

# Application of the FMECA method for identifying failures in wind turbine systems

Branislava Radišić<sup>a</sup>, Ljiljana Radovanović<sup>b</sup>, Borivoj Novaković<sup>c</sup>, Jasmina Pekez<sup>d</sup>, Slavica Prvulović<sup>e</sup>, Eleonora Desnica<sup>f</sup>

University of Novi Sad, Technical Faculty "Mihajlo Pupin", Zrenjanin, Republic of Serbia

<sup>a</sup> e-mail: [branislava.radisic@uns.ac.rs](mailto:branislava.radisic@uns.ac.rs), **corresponding author**,  
ORCID iD: <https://orcid.org/0009-0007-3664-2012>

<sup>b</sup> e-mail: [ljiljana.radovanovic@uns.ac.rs](mailto:ljiljana.radovanovic@uns.ac.rs),  
ORCID iD: <https://orcid.org/0000-0002-5234-4820>

<sup>c</sup> e-mail: [borivoj.novakovic@uns.ac.rs](mailto:borivoj.novakovic@uns.ac.rs),  
ORCID iD: <https://orcid.org/0000-0003-2816-3584>

<sup>d</sup> e-mail: [jasmina.pekez@uns.ac.rs](mailto:jasmina.pekez@uns.ac.rs),  
ORCID iD: <https://orcid.org/0000-0003-0454-5326>

<sup>e</sup> e-mail: [slavica.prvulovic@uns.ac.rs](mailto:slavica.prvulovic@uns.ac.rs),  
ORCID iD: <https://orcid.org/0000-0001-6353-7145>

<sup>f</sup> e-mail: [eleonora.desnica@uns.ac.rs](mailto:eleonora.desnica@uns.ac.rs),  
ORCID iD: <https://orcid.org/0000-0002-4724-5764>

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## Abstract:

*This paper presents the potential causes of component failures in wind turbine systems that affect their reliable and efficient operation. Component failures in wind turbines can lead to complete system failure, resulting in downtime, reduced reliability, and increased costs. To fully utilize wind energy, minimizing the risk of component failures is essential. By applying the FMECA method (Failure Mode Effects and Criticality Analysis – FMECA), critical components of wind turbine systems have been identified, providing the opportunity to prioritize problem-solving. The results emphasize the importance of maintenance and design optimization to reduce the risk of failures and maximize the utilization of wind energy.*

Introduction/purpose: The reliability of wind turbine systems plays a crucial role in ensuring a stable and efficient electricity supply from renewable sou-

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rces. The failure of any component can lead to system downtime, reduced reliability, and increased operational costs. In this context, it is essential to identify and analyze potential failures in order to improve overall system reliability. *The aim of this paper is to analyze the reliability of a wind turbine system using the FMECA method. The focus is on identifying the most critical components and understanding the causes and consequences of their failures, thereby contributing to the improvement of system design, maintenance, and operation.*

*Methods: This paper applies the FMECA (Failure Modes, Effects and Criticality Analysis) method, which enables a detailed assessment of potential system failures, their causes and effects, and the identification of the most critical system points based on quantitative parameters. The methodology includes the following steps: identification of key components of the wind turbine, including the rotor, gearbox, generator, control system, and other subsystems; definition of possible failure modes for each component, with corresponding mechanisms that may lead to failure (e.g., wear, overheating, mechanical damage, etc.); evaluation of the consequences of failures, both on the specific component and on the overall operation of the wind turbine; quantitative risk assessment through the assignment of values for: the probability of potential failure occurrence ( $R_1$ ), the severity of the potential failure ( $R_2$ ), and the probability of detecting the failure and preventing its manifestation ( $R_3$ ); calculation of the criticality level ( $R$ ) using the expression:  $R = R_1 \cdot R_2 \cdot R_3$ ; ranking of components based on  $R$  values to identify those that pose the greatest threat to system reliability and require prioritized monitoring or optimization.*

*Results: The results of the FMECA analysis indicate that the most critical components of the wind turbine system are: gearbox – the highest criticality level ( $R$  value), as gearbox failure can lead to complete system shutdown and costly repairs; generator – high severity of failure and moderate likelihood of failure detection; wind turbine control system – although failures are less frequent, the consequences can be severe due to the loss of control over the turbine. Based on the analysis, components have been classified according to maintenance and monitoring priorities to enable timely detection of potential failures and prevent major breakdowns.*

*Conclusion: The FMECA method is an effective tool for identifying and ranking potentially critical components of wind turbine systems. The results indicate that the gearbox, generator, and control system are the most sensitive points in the system. Their preventive maintenance, along with the implementation of condition monitoring systems and design improvements,*

can significantly enhance reliability and reduce operational costs. *The analysis can serve as a foundation for improving maintenance strategies and increasing wind farms operational efficiency.*

*Key words: wind energy, wind turbines systems, component failures, FMECA method, reliability, preventive maintenance.*

## Introduction

The advantages of using renewable natural resources, and especially wind energy, are considerable. In addition to being unlimited and renewable, wind potential also represents a clean source of energy. During wind exploitation, there is no air pollution, no smog, and no production of gases that cause acid rain or greenhouse gas emissions.

