Evaluating wind turbine power plant reliability through fault tree analysis

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EVALUATING WIND TURBINE POWER PLANT RELIABILITY THROUGH FAULT TREE ANALYSIS

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Abstract:
This study presents the application of the Fault Tree Analysis (FTA) method in analyzing the reliability of a wind turbine power plant. Examining all crucial system components and simulating potential failure probabilities demonstrated the system's overall reliability using two different coefficient simulations. This approach aims to identify which elements have the most significant impact on the reliability of wind turbine systems and, consequently, determine the critical points of the analyzed system. The displayed fault tree and appropriate tabular analysis present comparative analyses between these two simulations. From both case examples, it can be concluded that the system's generator plays a crucial role in influencing the overall reliability. By applying Boolean algebra and input coefficients for two cases, the values of potential wind turbine failures were obtained: in the first case, 11.7%, while in the second case, the percentage is 5.7%.

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FTA analysis, failure, reliability, wind, turbine

1. INTRODUCTION

Fault Tree Analysis represents an exceptionally potent maintenance and reliability management tool across various industries, including the energy sector. In recent decades, wind turbine installations have emerged as pivotal sources of renewable energy, and the efficient maintenance of these systems is paramount to ensure continuous and dependable wind energy production.

Applying Fault Tree Analysis (FTA) assumes particular significance in this context. FTA is a methodological approach that facilitates a comprehensive examination of the causes and consequences of failures within systems. It can be applied to all components of a wind turbine installation, including blades, generators, lubricants, electronics, and numerous other system parts. FTA empowers engineers to understand the factors leading to failures and identify critical points that require improvement or preventive maintenance. FTA is recognized as a widely adopted technique for exploring potential pathways leading to system or component failures [1]. This method finds broad application across various industries, including the military sector, railways, oil and gas, and aviation [2-4]. In addition to the above-mentioned basic branches of industry where FTA analysis is applied, such as the military industry, telecommunications, the automotive industry, and others, there are many different sectors in which it is applied, and some of the applications can be found in the papers [5-10]. In addition to the mentioned industries, the application of failure analysis extends to individual components of complex mechanical systems. In the paper [11], the application of failure analysis on roller bearings of a belt conveyor is described.

In this text, we will explore how FTA can be applied in the context of wind turbine installations. We will highlight the advantages of this method, including enhancing system reliability, reducing maintenance costs, and extending the equipment's operational lifespan. We will also delve into

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practical examples of applying Fault Tree Analysis in the wind turbine industry to understand its concrete contributions in this field better. This text aims to underscore the significance of FTA in wind turbine installations and demonstrate how this approach can be pivotal in maintaining sustainable and efficient renewable energy production systems.

The significance of the study lies in a comparative analysis, from which conclusions can be drawn regarding the elements that play a crucial role in the reliability of the wind turbine plant. In comparison to other studies, the difference lies in the variation of input coefficients.

FTA analysis can be enhanced with adequate knowledge and tools from the field of knowledge management, ensuring a more comprehensive analysis. Knowledge management enables the improvement of every process, including those in industries such as energy [12].

2. CREATING A FAILURE TREE ANALYSIS BASED ON A WIND TURBINE PLANT EXAMPLE

According to research [13], the fault tree should be composed of several fundamental steps:

- Identification of the failures under examination.
- In-depth understanding of the system.
- Creation of the fault tree.
- Assessment of failure probabilities.
- Risk control.

The quality of the analyzed system's performance is determined by analyzing reliability through the probability of failure occurrence, as defined in research [14]. In the paper [15], the authors investigate the reliability of hybrid energy systems using FTA analysis to establish the overall system failure rate. Wind turbine installations comprise numerous components that may be susceptible to potential failures, impacting the overall system reliability and directly influencing the plant's operation. Using modern diagnostic tools, Castellani and colleagues analyzed potential bearing failures in wind turbine installations [16]. A comprehensive Fault Tree Analysis (FTA) applied to offshore wind turbines is presented in the paper [17], where all the wind turbine components are considered. Luengo and Kailos [18] have defined potential causes and elements where failures can occur in wind turbine installations, as depicted in Table 1.

