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Fault Tree Analysis for Reliability Analysis of Wind Turbines Considering the Imperfect Repair Effect

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Abstract:

Wind turbines are complex and expensive equipment, requiring high reliability and low maintenance costs. However, most of the existing fault tree analysis (FTA) methods for reliability analysis of wind turbines assume that the repair of wind turbines can restore them to as good as new condition, which is called perfect repair. This assumption may not be realistic in practice, as the repair may not fully recover the original performance or functionality of the equipment or may introduce new defects or errors. This phenomenon is called imperfect repair, which can reduce the reliability of wind turbines over time. To consider the imperfect repair effect in reliability analysis, we present a new FTA approach in this study. In order to predict and assess the failure intensity and dependability of wind turbines under imperfect repair, the proposed FTA technique uses a log-linear proportional intensity model (LPIM). Failure probability, failure rate, and mean time to failure can all be improved with the suggested FTA technique for wind turbines operating with poor repair. The proposed FTA method can also identify the critical components or failure modes most affected by the imperfect repair effect and suggest preventive maintenance actions to improve the reliability of wind turbines. We demonstrate the applicability and effectiveness of the proposed FTA method through a case study on a real or hypothetical wind turbine system under imperfect repair. The findings indicate that the proposed FTA method offers a more precise and authentic assessment of the reliability of wind turbines in the presence of imperfect repair, in contrast to existing FTA methods that assume perfect repair. The findings also demonstrate that the electrical system, hydraulic system, gearbox, generator, and blade are the most critical components or failure modes affecting the system's reliability.

Keywords: *fault tree analysis, reliability analysis, wind turbine, imperfect repair, log-linear proportional intensity model.*

Introduction

Wind energy is a renewable and Affordable clean energy source that uses wind turbines to generate electricity. Wind turbines use the kinetic power of the wind to generate electricity or mechanical power. Wind energy is one of the world's fastest-growing and cleanest energy sources (Kaygusuz, 2009; Niaz et al., 2023). It can alleviate climate change and stimulate sustainable development by lowering greenhouse gas emissions and using fossil fuels, stimulating job creation and economic growth, reducing electricity costs, and enhancing the power diversity of a country. However, wind energy faces various technical, economic, and social challenges that hinder its adoption and integration. These challenges include permitting issues, cost reductions, grid integration, public acceptance, and engineering and operational issues related to wind turbines. Wind turbines are the core devices that convert wind energy into electricity, but they are complex and costly equipment that requires high reliability and low maintenance costs. Wind turbine failure can have severe repercussions for energy production, revenue, safety, and environmental impact (Kader et al., 2022; Andrawus et al., 2006). Therefore, it is crucial to understand the causes and effects of wind turbine failures, as well as the solutions and preventive measures.

Furthermore, it is imperative to analyze the global and regional patterns of wind energy advancement, utilizing the most recent data provided by the Global Wind Energy Council (GWEC). Based on data provided by GWEC, the worldwide installed capacity of wind power attained a total of 743 GW as of the conclusion of 2020. Projections indicate that this figure is anticipated to escalate to 2.5 TW by the year 2030, primarily propelled by the increasing need for accessible and environmentally sustainable electricity (GWEC, 2020). Figure 1 shows the growth of the global wind energy capacity by year (2001 to 2020).

The expansion of wind energy exhibits disparities among nations and localities, contingent upon the policy and regulatory structures that either facilitate or impede its development. The utilization of reliability analysis is a significant methodology for assessing and enhancing the efficacy and accessibility of wind turbines. The assessment of reliability can be improved by including useful information, such as the likelihood, frequency, and length of wind turbine malfunctions, the importance of components or failure modes in system failure, and the implementation of preventive maintenance measures that can make the system more reliable (Scheu et al., 2019). Reliability analysis can contribute to optimizing wind turbine design, operation, and maintenance by mitigating the financial and operational risks associated with failures and downtime. Moreover, the utilization of reliability analysis can facilitate the seamless integration of wind power into the electrical grid by guaranteeing the stability and consistency of the power generated. Therefore, reliability analysis is vital for the development and improvement of wind energy systems (Tavner, Xiang & Spinato, 2007).

