment, and so on. **Figure 7** shows failure rates of subassemblies of onshore and offshore wind turbine systems. Different failure causes may lead to different generator failure modes, including design issues, operation issues, maintenance and external environment, which is shown in **Table 3**. **Figure 8** shows three common failure modes of the generator where the bearing failure is the most common.

3.3. Rotor blade failure modes

The rotor blades of wind turbine are driven by the wind energy and transform wind energy to mechanical energy. Because blades often suffer alternating stress and complex environments, they have high failure rates, with the main failure modes being fatigue, fracture, crack, wear, freezing and sensor failure. **Figure 9** shows failure modes of the blades. Due to

Objects	Function	Failure mode	Cause	Detection method
Blades	Capture wind	Fracture, edge crack, stuck, motor failure, pitch bearing failure	Fatigue loads higher than anticipated, extreme loads, environment influences, imbalance	Excessive vibration sensed by rotor bearing accelerometer in hub; high stresses recorded by operating instrumentation
Main shaft	Transmit large torque	Fracture	Fatigue loads underestimated; operation of WTG at off-design conditions; material properties below specs	Low-speed sensor; bearing vibration sensor
Yaw system	Enable the nacelle to rotate on the tower	Increased bearing friction	Cracked roller; galled surface; lack of lubrication	Yaw error signal
High-speed shaft	Stop and hold the shaft during shutdown and operation	Low or higher brake torque	Environment effect	Tachometer
Gearbox	Transmit torque with speed increase	Internal gear tooth failure	Fatigue loads underestimated; exceeding design load; improper material; loss of lubricating oil	Vibration sensor
Hub assembly	Transmit torque from blades	Structure failure; bolt failure	Excessing design loads; excessive preload; stress corrosion	Rotor bearing accelerometer; periodic inspection for loose or missing bolts
Oil seals	Retain oil in main bearing housing; exclude foreign matter	Cut or wear in lip	Installation damage; wear	Low oil switch
Filters	To extract and hold all particulate contaminants from hydraulic fluid	Case leakage	Damage to case or seals	Low oil; level switch
Generator	Generate electric power	Overheat; fault; jammed bearing; bearing seizure; overspeed;	Overload; no excitation; environmental effects; misalignment; fatigue; mechanical failure; loss of drivetrain control	Protective relays; overspeed detection; testing
Lubrication	Lubricate gearbox and rotor bearing	Loss of oil; overheating; oil under temperature	Pump failure; leakage; diverting valve failure; ambient temperature above or below design conditions; excessive friction losses; diverting valve failure	Oil flow switch; oil temperature sensor; air temperature

Table 2. Summary of failure modes of components.

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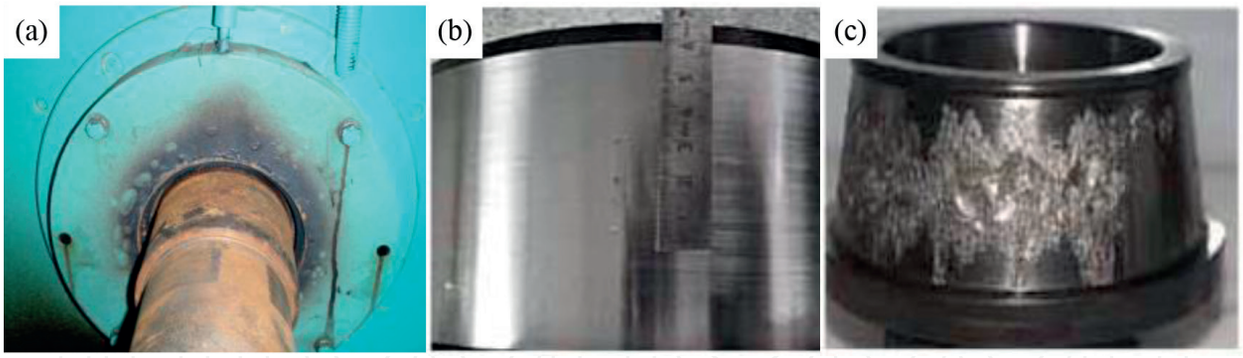


Figure 5. Bearings failure: (a) bearing in gearbox; (b) and (c) failure appearance of bearing.



Figure 6. Bolt faults of wind turbine gearbox.

the high location of rotor blades, they are difficult to repair and maintain which leads to high cost. Hence, in order to produce high-reliability blades, it is important and meaningful to study the relationship among failure modes, reliability and internal/external loads.