Table 1. Potential failures in a wind turbine

Wind turbine elements	Potential failures
Rotor	Misalignment of yaw
	Uneven air gap
	Misalignment of the shaft
	Torsional oscillation
	Mass imbalance
	Aerodynamic asymmetry
Tilt control	Premature brake activation
	Operational instability due to hydraulic system failure
	Leakage in the hydraulic system
	Air contamination in the hydraulic system
	Yaw angle asymmetry
	Inability to achieve aerodynamic braking
Control and energy management system	Overheating
	Wind speed/direction measurement errors
	Cracks and surface wear
	High vibrations
	Fatigue and corrosion
	Lightning strikes
Gear	Gear tooth damage
	Cracks
	Shaft coupling failure – gearbox
	Loss of lubricant water content
	Presence of contaminants in the lubricant
	Changes in lubricant viscosity
Generator	Gear tooth damage
	Cracks
	Shaft coupling failure – gearbox
	Loss of lubricant water content
	Presence of contaminants in the lubricant
	Changes in lubricant viscosity
Tower and foundations	Fatigue
	Cracks
	Corrosion
	Earthquakes

In the papers [19-26], standard failures in wind turbine systems are described, and Fault Tree Analysis (FTA) is presented as a method for defining potential failures and calculating the reliability of the entire system. The correctness and reliability of all wind turbine components guarantee maximum power output, which ultimately leads to the full utilization of its potential. All parameters related to cost-effectiveness and utilization of wind turbine installations are detailed in the paper [27].

3. MATERIAL AND METHODS

Research on the application of fault tree analysis in wind turbine plants aims to address key engineering needs. Focused on enhancing reliability and performance, the analysis identifies critical failure points, enabling design optimization and efficient maintenance planning to reduce costs and downtime. It also contributes to increased system safety and allows adaptability to various operating conditions, including variable weather conditions. This research supports the improvement of engineering standards by providing deeper insights into the causes of failures and facilitates effective monitoring of the plant's life cycle. Additionally, it contributes to the sustainability of wind turbine systems, minimizing their environmental impact. All these components make fault tree analysis an essential tool for improving the reliability, sustainability, and performance of wind turbine plants. The initial identification of key system components is followed by constructing a fault tree using a hierarchical approach, incorporating Boolean algebra to precisely model logical relationships among events. The quantification of the probability of failure for each component, along with statistical analysis, contributes to the assessment of system reliability. For assistance in creating and analizyng a fault tree, the software tool TopEvent FTA Express was utilized.

3.1 Application of FTA Analysis on a 2 MW Wind Turbine Installation

In this study, Fault Tree Analysis was applied to the case of a standard vertical wind turbine with a potential power output of 2 MW. All significant components directly or indirectly affecting the wind turbine operation were considered and included in the analysis to yield results on potential turbine failures. In this instance, two potential scenarios were presented, with different arrangements of coefficients for the potential failure of turbine components, and a comparative analysis was conducted to determine the elements that hold the most significant importance for the reliable functioning of the turbine. The quantitative analysis entailed the utilization of statistical methodologies for the interpretation of amassed data. The integration of probability coefficients into the fault tree facilitated a probabilistic evaluation of conceivable turbine failures, thereby augmenting the comprehensiveness of the system's reliability assessment.

Fig. 1 depicts a wind turbine installation for which a Fault Tree Analysis was conducted, including all relevant elements crucial for setting up the appropriate FTA analysis, as per [28].

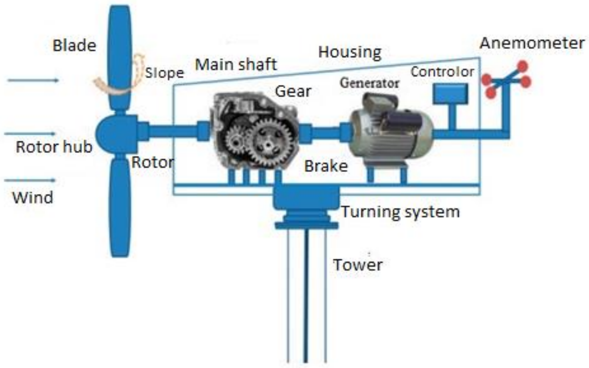

Fig. 1. Wind turbine

The wind turbine is composed of various essential components, encompassing a rotor equipped with blades to harness wind energy, a rotor shaft facilitating the transmission of rotational energy, a main shaft that both sustains rotation and conveys energy to the generator, and a generator responsible for converting mechanical energy into electrical energy. Additionally, it features a blade carrier allowing unrestricted movement aligned with the wind direction, a wind vane to optimize blade orientation, a gearbox to fine-tune the rotation speed of the main shaft for the generator, a control system overseeing wind speed and adjusting blade orientation, and a tower providing structural support to the upper section of the wind turbine while positioning the generator at a specific elevation above the ground. These interconnected elements form a cohesive system adept at efficiently transforming wind energy into electrical power, underscoring the pivotal role of wind turbines as indispensable contributors to renewable energy generation.