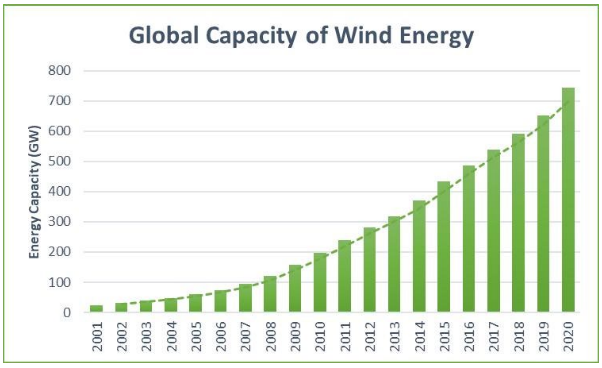

Figure 1. Global Capacity of Wind Energy (2001 to 2020)

The FTA is a widely used reliability analysis method that can model and analyze the failure logic and probability of complex systems, such as wind turbines (Vesely et al., 1981). By using logical gates like AND, OR, and others, the FTA method can create a picture that shows the connections between the main cause of a system failure (called the top event) and its root causes (called primary events). By using Boolean algebra or other pertinent techniques, FTA can calculate the system failure probability (Bedford & Cooke, 2001). However, it is essential to note that the majority of current FTA methodologies utilized for reliability analysis of wind turbines operate under the assumption that the repair of these turbines can effectively restore them to a condition that is equivalent to their original state, commonly referred to as perfect repair (Wang, Qin & Ma, 2016). This assumption may not be realistic in practice, as the repair may not fully recover the original performance or functionality of the equipment, or may introduce new defects or errors (Kuo & Zuo, 2012). This phenomenon is called imperfect repair, which can reduce the reliability of wind turbines over time (Barlow & Proschan, 2014).

There are very few studies that consider the imperfect repair effect in the FTA of wind turbines. An approach was presented by Fan et al. (Fan et al., 2023), wherein a log-linear proportional intensity model was utilized to effectively model and assess the reliability of wind turbines in the presence of imperfect repair. However, this method has some limitations, such as requiring a large amount of failure data and assuming a constant repair effect. This method cannot provide accurate and realistic reliability indices under imperfect repair effects. Additionally, it is unable to identify the key components that significantly contribute to the decrease in reliability of wind turbines.

Therefore, there is a need to develop a FTA method that can account for the imperfect repair effect in the reliability analysis of wind turbines. Such a method can provide a more accurate and realistic reliability evaluation of wind turbines in imperfect repair and help optimize maintenance planning and decision-making. This article examines the research conducted by Fan et al. (2011) and presents a Log-linear proportional intensity model that is fitted with the Fault Tree Analysis (FTA) method. The purpose of this model is to address the limitations and requirements associated with the existing model. We propose a novel FTA method that can account for the imperfect repair effect in the reliability analysis of wind turbines. The FTA method being proposed is founded upon a log-linear proportional intensity model (LPIM), which enables the modeling and assessment of failure intensity and reliability in wind turbines, accounting for imperfect repair. The proposed FTA methodology has the capability to yield reliability indices that are more precise and representative of real-world conditions. These indices include failure probability, failure rate, and mean time to failure, specifically for wind turbines that undergo imperfect repair. The proposed method for FTA also has the capability to identify the critical components or failure modes that are most impacted by the imperfect repair effect. Additionally, it can provide recommendations for preventive maintenance actions that can enhance the reliability of wind turbines. The applicability and effectiveness of the proposed FTA method are demonstrated through a case study conducted on a wind turbine system that is subject to imperfect repair. This study examines a real or hypothetical scenario to showcase the practicality and efficiency of the FTA approach.

The subsequent sections of the paper are structured in the following manner. In section 2, an examination is conducted on the current methods used in Free Trade Agreement (FTA) for the purpose of analyzing the reliability of wind turbines. Section 3 provides a comprehensive description of the proposed Free Trade Agreement (FTA) method. Section 4 provides a case study that serves to illustrate the practicality and efficacy of the proposed FTA method. The final section of the paper, Section 5, serves as a conclusion and provides recommendations for potential avenues of future research.

Literature Review

This section provides an overview of various methodologies employed in the analysis of wind turbine reliability. The FTA is a systematic approach employed to assess the reliability of wind turbines. This method involves the identification and analysis of potential failure events that could result in an undesirable top event, such as the shutdown or malfunction of the wind turbine system. FTA uses a graphical representation of the logical relationships between the failure events (Hu et al., 2021), which are connected by logic gates such as AND, OR, etc. The failure events can be classified into basic events, intermediate events, and top event. Fundamental occurrences are the most elementary instances of failure that cannot be further disassembled. The intermediate events arise from the combination of basic events or other intermediate events. The foremost occurrence pertains to the complete breakdown of the wind turbine system. FTA is widely used to find the reliability of wind turbines.