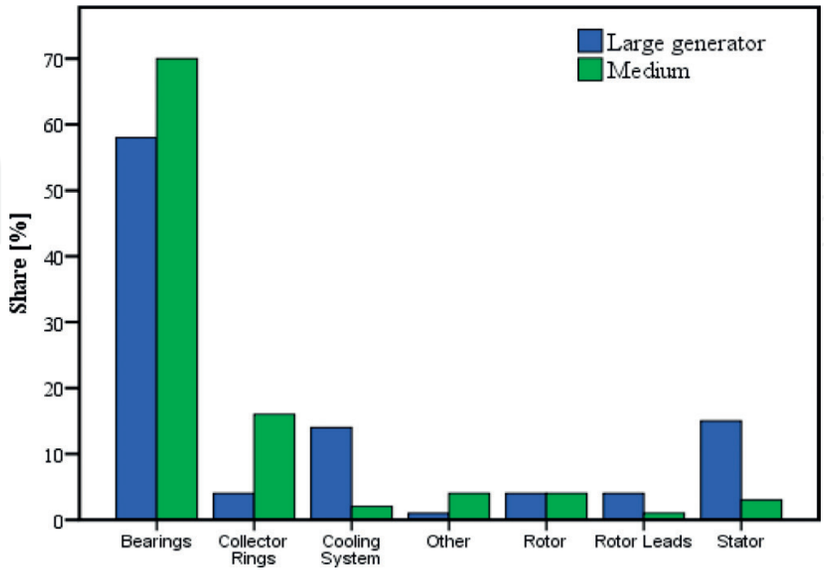


Figure 7. Failure rates of subassemblies of onshore and offshore.

Items	Failure modes
Design issues	(1) Electrical insulation inadequate; (2) loose components (wedges, banding); (3) crimped lead connections; (4) transient shaft voltages; (5) rotor lead failures and (6) complex structure
Operations issues	(1) Improper installation; (2) voltage irregularities; (3) improper grounding; (4) overspeed conditions and (5) transient damage
Maintenance practices	(1) ignoring alignment; (2) cooling system failures leading to heat related failure; (3) bearing failure and (4) rotor lead failures
Environmental condition	(1) Wind leading; (2) thermal cycling; (3) moisture/arid; (4) contamination and (5) electrical storms

Table 3. Failure modes of the generator.

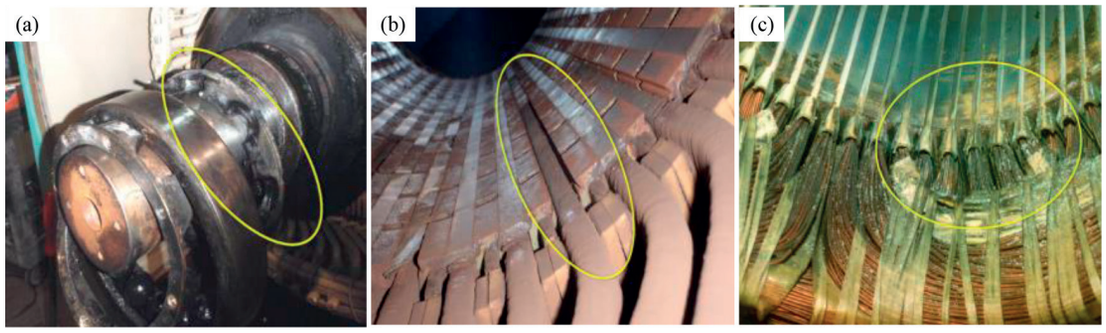


Figure 8. Generator failure: (a) bearing, (b) magnetic wedge loss and (c) contamination.

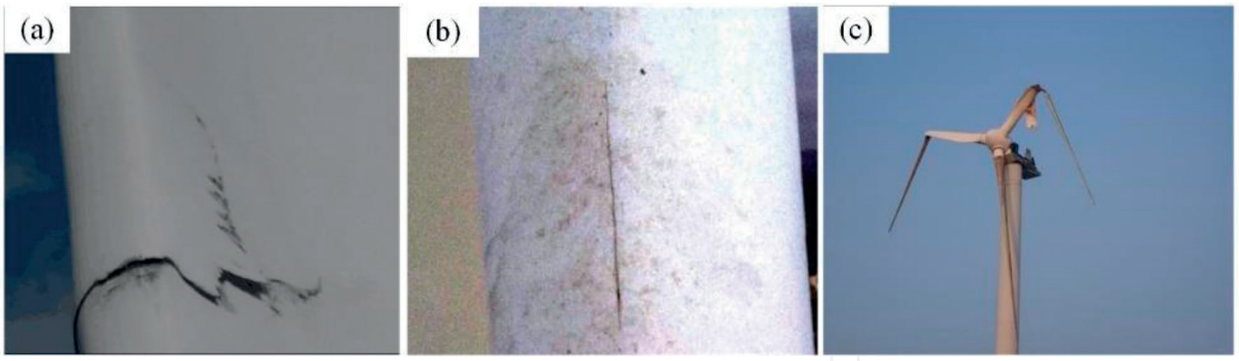


Figure 9. Failure modes of the blades. (a) Trailing edge crack; (b) leading edge failure and (c) blade fracture.