Also, wind energy is one of the cheapest sources of energy. In order to fully utilize the potential of wind energy, it is important to understand the devices through which it is converted into mechanical work, namely wind turbine systems. A wind turbine system is a complex electromechanical system that converts wind energy into electrical energy. It consists of various subsystems and components such as: tower – a load-bearing structure in the form of a column, made of steel/concrete; wind turbine – includes the rotor and blades driven by the wind; mechanical shaft – accelerates the gearbox through rotation; gearbox – serves to increase the rotor's rotation rate from a low value to a speed sufficient to drive the generator; generator – converts mechanical energy into electrical energy; yaw system – tracks the wind direction; control and power electronics system – regulates the generator's rotational speed and controls the output voltage; hydraulic and cooling system; connection to an energy storage system or the power grid.

The greatest problem during the operation of a wind turbine system is component failure, which can lead to the failure of the entire system, resulting in system downtime, reduced reliability, and increased costs. For ranking system components according to their level of criticality, the Failure Mode, Effects and Criticality Analysis (FMECA) method is highly significant.

## Wind potential and wind turbine system

"Wind represents the large-scale movement of air" (Jovanović & Baroš, 2023). Wind is the horizontal flow of air masses caused by differences in temperature, i.e. differences in air pressure. It is considered that wind is a consequence of solar radiation, since it heats the planet Earth unevenly, which leads to variations in air pressure. After

hydropower, wind energy is the most economical renewable energy source (Adamović et al, 2013). Wind turbine systems are a type of power plant that use wind energy. They consist of a supporting structure, i.e. a tower, a wind turbine, a generator, a component that regulates the generator's rotational speed and the output voltage of the wind generator, and a system for energy storage or a connection to the electrical grid. The main condition for installing a wind generator is wind speed, which depends on terrain characteristics, surrounding objects, and their heights. The wind should blow at an average speed of 6 m/s, for 2800 hours per year (a year has 8760 hours), in order for a certain location to be considered suitable for wind farm construction (Jovanović & Baroš, 2023). The working principle of a wind generator is as follows: the wind drives the wind turbine, which is located at the top of the supporting structure and usually consists of three blades. The turbine is connected to an electric generator, which converts mechanical energy into electrical energy. The mechanical assembly forms the link between the turbine and the generator, and it consists of: a low-speed shaft, a gearbox (speed multiplier), a brake, and a high-speed shaft (Hrnjak & Katić, 2021). "The heavier the air, the more energy is obtained at the wind turbine" (Adamović et al, 2014). The density of air is 1.225 [kg/m<sup>3</sup>] at a standard atmospheric pressure of 1013 [mbar] and a temperature of 15 [°C]. During winter, more energy will be produced at the same wind speed than in summer, because cold air is denser than warm air. A proper choice of technology greatly influences reliability. "The failure rate increases with larger turbines, but downtime duration decreases with increased turbine size" (Adamović et al, 2014). It is important to highlight the role of maintenance, which ensures higher availability without excessive cost increase.

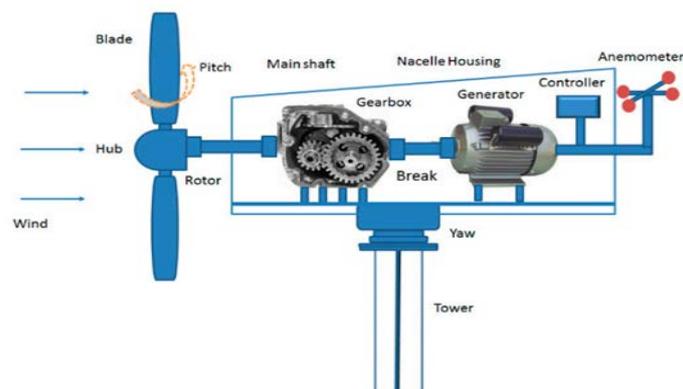


Figure 1 – Wind Turbine System (Gao & Liu, 2021)

Equipment reliability can be improved through preventive maintenance measures, as timely repairs prevent the wear of certain components. Figure 1 shows the wind turbine system.

The reliability of a wind turbine system is defined as the probability that the system will perform a specific function without failure under given conditions for a defined period of time.

Every production system must ensure two things, namely:

- reliability of operation, which enables uninterrupted process flow,
- safety of human life and health, as well as the preservation of material and natural resources.

The term failure refers to a condition in which the quality of the system is compromised (Adamović & Radovanović, 2008). The production of energy largely depends on the reliability of the wind turbine system. By understanding failures and minimizing them, high reliability can be achieved. Through maintenance planning, more efficient maintenance is ensured, and the possibility of reducing failures increases. In order to select the most effective maintenance strategy, it is necessary to identify the most critical components of the wind turbine system, which are prone to failure. It is also essential to consider reliability improvement and the reduction of maintenance costs.