Fig. 2 shows the stable failure analysis for a 2 MW wind turbine.

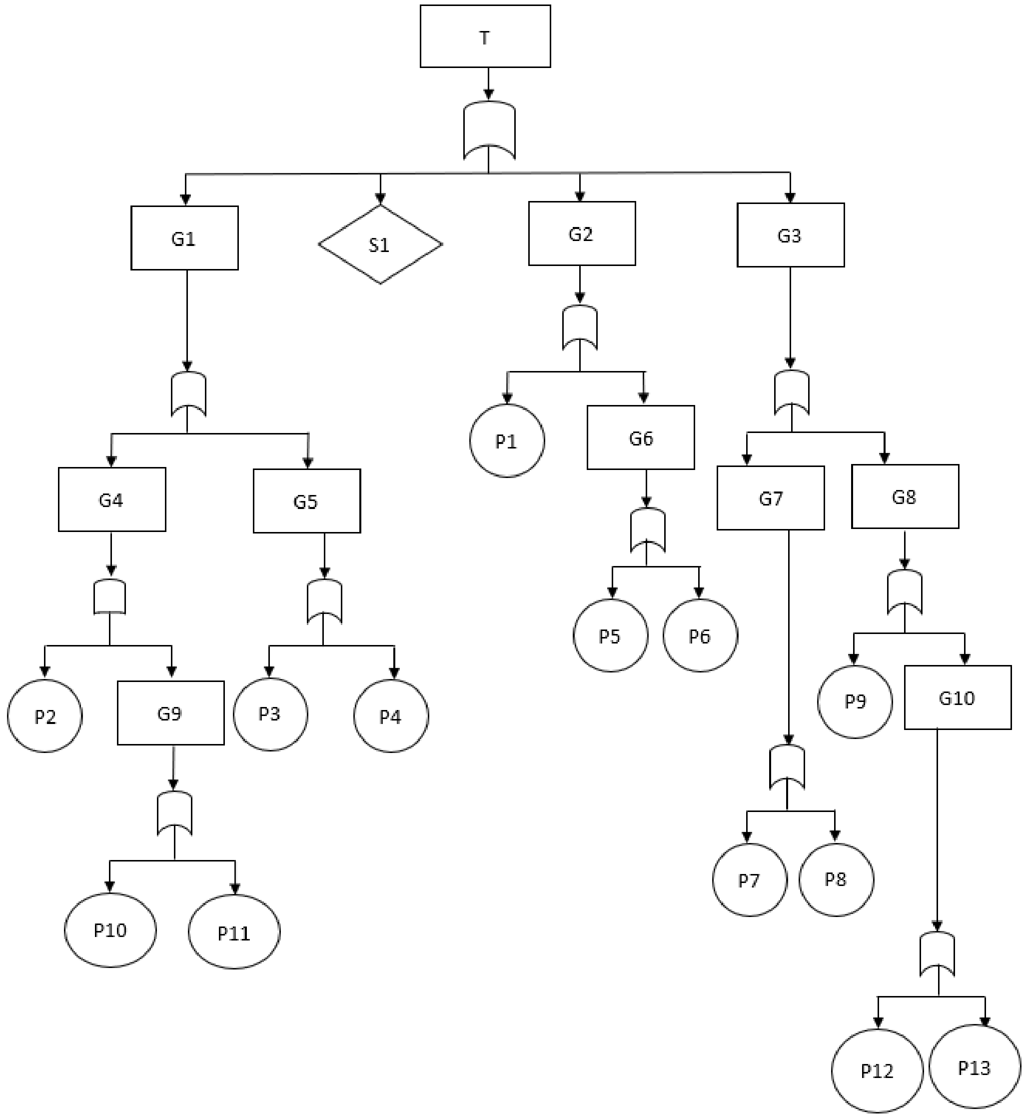

Fig. 2. Fault Tree Analysis (FTA) of a Wind Turbine Installation

In Table 2, Boolean variables are provided to represent the fault tree shown in Fig.2.