4. Wind turbine reliability analysis

The reliability definition is the probability that subassembly will meet its required function under a stated condition for a specified period of time. For an unrepairable system, the rating scale is reliability; for a repairable system, the rating scale is availability. Wind turbines consist of both unrepairable systems and repairable systems like gears, bearings, bolts and electronic components. So both reliability and availability should be considered to assess the

wind turbines. **Figure 10** shows the failure rates of different subassemblies and its downtime after failure. The results in **Figure 10** show that the lower the subassembly's reliability, the longer is the downtime of the corresponding subassembly.

The reliability of wind turbine system is becoming more and more important with the continued growth and expansion of markets for wind turbine technology. In addition, wind turbines with reduced repair and maintenance (R&M) requirements and higher reliability are needed emergently. However, wind turbines produced by different companies have different reliability. There is no unified evaluation criterion. The current reliability analysis methods mainly focus on gear transmission systems of wind turbines and ignore the influences of other systems. The effects of the reliability model are limited if the system is simplified and seen as a series or parallel connection. Due to high costs of repair and maintenance, it is essential to study the health management systems of wind turbines and develop maintenance strategies in order to improve reliability and reduce unexpected repair and maintenance. The high-reliability systems can be achieved from three aspects, as shown in **Figure 11**.

4.1. Reliability analysis methods

There are two kinds of reliability analysis methods: statistical method based on database and stress-strength interference theory based on loads.

4.1.1. Statistical method based on database

The failure rates of wind turbines are time-varying during its lifetime, but the failure rates of repairable systems follow a bathtub curve. With a service life of around 20 years, wind turbine failure rates are assumed to follow the famous bathtub curve, as shown in **Figure 12**. Weibull

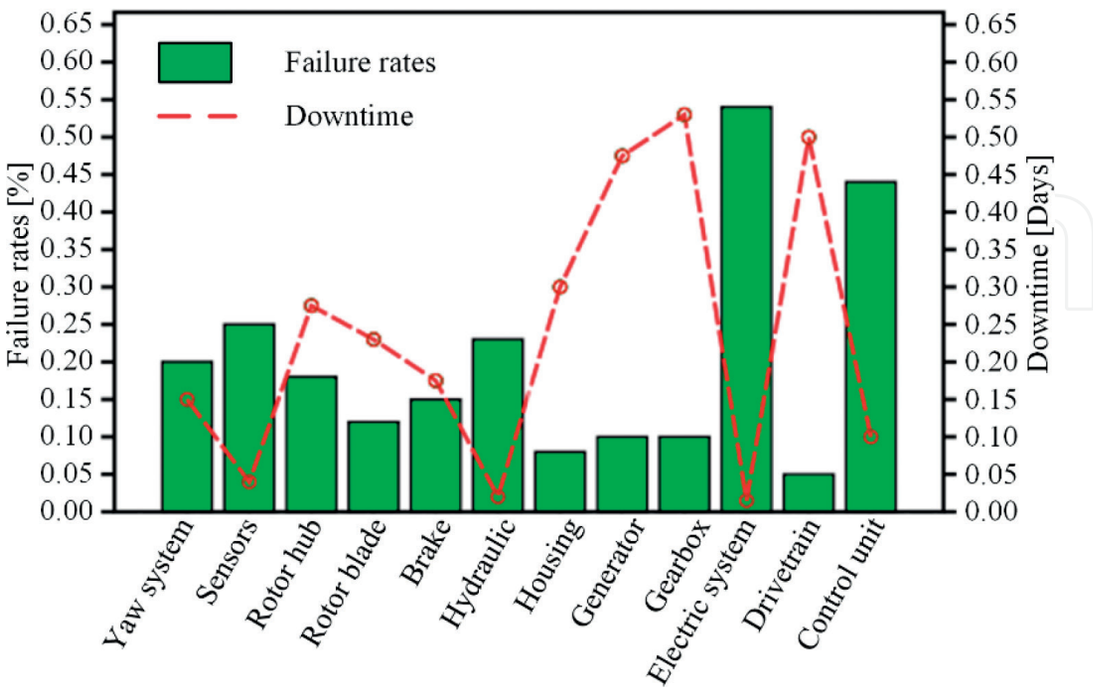


Figure 10. Failure rates and downtime for different subassemblies (DFIG).

