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Life cycle reliability and maintenance analyses of wind turbines

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Abstract

Wind power generation is an effective form of clean, renewable energy which operate both on land and offshore. The primary means of converting wind to power is by wind turbines. The issue with wind turbines is the life cycle reliability, operation and maintenance tasks associated. Frequent premature failures resulting in reactive maintenance can be costly which results in downtime and loss of production. Currently, prognostic health management is conducted on wind turbines by a supervisory control and data acquisition system. However, using this approach, only reactive and preventative maintenance is being utilised. This paper analyses life cycle reliability and maintenance of wind turbines which applies the concept of failure mode and effects analysis (FMEA) and bond graph modelling to simulate the effects of maintenance strategies on the life cycle cost of wind turbines. To ensure wind turbines life cycle reliability, the components failures would occur in sync with the biannual maintenance. This will ensure effective use of resources, such as transportation and personnel costs, associated with the maintenance action. Preventative maintenance can also be conducted in accordance to the MTTF values.

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Keywords: Wind power; wind turbine; operation; maintenance; life cycle reliability

1. Introduction

Wind power is an effective form of clean, renewable energy which operate both on land and offshore. It does not consume fuel or emit carbon emissions during its operation and is predicted to be 'the most cost competitive electricity source on macro-economic level by 2025 [1]. The primary function of a wind turbine is to harvest wind energy. It is done through converting kinetic energy of blades rotating into electrical energy.

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Wind farms are unreliable sources of energy generation which require frequent maintenance. They need to continuously adapt to different wind loads as wind conditions change over time and are highly unpredictable. The conditions in which wind turbines operate often cause system failures. Saxena and Rao [2] analysed wind turbine failures for a wind farm in India. They found that failure duration of yaw motor was highest, followed by failure duration of gear-oil pump, and then hydraulic unit of blade tip air brakes system.

Technology has improved significantly to minimize failure rates of components, however, failures of common parts are continually occurring. These failures are critical as it cause downtime and prevents the primary function of power generation. There have been 1868 accidents reported since 1900, of which 118 were critical, 174 structural failures and 345 blade failures [3]. Failures are highly undesirable in any system, whether it be mechanical or physical. Historical data shows a high failure rate in the gearboxes which require replacing every 5 to 7 years [4]. Structural damage occurs frequently as a consequence of high wind loads, fire damage and wildlife impact which have high financial risks due to environmental impacts. Due to the complexity of the components, the repair cost of is very high [5]. It is the general belief that better quality of components would lead to more reliable systems, however, not much research is found in literature on predicting these failures at the design stage.

Wind turbine operation is dependent on wind speeds to generate power. Elmore and Gallagher [6] found that use of non site-specific wind velocity data, such as that available from a regional database could be a cost-effective means for predicting wind turbine performance. The concluded that Monte Carlo models could predict wind turbine performance using remote wind velocity data. Heller [8] from Lawrence Livermore National Laboratory published the results of statistical analysis of field observations to help turbine manufacturers to refine their power curves and incorporate findings about what atmospheric processes are important in wind power forecasting. However, many wind turbines' performance still declined significantly and became uneconomical to operate after 10 years of operation. The wind turbine would then be decommissioned and replaced with a newer replacement.

This paper analyses life cycle reliability and maintenance of wind turbines. The analysis applies the concept of failure mode and effect analysis (FMEA) and Bond graph modelling to simulate the effect of changing maintenance strategies on the life cycle cost of wind turbines. The analysis results can be used to determine the optimum maintenance schedules and preventive part replacements.

2. Literature review

A wind turbine is a complex collection of components comprising rotors, pitch system, drive train, gearbox, generator, electrical system, mechanical brakes, yaw system, sensors, control system and hydraulics. To understand how these intervals and what activities are required in each visit, it is important to develop mathematical models to analyse the effect of different visit intervals and maintenance strategies. This literature review examines the key modelling research relevant to wind turbine lifecycle operation analysis.