Table 2. Boolean variables for the fault tree of a wind turbine

T	Wind generator failure	**G4**	Rotor and stator failure	**G9**	Rotor and stator failure	**P4**	Abnormal vibrations	**P9**	Abnormal vibrations
S1	Tower failure	**G5**	Bearing failure	**G10**	Gear tooth damage	**P5**	Blade damage	**P10**	Failed synchronization
G1	Generator failure	**G6**	Meteorological unit failure	**P1**	Yaw motor failure	**P6**	Anemometer damage	**P11**	Broken rods
G2	Yaw system failure	**G7**	Poor lubrication	**P2**	Abnormal signals	**P7**	Presence of contaminants in the oil	**P12**	Gear tooth cracks
G3	Gearbox failure	**G8**	Faulty equipment	**P3**	Asymmetry	**P8**	Poor oil quality	**P13**	Poor gear design

3.2 The Application of Boolean Algebra in Defining Potential Failures in Wind Turbines

Boolean algebra enables the precise representation of logical relationships among different events or components contributing to system failure. Through this mathematical discipline, analysts can construct fault tree diagrams that qualitatively and quantitatively describe potential paths to system failure. This methodology provides a structured approach to identifying critical failure points, facilitates the quantification of the probability of undesirable events, and allows for systematic optimization of system reliability. Therefore, the application of Boolean algebra in fault tree analysis plays a pivotal role in enhancing the design and maintenance of systems, contributing to a comprehensive understanding and improvement of the reliability of complex engineering systems.

For the presented wind generator fault tree, the Boolean equations for each logic gate are as follows (1):

$$
\begin{gathered}
T = G1 + S1 + G2 + G3 \\
G1 = G4 + G5 \\
G2 = P1 + G6 \\
G3 = G7 + G8 \\
G4 = P2 * G9 \\
G5 = P3 + P4 \\
G6 = P5 + P6 \\
G7 = P7 + P8 \\
G8 = P9 + G10 \\
G9 = P10 + P11 \\
G10 = P12 + P13
\end{gathered}
\tag{1}
$$

After the equations are formulated, variable substitutions can be performed with their expressions until the top event is obtained as a function of only the basic events in the following manner (2):

$$
\begin{gathered}
G1 = G4 + G5 \\
G4 = P2 * G9 \\
G5 = P3 + P4 \\
G9 = P10 + P11 \\
\Rightarrow \\
G4 = P2 * (P10 + P11) \\
= P2 * P10 + P2 * P11 \\
G1 = P2 * P10 + P2 * P11 + P3 + P4 \\
G2 = P1 + G6 \\
G6 = P5 + P6 \\
\Rightarrow \\
G2 = P1 + P5 + P6 \\
G3 = G7 + G8 \\
G7 = P7 + P8 \\
G8 = P9 + G10 \\
G10 = P12 + P13 \\
\Rightarrow \\
G8 = P9 + P12 + P13 \\
G3 = P7 + P8 + P9 + P12 + P13
\end{gathered}
\tag{2}
$$

Finally, it is necessary to reduce the obtained expression, which in this case is impossible, indicating that minimal cut sets were obtained in the second step. The final equation (3), appears as follows:

$$
\begin{gathered}
T = G1 + S1 + G2 + G3 \\
G1 = P2 * P10 + P2 * P11 + P3 + P4 \\
G2 = P1 + P5 + P6 \\
G3 = P7 + P8 + P9 + P12 + P13 \\
\Rightarrow \\
T = P2 * P10 + P2 * P11 + P3 + P4 \\
+ S1 + P1 + P5 + P6 \\
+ P7 + P8 + P9 + P12 \\
+ P13
\end{gathered}
\tag{3}
$$

Knowing how failures can impact system reliability, the author subsequently presented equations for the probability of failure and applied them to the given fault tree. The equation (4), for the probability of failure of the given fault tree is presented below:

$$
\begin{gathered}
P(T) = P(G1) + P(S1) + P(G2) + P(G3) \\
- P(G1) * P(S1) - P(G1) \\
* P(G2) - P(G1) * P(G3) \\
- P(S1) * P(G2) - P(S1) \\
* P(G3) - P(G2) * P(G3) \\
+ P(G1) * P(S1) * P(G2) \\
* P(G3)
\end{gathered}
$$

$$
\begin{gathered}
P(G1) = P(G4) + P(G5) - P(G4) \\
* P(G5) \\
P(G4) = P(P2) * P(G9) \\
P(G9) = P(P10) + P(P11) - P(P10) \\
* P(P11) \\
P(G5) = P(P3) + P(P4) - P(P3) \\
* P(P4) \\
P(G2) = P(P1) + P(G6) - P(P1) \\
* P(G6) \\
P(G6) = P(P5) + P(P6) - P(P5) \\
* P(P6) \\
P(G3) = P(G7) + P(G8) - P(G7) \\
* P(G8) \\
P(G7) = P(P7) + P(P8) - P(P7) \\
* P(P8) \\
P(G8) = P(P9) + P(G10) - P(P9) \\
* P(G10) \\
P(G10) = P(P12) * P(P13) - P(P12) \\
* P(P13)
\end{gathered}
\tag{4}
$$