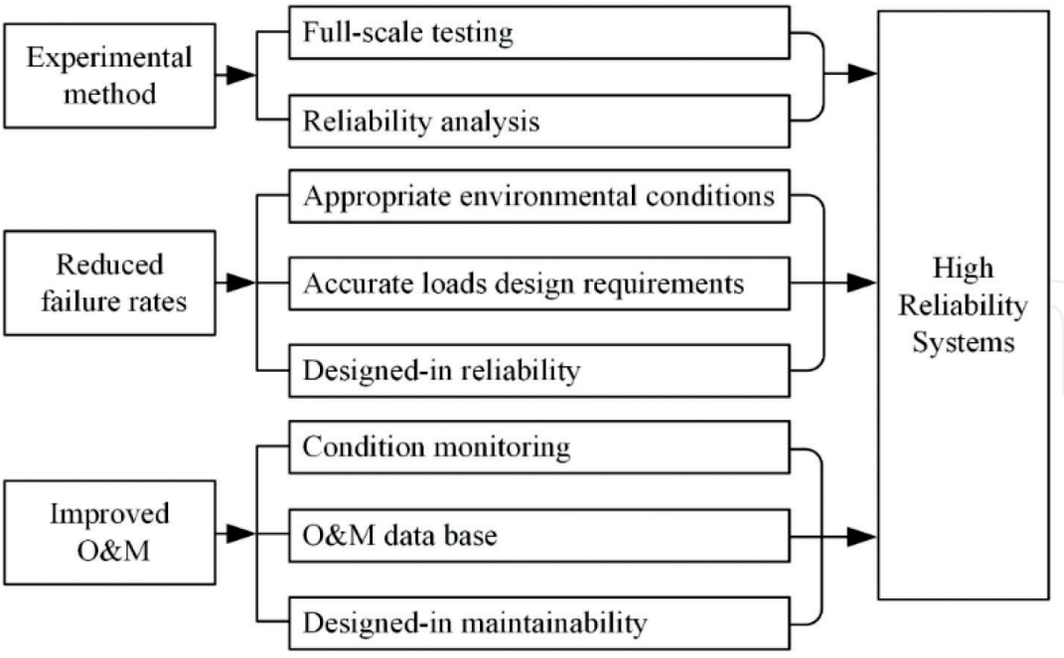


Figure 11. The requirements for developing the high-reliability systems.

distribution, gamma distribution and lognormal distribution are three commonly used methods in wind turbine reliability analysis. A method with mixtures of Weibull distribution with increasing hazard rates is written as follows [11]:

$$F(t) = \lambda\left[1-\exp\left(-\left(\frac{t-t_0}{\eta_1}\right)^{\beta_1}\right)\right] + (1-\lambda)\left[1-\exp\left(-\left(\frac{t-t_0}{\eta_2}\right)^{\beta_2}\right)\right] \quad (1)$$

where t is time, $t > 0, \beta_1 \cdot \beta_2 > 1,\ \beta_1 \cdot \beta_2$ are shape parameters, β_1, β_2 are scale parameters and λ is the mixing parameter, $t_0 = 0, \eta_1 = 10, \eta_2 = 100, \beta_1 = 5, \beta_2 = 5$.

Figure 13 shows the fault probability density function. The results in **Figure 13** show that there are two peaks which represent early failures and wear out failures, respectively, and the failure

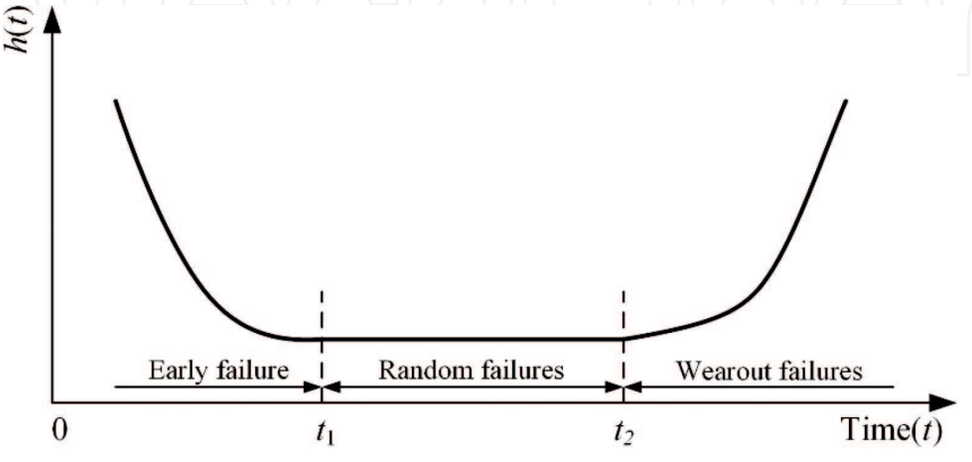


Figure 12. Bathtub curve of failure rates for repairable system.