2.1. Wind turbine reliability

Wind turbine reliability depends on the reliability of some key components. For example, gearbox failures are seen as the most common and most critical failure. A gearbox failure ceases the primary function of electricity generation and faces downtime for repairs or replacement. Structural damage to the blades and tower are another common mode of failure. The blades may have experienced high wind loads or bird strikes, resulting in broken blades. Chou & Tu [9] analysed the failure of a wind turbine tower caused by Typhoon Jangmi. They concluded that the bolts were inadequate and quality control was the cause of the damage. Lui & Shang [10] conducted failure analysis on wind turbine blade bolts. Laboratory testing of stress, strain, alternating loads, tensile loads, hardness and toughness were undertaken and concluded failure of bolts occurred from fatigue due to high alternating loads.

Electrical system within the generator can cause an ignition, burning fuel vapors within the nacelle. Once a fire has started within the nacelle, it is highly unlikely to be extinguished due to the location and height of the fire. Since the 1980s, up to 30% of reported wind turbine accidents related to fire, with 90% of those leading to significant downtime or total loss of system [11].

2.2. Wind turbine modelling

Wind turbine can be modelled in different ways. Chen [12] studied the functional expressions of wind turbine blade chord and twist angle span-wise distribution and developed a new common functional equation of the blade shape. A 2.3 MW wind turbine blade shape optimization model was established. Echavarría et al [13] presented a new design philosophy based on functional redundancies and reconfiguration that can help to increase availability of wind turbines. In the event of a fault, the new design capabilities could be used to substitute the function of a faulty component and the system's availability for operation could be analysed.

The technique Bond Graph uses power nodes to describe energy and power transfers in a dynamic system explicitly indicated by causal strokes. Bakka and Karimi [14] addressed the problem of bond graph methodology as a graphical approach for the modeling of wind turbine generating systems and validated a specific wind turbine generating system. Tapia and Medina [15] proposed a bond graph doubly-fed wind turbine generator control. The bond graph methodology and the concept of bicausality were used to derive and verify the control law system of the wind turbine.

Bond graph modelling methodology has the advantage of representing the energy transfers by either a flow or effort between components. Each component is represented by a bond group; source, sink, transformer, gyrator or a junction. Further to a junction (1-junction and 0-junction), passive elements such as resistance, inductance or capacitance may be assigned. These elements represent operating characteristics of the component.

2.3. Wind turbine maintenance

Maintenance of wind turbines are conducted twice a year at 6 month intervals. A typical maintenance would involve thorough inspection of the entire system, replacement of fluids, lubrication and servicing of mechanical parts. Repairs and replacements would be conducted if deemed necessary by the technician. These time based inspections and maintenance activities are often expensive and require undesired downtime [16].

Prognostic Health Management (PHM), a form of conditional monitoring, was proposed by Abichou et al [17] as the best strategy to reduce cost of operation and maintenance. Lekou et al [18] conducted conditional health monitoring on gearboxes and bearing using vibration acoustic emissions. They utilized accelerometers and strain gauge bridges to determine the operating frequency to use as a baseline measure for conditional monitoring. Failing components were tested to measure frequencies and compared to baseline measure to determine early failure detection.

2.4. Supervisory control and data acquisition system (SCADA)

Prognostic health management (PHM) is conducted through a SCADA system. Ongoing data is collected and analyzed for abnormalities during operation. The SCADA also monitors the health of the system through various sensors which assist with optimizing maintenance scheduling and improve reliability. The sensor readings, matched with historical failure readings, are used to predict failures before they occur. Guo and Infield [19] developed the Nonlinear State Estimation Technique (NSET) to model turbine tower vibration to good effect, providing an understanding of the tower vibration dynamic characteristics and the main factors influencing these. SCADA data from a single wind turbine was used to validate the model.

Guo et al [20] developed tower vibration model comprises two different parts: a sub-model used for the conditions that below rated wind speed and another for that above rated wind speed. With SCADA of one wind turbine, the NSET model showed good preparation for the condition monitoring for wind turbine's key components. Wang et al [21] reviewed different methods of data driven approaching for SCADA data interpretation has been reviewed and an artificial intelligence (AI) based framework for fault diagnosis and prognosis of WTs using SCADA data was proposed.