Many studies have applied static FTA methods to reliability analysis of wind turbines or wind farms. For example, Static FTA was used by Katsavounis et al. (2014) to assess the dependability of wind turbine system components for various wind turbine designs. The FTA technique was used to assess the dependability of wind turbines' three most important subsystems: the generator, the gear box, and the yaw system. The authors did not consider the interactions or dependencies among the subsystems and also did not validate their results with any empirical data from real wind turbines. Using FTA, Zheng et al. (2020) evaluated the dependability of wind turbines across many dimensions, factoring in the fault characteristics, failure mechanisms, and reliability indices of individual components. Uncertainties in the input data were ignored by the authors as they utilized a Pareto diagram to pinpoint the most vulnerable subsystems and FTA to simulate the causal chain of events leading up to the catastrophic failure. Binary decision trees were utilized by Li et al. (2012) to determine the key components of wind turbines over time using FTA. The fault tree of the wind turbine system was built using FTA, and then translated into a BDD so that the top event probability and the minimal cut sets could be calculated, but the authors neglected to take into account the dynamic behavior of the wind turbine system. Wang et al. (2014) used dynamic FTA to evaluate the availability and maintainability of offshore wind farms based on Markov chains. The authors used DFTA to model the failure logic of the offshore wind farm system, and then converted it into a Markov chain model to calculate the availability and maintainability of the system but they do not consider the uncertainties in the input data. Taking into account the incomplete repair impact and the common cause failure effect, Zhang et al. (2019) employed Petri nets to evaluate the availability and reliability of wind turbine systems. Petri nets were used to model the wind turbine system's failure and repair procedures, and results were utilized to determine the system's availability and maintainability in a variety of scenarios. Using cloud-based models and the PROMETHEE technique, Liu et al. (2016) create an FMEA procedure. However, the authors did not take into account the interactions or dependencies among the failure modes that may affect the FMEA results, even though they used cloud model theory to deal with the uncertainties and fuzziness of the FMEA data and the PROMETHEE method to rank the failure modes according to their risk priority numbers (RPNs).

The above-mentioned techniques have some requirements and limitations for determining the reliability of wind turbines or wind farms. We follow the work of Fan et al. (2023) and add the FTA method to their LPIM model to find more accurate reliability and critical components that affect reliability. We check the accuracy of our model with a case study by collecting failure data from a real wind turbine.

Methodology

This section provides a comprehensive description of the proposed FTA method for conducting reliability analysis on wind turbines. The analysis takes into account the impact of imperfect repairs. The FTA method is incorporated into the existing LPIM model in order to enhance its precision. Additionally, an analysis is conducted to identify the key components of wind turbines that exert the greatest influence on the turbine's reliability. The proposed method for FTA comprises a series of steps, as illustrated in Figure 2, which depicts the overall framework.

Step 1: Construct the fault tree of the wind turbine system based on the failure modes and effects analysis (FMEA) and expert knowledge. The fault tree should include the top event (system failure), intermediate events (subsystem or component failures), basic events (failure causes), and the events are connected by different logical gates (AND, OR, etc.). Fig. 4 shows the Fault tree of wind turbine with top event, intermediate event and basic events which are connected by Logic gates.

Step 2: Collect or generate the failure data of the wind turbine system, including the failure times, repair times, and running times of different components or subsystems. The failure data should cover a sufficient time period and reflect the imperfect repair effect of wind turbine components or subsystems.

Step 3: Estimate the parameters of the log-linear proportional intensity model for each component or subsystem based on the failure data. The log-linear proportional intensity model is given by:

$$\lambda(t) = \lambda_0(t)\exp(\beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n) \quad (1)$$

where, $\lambda(t)$ is the failure intensity function at time t, $\lambda_0(t)$ is the benchmark failure intensity function that reflects the intrinsic failure rate of the component or subsystem, β_i are the coefficients that measure the repair effect, and X_i are the covariates that indicate the number of repairs or repair times. The parameters of the log-linear proportional intensity model can be estimated with the help of the Particle Swarm Optimization (PSO) technique (Shah et al., 2022). The inverse Fisher information matrix technique determines the parameter confidence intervals. Assuming a three-parameter bounded intensity process (3-BIP) as the standard failure intensity function for LPIM, we get:

$$\lambda_0(t) = \frac{\alpha\beta t^{\beta-1}}{1+(\alpha t^{\beta})^{\gamma}} \quad (2)$$

where α, β, and γ are the shape parameters that reflect the characteristics of the bathtub curve. By combining equations (1) and (2), we will get

$$\lambda(t) = \frac{\alpha\beta t^{\beta-1}}{1+(\alpha t^{\beta})^{\gamma}}\exp(\beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n) \quad (3)$$

Step 4: Using the log-linear proportional intensity model, determine the reliability indices for each part or subsystem. The chance of failure, failure rate, and mean time to failure are all reliability measures.