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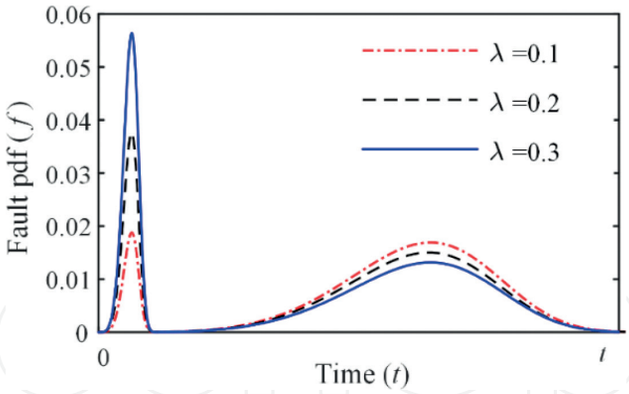


Figure 13. Fault probability density function.

rates are obvious higher at these two peaks. When the weighting factor equals 0.1, 0.2 and 0.3, the differences just happen at the peaks. Therefore, a proper weighting factor should be selected to meet the failure rate changes of wind turbines in different working environments. **Figure 14** shows the change of failure rates over time. The results in **Figure 14** show that a wind turbine is at running-in stage where its wear is large, and the failure rates are fluctuating and then stable. The failure rates of wind turbines will become higher and higher at the wear-out stage. Failure rate function curves with different weighting factors just show a difference at peak values, which has something to do with capacity and conditions. **Figure 15** shows the reliability function diagram which has three phases. The reliability in Phase I decreases sharply because newly installed wind turbines need to adapt to the environment. The reliability in Phase II is stable. There is a sharp decline in Phase III, which represents that the wind turbine has entered into wear-out failures, and its failure rates are high. Above all, it can be found that the bathtub curve can simulate the failure rate change among its service life as well.

4.1.2. Stress-strength interference theory based on loads

Random loads and fatigue strength of wind turbine subassemblies follow a normal distribution. The probability density function of stress and strength is expressed by the following equations:

$$f(S) = \frac{1}{\sqrt{2\pi}\,\sigma_s}\exp\left(-\frac{1}{2}\left(\frac{S-u_s}{\sigma_s}\right)^2\right) \tag{2}$$

$$g(\delta) = \frac{1}{\sqrt{2\pi}\,\sigma_\delta}\exp\left(-\frac{1}{2}\left(\frac{\delta-u_\delta}{\sigma_\delta}\right)^2\right) \tag{3}$$

where S, δ are stress and strength random variables, respectively; σ_s, σ_δ are the standard deviation of stress random variable and strength random variable, respectively; and u_s, u_δ are the expectation of stress random variable and strength random variable, respectively.

Figure 16 is a common practice to represent stress-strength interference. The figure shows the probability density function of stress and strength and their interference (overlap) over time.

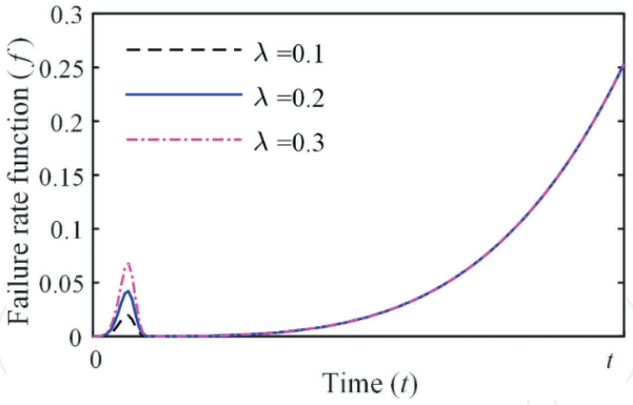


Figure 14. Failure rate function.

The interference is failure probability. The larger the area of the interference, the higher is the failure probability. Moreover, the interference area will become larger and larger over time in service life. The reliability of the system is:

$$\text{Reliability} = 1 - \text{Interference} \tag{4}$$

A new random variable z can be introduced, which is defined by

$$z = \delta - S \tag{5}$$

Then, the random variable z also follows normal distribution, so the reliability of stress-strength interference theory model is:

$$R = \int_0^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma_z} \exp\left(-\frac{(z-u_z)^2}{2\sigma_z^2}\right) dz \tag{6}$$

where σ_z is the standard deviation of z and u_z is the expectation of z.