3. Wind turbine reliability modelling by MADe

To develop a lifecycle reliability plan, the analysis should be based on a combination of FMEA, power modelling, lifecycle costing and continuous monitoring. The research methodology will initially start with understanding all the governing parameters of the reliability of wind turbine at different stages of its lifecycle. A key element in this investigation is the determination of an optimum maintenance plan for the system.

This requires a failure mode analysis of the wind turbine at different working environment. Maintenance Aware Design environment (MADe) is an engineering decision support tool. It is a model-based software which captures operating parameters such as functions, failure rates and costs for analyses. The modelling work starts with creating the model and assigning a function to the top level; this is to convert linear velocity to electrical energy. Component blocks are then created to represent components or subsystems within the system. Fig.1 shows the system model at the highest level of indenture. In this situation we have simulated a high wind load showing the failure propagation path through the system. The numbers indicate the sequence of failures. Lower levels of indenture within the model captures the subsystem components and parts; with each subsystem, component and part having an individual failure diagram to capture failure mechanisms, faults and causes.

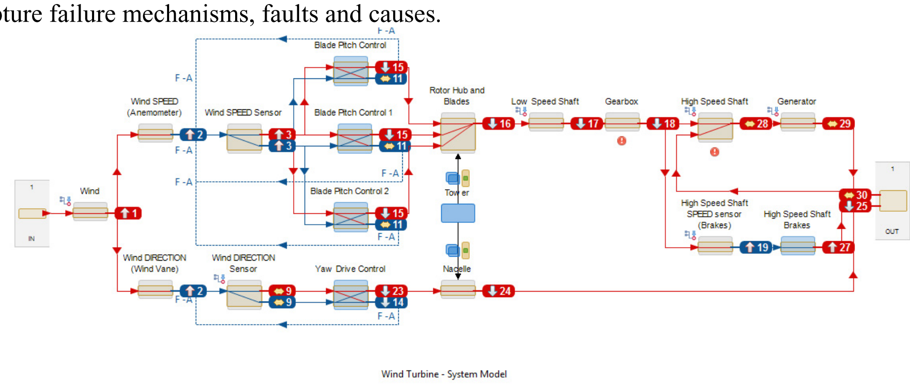

Fig. 1. Wind turbine system level

3.1. Bond graph modelling

The bond graph model, Fig.2, can be used to simulate faults and provide response curves for specific components. All components and parts are extracted to the top level of indenture. This model takes into account energy flows, sources and sinks.

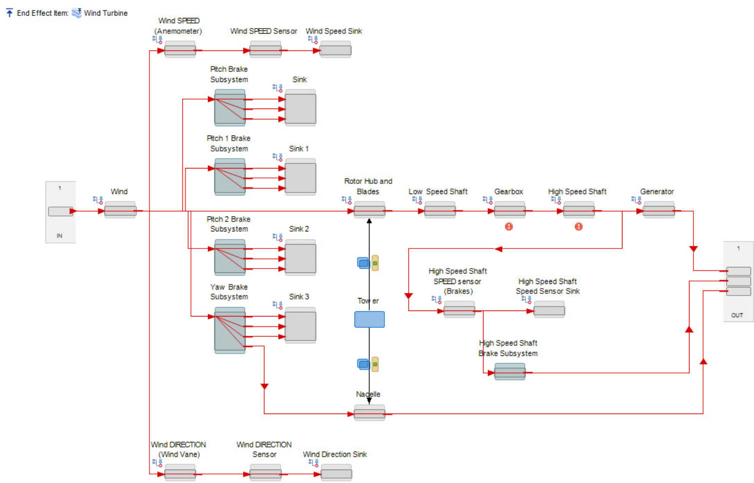

Fig. 2. Bond diagram

The bond values assigned to each component are relative values to each component as the purpose of the simulation is to map the responses when it exceeds a specific margin. All sinks were set to 0.0 as they were the end effect and no further energy is being transmitted past that point. All sources are set to 10 as an arbitrary scale. Resistance values throughout the system are set relative to each other.

The reliability of the system model is affected by the operating conditions. Strong wind forces more energy to flow through the bond graph model components. If the limit of energy is reached, the component fails and hence triggers failure rate and reliability computation in the simulation.