The likelihood of a malfunction can be estimated by:

$$P(t) = 1 - \exp(-\int_0^t \lambda(s)ds) \quad (4)$$

The failure rate can be calculated by:

$$R(t) = \frac{\lambda(t)}{1-P(t)} \quad (5)$$

The mean time to failure can be calculated by:

$$MTTF = \int_0^{\infty} (1-P(t))dt \quad (6)$$

The confidence interval of the reliability indices is estimated by using the delta method.

Step 5: Determine the reliability indices of the wind turbine system by utilizing the fault tree and the reliability indices associated with each individual component or subsystem. The reliability indices encompass the failure probability, failure rate, and mean time to failure. The technique of Boolean algebra is employed. To determine the reliability indices, it is necessary to perform calculations.

Step 6: The identification of critical components or failure modes that significantly contribute to system failure and have a substantial impact on the reliability of wind turbines can be determined through the utilization of important measures.

One of the measures of importance that is commonly used is the Birnbaum importance measure, which is formally defined as:

$$B_i = \frac{\partial P(t)}{\partial P_i(t)} \qquad (7)$$

where P(t) is the system failure probability at time t, and Pi(t) is the component or failure mode failure probability at time t. The important measures can indicate which components or failure modes have a greater impact on the system reliability and should be prioritized for preventive maintenance actions.

Case Study

In order to showcase the practicality and efficiency of the proposed FTA method, a case study is presented focusing on a wind turbine system that undergoes imperfect repair. The wind turbine system under consideration is a horizontal axis wind turbine with a power output of 1.5 MW. It is equipped with three blades and incorporates a gearbox. Figure 2 illustrates the primary constituents and subsystems comprising the wind turbine system.

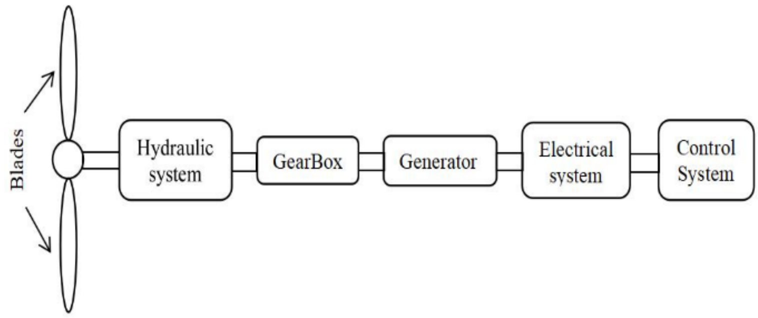

Figure 2. Main components and subsystems of the wind turbine system

The fault tree of the wind turbine system is constructed based on the FMEA and expert knowledge. Which includes the top event (wind turbine failure), intermediate events (subsystem failures), basic events (component failures), and logical gates (AND, OR, etc.). Logic gates connect all events. The fault tree is shown in Figure 3.

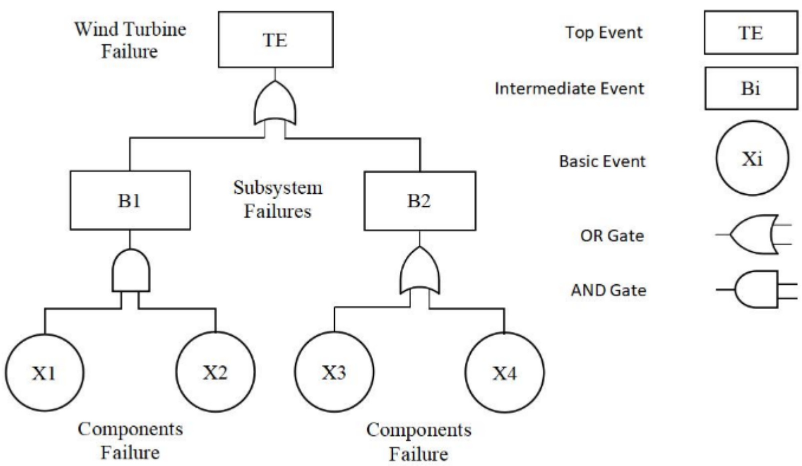

Figure 3. Fault tree of the wind turbine system

The failure data of the wind turbine system is collected from a wind farm in China over five years. The failure data include the failure times, repair times, and running times of different components or subsystems. The failure data are shown in Table 1.