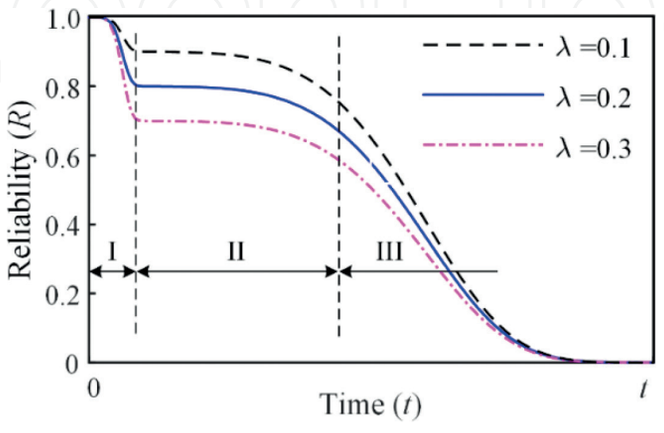


Figure 15. Reliability function.

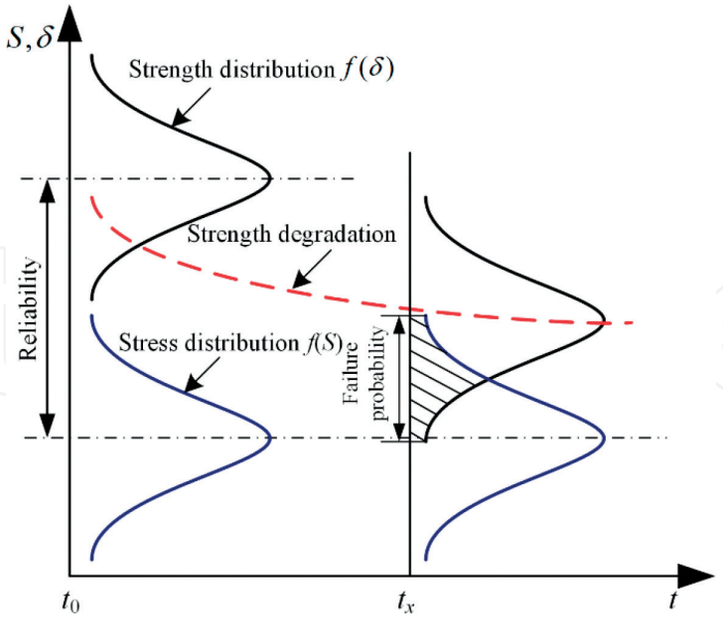


Figure 16. Graphical representation of stress-strength interference.

The dynamic reliability of gears can be calculated by the reliability calculation equation with the mean and standard deviation of gear fatigue stress and fatigue strength. **Figure 17** shows the reliability of high-speed stage gear. The figure shows that the reliability declines heavily before 20,000 h.

4.2. Current gearbox reliability analysis

High-performance gearboxes with large transmission ratios are available, which have been used in many areas. However, wind turbine gearboxes have more challenging and a greater

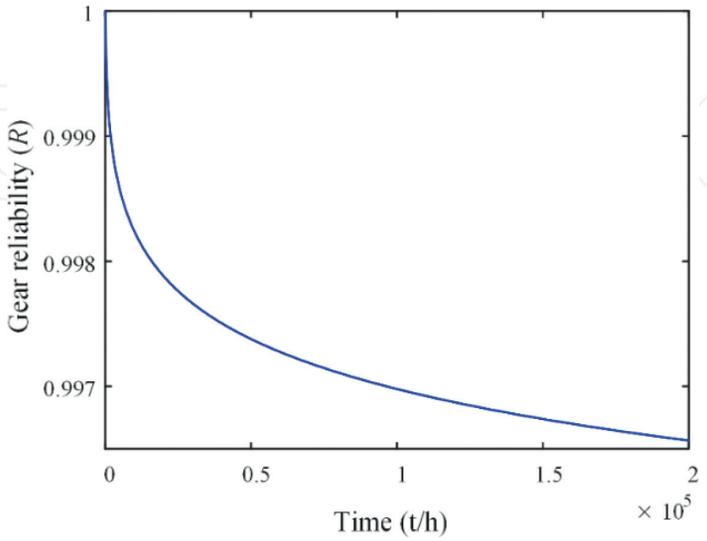


Figure 17. Reliability of high-speed stage gear.

number of technical requirements, like high reliability, safety and up to 25 years of operating life. Due to its complex structure and variable conditions, gearboxes have been and still are a source of failure and so have been paid more attention in the industry. Nowadays, the capacity of the multistage planetary wind turbines that are installed is up to the megawatt power classes. Hence, it is important to point out that the reliability of wind turbine gearboxes has great influences on wind turbines.

The current reliability research methods of the wind turbine gearbox include finite element method (FEM), lumped mass method (LMM), statistical methods based on database, experiment method (EM), simulation with software, and so on. Statistical methods based on database are most commonly used.