Subsequently, calculations of failure probabilities will be conducted for two different scenarios, specifically for varying failure probabilities of primary basic events, the values of which are provided in Table 3.

Table 3. Failure probabilities of basic event components

Components	Case I	Case II
P(S1)	0.151	0.254
P(P2)	0.233	0.134
P(P1)	0.134	0.154
P(P9)	0.25	0.21
P(P10)	0.63	0.16
P(P11)	0.37	0.84
P(P3)	0.21	0.72
P(P4)	0.79	0.28
P(P5)	0.16	0.81
P(P6)	0.84	0.19
P(P7)	0.27	0.75
P(P8)	0.73	0.25
P(P12)	0.5	0.3
P(P13)	0.5	0.7

4. RESULTS AND DISCUSSION

Two cases with values of potential failures of basic events are presented.

The results of the first case are presented in Table 4.

Table 4. Failure probabilities of intermediate event and peak event components

Components	Case I
P (G1)	0.864
P (G2)	0.884
P (G3)	0.963
P (G4)	0.179
P (G5)	0.834
P (G6)	0.866
P (G7)	0.803
P (G8)	0.813
P (G9)	0.767
P (G10)	0.75
P (T)	0.117

The probability of failure of the entire system, i.e., the wind generator, is 11.7 %.

The results of the second case are presented in Table 5.

Table 5. Failure probabilities of intermediate event and peak event components

Components	Case II
P (G1)	0.821
P (G2)	0.870
P (G3)	0.968
P (G4)	0.116
P (G5)	0.798
P (G6)	0.846
P (G7)	0.813
P (G8)	0.834
P (G9)	0.866
P (G10)	0.790
P (T)	0.057

The probability of failure of the entire system, i.e., the wind generator, is 5.7 %.

The research results are provided in Table 6, showing the probabilities of failure for intermediate event components and the top event, i.e., the wind generator.

Table 6. Failure probabilities of intermediate event and peak event components

Components	Case I	Case II
G1	0.864	0.821
G2	0.884	0.87
G3	0.963	0.968
G4	0.179	0.116
G5	0.834	0.798
G9	0.767	0.866
G6	0.866	0.846
G7	0.803	0.813
G8	0.813	0.834
G10	0.75	0.79
T	0.117	0.057
G1	0.864	0.821
G2	0.884	0.87
G3	0.963	0.968

Based on the specified input parameters, i.e., coefficients for two cases in the fault tree analysis of a 2 MW wind turbine, it is evident that the significance of elements and the potential for their failures, defined through input coefficients, significantly influences the overall potential failures of the wind turbine. In the first case, employing Boolean algebra and defining input coefficients, the fault tree analysis yielded a probability value of 11.7 % for the occurrence of a potential failure in the analyzed wind turbine. By altering the input parameters for the components of the wind turbine plant, the percentage for potential failure decreases to 5.7 %, directly indicating the components that could more significantly impact the potential failure of the wind turbine.

5. CONCLUSION

Resource preservation is another crucial advantage of applying Fault Tree Analysis (FTA). Analyzing the causes of failures and errors makes it possible to reduce the time required for repairs and regular maintenance of wind turbines. This directly impacts extending the system's operational lifespan and significantly reducing overall operating costs.

In conclusion, FTA analysis is a sophisticated method that provides a detailed understanding of critical reliability and safety aspects in wind turbine installations. Its application allows engineers to systematically identify, analyze, and address potential issues, thereby enhancing the efficiency and safety of these vital energy resources. Improving wind turbine performance is also possible through FTA analysis. Identifying potential failures enables the implementation of preventive measures, including regular maintenance, staff training, and system design improvements. In this way, wind turbines can achieve better performance and efficiency.

In the presented example, the most significant difference in the final calculation of potential failure occurrences is caused by the G1 field, representing the potential failure of the system's generator. Therefore, this element can be considered one of the critical components of wind turbine installations for reliable system operation.

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