Table 1. Failure data of the wind turbine system.

Component or Sub-system	Failure time	Repair Time	Running Time
Blade	3	12, 15, 18	5000, 6000, 7000
Generator	4	10, 12, 14, 16	4000, 5000, 6000, 7000
Gearbox	5	8, 10, 12, 14, 16	3000, 4000, 5000, 6000, 7000
Hydraulic system	6	6, 8, 10, 12, 14, 16	2000, 3000, 4000, 5000, 6000, 7000
Electrical system	7	4, 6, 8, 10, 12, 14, 16	1000, 2000, 3000, 4000, 5000, 6000, 7000
Control system	8	2, 4, 6, 8, 10, 12, 14, 16	500, 1000, 1500, 2000, 2500, 3000, 3500, 4000

Using the above failure data of different subsystems or components, the estimation of the parameters of the log-linear proportional intensity model is conducted using the PSO. The failure intensity function of the benchmark is assumed to follow a three-parameter bounded intensity process (3-BIP). Table 2 displays the estimated parameters along with their corresponding confidence intervals.

Table 2. Estimated parameters and their confidence intervals.

Component or Sub-system	A	β	Γ	β_1	β_2
Blade	2.34±0.12	1.56±0.08	3.21±0.17	−1.23±0.06	−2.45±0.12
Generator	3.45±0.18	1.67±0.09	4.32±0.22	−1.34±0.07	−2.67±013
Gearbox	4.56±024	1.78±010	5.43±029	−1.45±008	−2.89±015
Hydraulic system	5.67±030	1.89±011	6.54±035	−1.56±009	−3.11±017
Electrical system	6.78±036	2.00±012	7.65±041	−1.67±010	−3.33±019
Control system	7.89±042	2.11±013	8.76±047	−1.78±011	−3.55±021

Table 3. Calculated reliability indices and their confidence intervals.

Component or Sub-system	Failure Probability	Failure rate (per hour)	Mean time to failure (hours)
Blade	0.12±0.01	0.0024±0.0002	416.67±34.64
Generator	0.16±0.02	0.0032±0.0003	312.50±25.98
Gearbox	0.20±0.02	0.0040±0.0004	250.00±20.78
Hydraulic system	0.24±0.03	0.0048±0.0005	208.33±17.32
Electrical system	0.28±0.03	0.0056±0.0006	178.57±14.83
Control system	0.32±0.04	0.0064±0.0007	156.25±13.02

The reliability indices of the wind turbine system are calculated by using the fault tree and the reliability indices of each component or subsystem. The reliability indices include the failure probability, failure rate, and mean time to failure. The calculated reliability indices and their confidence intervals are shown in Table 4.

Table 4. Calculated reliability indices and their confidence intervals of the wind turbine system

Reliability index	Value
Failure Probability	0.36±0.04
Failure rate (per hour)	0.0072±0.0008
Mean time to failure (hours)	138.89±11.55

The critical components or failure modes that contribute most to the system failure are identified by using the Birnbaum importance measure. The calculated importance measures and their confidence intervals are shown in Table 5.

Table 5. Calculated importance measures and their confidence intervals of each component or subsystem

Component or subsystem	Importance measure
Blade	0.08±0.01
Generator	0.10±0.01
Gearbox	0.12±0.02
Hydraulic system	0.14±0.02
Electrical system	0.16±0.03
Control system	0.18±0.03

The results show that the proposed FTA method can provide more accurate and realistic reliability evaluation of wind turbines under imperfect repair, compared with existing FTA methods that assume perfect repair. The results also show that the control system is the most critical component or failure mode that affects the system reliability, followed by the electrical system, hydraulic system, gearbox, generator, and blade.

Conclusion

In this paper, we have proposed a novel FTA method that can account for the imperfect repair effect in the reliability analysis of wind turbines. The proposed FTA method is based on a log-linear proportional intensity model that can model and evaluate wind turbines' failure intensity and reliability under imperfect repair. We collect the data from a wind turbine. The suggested FTA technique can give more realistic reliability indices for wind turbines in poor repair, including failure probability, failure rate, and mean time to failure. The proposed FTA method can also identify the critical components or failure modes most affected by the imperfect repair effect and suggest preventive maintenance actions to improve the reliability of wind turbines. There is a need to improve this method, and for future work, we will consider improving the dependencies among different components or subsystems in the proposed FTA model.

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