The researchers in national renewable energy laboratory (NREL) have done much milestone work. Generator and gearbox models have been produced in Matrix Laboratory (MATLAB) and NREL's Fatigue, Aerodynamics, Structures and Turbulence (FAST) [12]. NREL proposed that it is essential to bring all the parties involved in the gearbox-design process together to achieve the common goal of improving the reliability and lifetime of gearboxes [13]. The effects of different constant rotor torque and moment conditions and intentional generator misalignment on gearbox motion and high-speed shaft loads are examined [14].

The condition monitoring and fault diagnosis based on condition monitoring system (CMS) and supervisory control and data acquisition (SCADA) are also popular in wind turbine industry. The whole condition monitoring and assessment process within the system boundary include hard platform, condition monitoring and administrators of wind farms. Hard platform for wind farms includes the wind turbines, meteorological stations and monitoring data

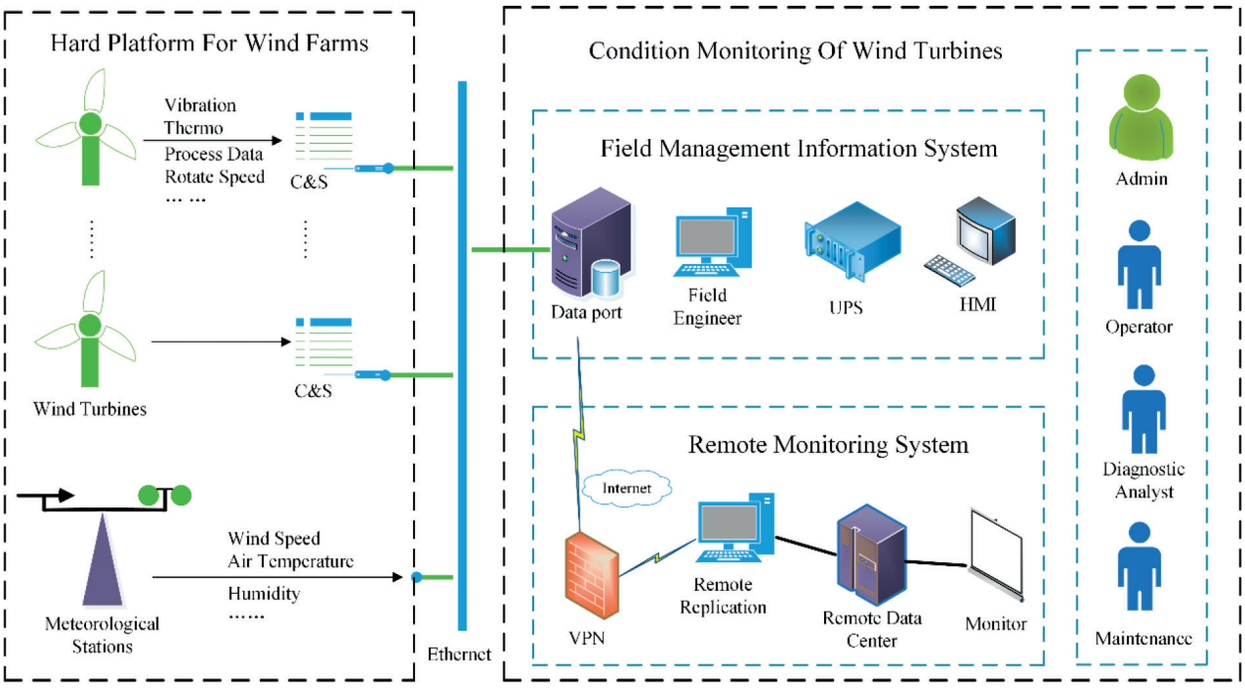


Figure 18. Flowchart of the condition monitoring and assessment process.