4. Simulated results

The system model with the bond graph model incorporated has been simulated on the basis of 20 years service life and typical 60% to 70% utilisation rate. Maintenance actions were set per component as one of the strategies: scheduled, condition based, breakdown. The simulated results are shown in Table 1. These results match closely to the mean time to failure of historical failure rates.

Table 1. Simulated results of the system model under set maintenance strategies

Component	Maintenance strategy	Estimated MTTF (Years)
Gearbox	Condition Based Repair - Continuous Monitoring	5.50
Generator	Condition Based Service - Periodic Inspection	9.00
High Speed Shaft	Condition Based Replace - Continuous Monitoring	4.145
High Speed Shaft Brake Control	Condition Based Service - Continuous Monitoring	2.33
High Speed Shaft Brake Coupling	Condition Based Replace - Periodic Inspection	12.10
High Speed Shaft Brake Disc	Condition Based Service - Periodic Inspection	15.29
High Speed Shaft Electric Motor	Scheduled Service	4.66
High Speed Shaft Brake Hydraulic Pump	Condition Based Service - Continuous Monitoring	4.35
High Speed Shaft Brake Pipe	Condition Based Replace - Periodic Inspection	12.77
High Speed Shaft Brake Piston	Condition Based Replace - Periodic Inspection	17.94
High Speed Shaft Speed sensor (Brakes)	Breakdown Replace	4.00
Low Speed Shaft	Condition Based Replace - Continuous Monitoring	15.00
Nacelle	Condition Based Repair - Periodic Inspection	4.20
Pitch Brake Controls	Condition Based Service - Continuous Monitoring	2.33
Pitch Brake Couplings	Condition Based Replace - Periodic Inspection	12.1
Pitch Brake Discs	Condition Based Service - Periodic Inspection	15.29
Pitch Brake Electric Motors	Scheduled Service	4.66
Pitch Brake Hydraulic Pumps	Condition Based Service - Continuous Monitoring	4.35
Pitch Brake Pipes	Condition Based Replace - Periodic Inspection	12.77
Pitch Brake Pistons	Condition Based Replace - Periodic Inspection	17.94
Pitch Couplings	Condition Based Replace - Periodic Inspection	12.10
Pitch Electric Motors	Scheduled Service	4.66
Pitch Gearboxes	Condition Based Service - Continuous Monitoring	5.50
Pitch Shafts	Condition Based Replace - Periodic Inspection	15.00
Pitch Shaft Speed Sensors (Brakes)	Breakdown Replace	4.00
Rotor Hub and Blades	Breakdown Replace	7.14
Wind Vane	Breakdown Replace	12.43
Anemometer	Breakdown Replace	12.43
Wind Direction Sensor	Breakdown Replace	4.00
Wind Speed Sensor	Breakdown Replace	4.00
Yaw Brake Control	Condition Based Service - Continuous Monitoring	2.33
Yaw Brake Coupling	Condition Based Service - Periodic Inspection	12.10
Yaw Brake Disc	Condition Based Service - Periodic Inspection	15.29
Yaw Brake Electric Motor	Scheduled Service	4.33
Yaw Brake Hydraulic Pump	Condition Based Service - Continuous Monitoring	4.35
Yaw Brake Pipe	Condition Based Replace - Periodic Inspection	12.77
Yaw Brake Piston	Condition Based Replace - Periodic Inspection	17.94
Yaw Coupling	Condition Based Service - Periodic Inspection	12.10
Yaw Drive Control	Condition Based Service - Continuous Monitoring	2.33
Yaw Electric Motor	Condition Based Service - Periodic Inspection	4.66
Yaw Gearbox	Condition Based Service - Continuous Monitoring	5.50
Yaw Shaft	Condition Based Replace - Periodic Inspection	10.00
Yaw Shaft Speed Sensor (Brakes)	Breakdown Replace	4.00

5. Conclusion

Wind turbine maintenance has been controlled and maintained to ensure lifetime operations. The system will undergo biannual servicing and breakdown maintenance to ensure the life of components are preserved. To ensure the maintenance is feasible, the components failure would occur in sync with the biannual maintenance to minimise transportation costs. From the findings of this research, MTTF are computed from a maintenance schedule with simulated wind load on the wind turbine. Preventive maintenance strategies can then be determined from the MTTF predictions.

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