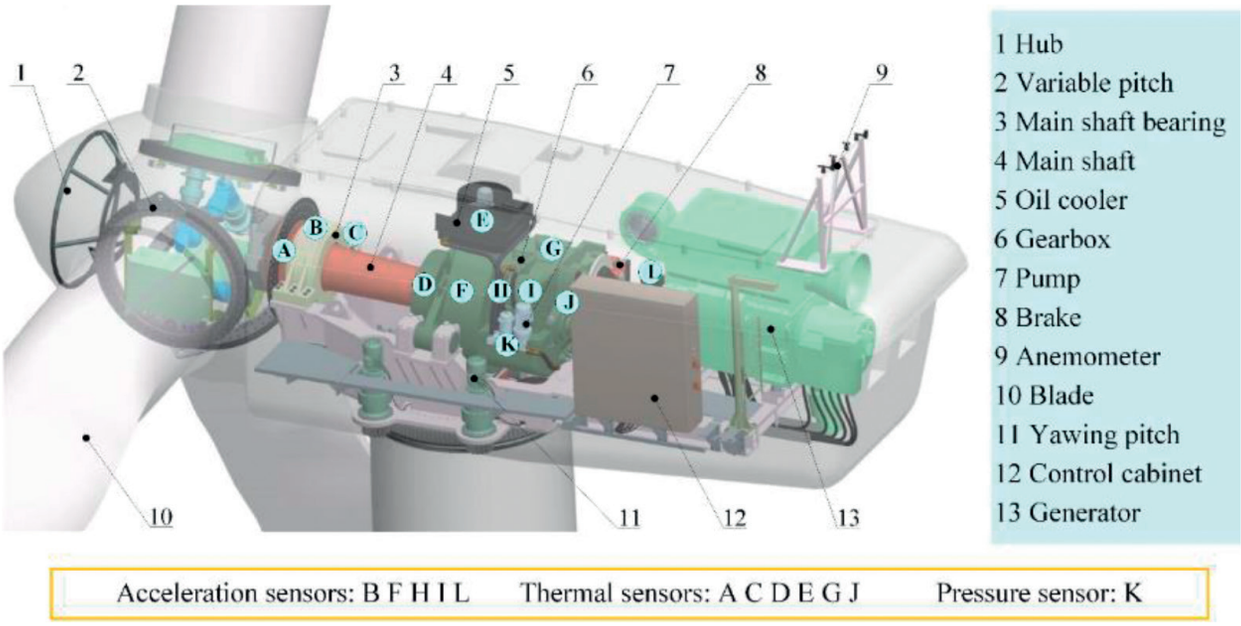


Figure 19. The distributions of the sensors.

via CMS and SCADA. Condition monitoring can be divided into remote monitoring system (RMS) and field management information system (FMIS); where, the FMIS includes data port, field engineer, uninterruptible power system (UPS) and human-machine interaction (HMI), and the RMS includes remote replication and a data center. The boundaries of the condition monitoring and assessment process for the wind turbine gearboxes are shown in **Figure 18**.

The condition monitoring systems of the CMS and SCADA can reflect the real-time running status of the wind turbine gearbox. The framework of the indices and project layers for the assessment of the wind turbine gearbox are established based on the CMS and SCADA. The goal layer can be classified into five project layers, and simultaneously, each project layer consists of the monitoring indices. For example, the goal layer can be divided into main shaft bearing (MSB), planetary stage (PS), low-speed stage (LSS), intermediate-speed stage (IMS), high-speed stage (HSS) and external factors (EF). The monitoring objects mainly consist of the nacelle, main shaft, bearing, cooling system, lubrication system and other related variables. **Figure 19** shows the location distribution of the sensors.

5. Conclusions

In order to solve reliability problems in wind power industry, scholars all over the world proposed many methods. But these reliability analysis methods mainly focus on gear transmission systems of wind turbines and ignore the influences of other systems. The effects of the reliability analysis are limited if the system is simplified and seen as a series or parallel connection. Based on the abovementioned analysis and field research, some key conclusions are proposed:

(1) The reliability research based on the fatigue life.

The fatigue failure is the common failure modes of wind turbines. It needs to study the whole wind turbine fatigue life and reliability. With design parameters and the dynamic model, the failure correlation of key components is calculated. Following this, matrixes of loads and contact stresses can be calculated considering the operation environment of wind turbines. Finally, it is possible to produce the fatigue cumulative damage of key components.

(2) The gradual change mechanism and physical representation of component health status.

Combining loads and fault statistical data, the gradual change mechanism of health status needs to be studied with the function of key components and mechanism characteristics, and to seek the physical representation that is related to the component health status. This is helpful to develop the trend model and thresholds of the physical representation of fault status. Following the abovementioned method, it is possible to assess and pre-estimate the reliability of components and subassemblies.

(3) Reliability research based on the whole wind turbine's dynamics.

Considering the influences of the random wind speed and waves, the dynamic model is established including components from blades to the foundation, by which the dynamic reliability of the wind turbine structure and drivetrain is studied. Following this, it is possible to evaluate the dynamic reliability of the whole wind turbine. However, the current reliability research ignored the influences of waves on the foundation and the tower, which would bring big errors to the reliability research. Therefore, it is essential and urgent to develop a set of the reliability engineering model and test method of wind turbines considering the influences of waves and the sea wind.

(4) Remote real-time assessment system of the wind turbine reliability based on the fusion data.

It is clear that most wind turbines have been installed both SCADA and CMS, but they are independent and cannot achieve the mutual support of test results. Therefore, it is meaningful to mix two sets of the test data based on SCADA and CMS. Following this, the feature data can be extracted and transferred to the data center by the Internet. When the feature data reach the data center, they can be used to calculate and assess the dynamic reliability of wind turbines through engineering models and hardware and software equipment immediately, which will cut the operation and maintenance cost and improve the operating efficiency of wind turbines sharply.

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