Reliability analysis of a wind turbine system is based on a systematic approach to its subsystems, since the overall reliability directly depends on the reliability of the subsystems (Botsaris et al, 2012).

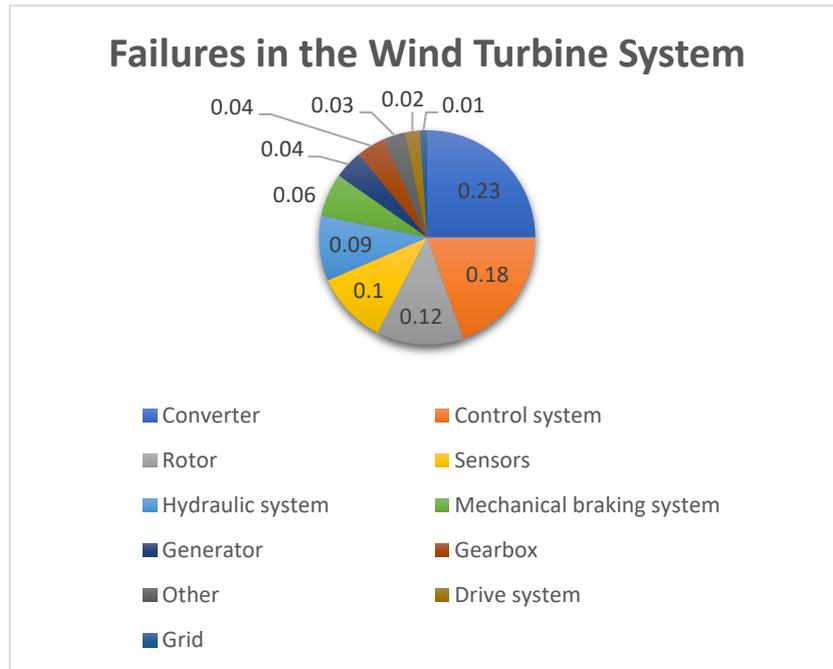
Wind energy is one of the dominant renewable energy sources worldwide. However, wind turbine systems are often prone to failure, and Hossain et al. (2018) argue that the harsh environmental conditions in which wind turbines are deployed are the main cause of such failures. The authors emphasize that implementing reliable condition monitoring is essential.

Graph 1 presents the types of failures that occur in a wind turbine system.

For generators, the causes leading to failure include:

- open/short circuit,
- insulation damage,
- imbalance,
- broken rotor bar,
- bent shaft,
- bearing failure,
- air gap eccentricity,

- magnet failures,
- rotor mass imbalance.



Graph 1 - Types of failures in the wind turbine system (Hossain et al, 2018)

Gearbox failures account for about 35% of total wind turbine failures, and the most common include:

- gear tooth abrasion,
- tooth cracking,
- tooth breakage,
- surface fatigue.

These faults can lead to significant temperature increases.

Tower failures are mainly caused by:

- structural corrosion,
- structural cracks,
- structural damage.

Tower failures are triggered by improper installation, overloading, poor quality control, as well as by extreme weather conditions such as lightning, fire, and earthquakes (Hossain et al, 2018).

An increasing number of countries aim to produce the highest share of their electricity from wind energy. It is evident that as wind turbines

develop, both their dimensions and weight increase. Figure 2 shows the trend in the increase of rotor diameter and wind turbine power.

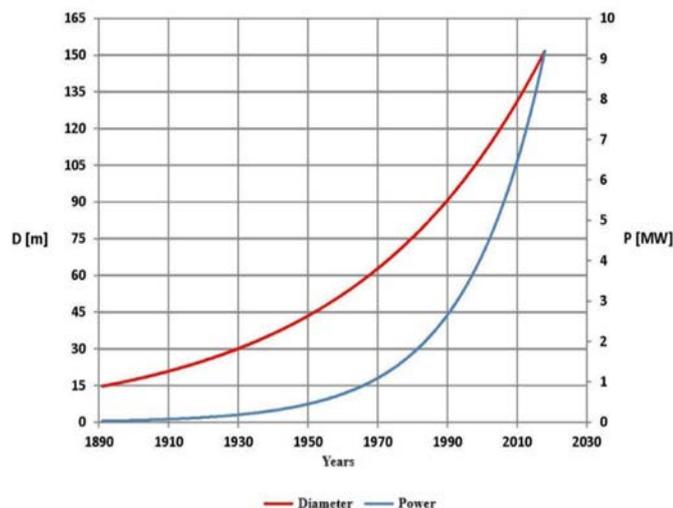


Figure 2 - Trend in the increase of rotor diameter and wind turbine power (Hossain et al, 2018)

## Failure mode, effects and criticality analysis (FMECA)

For the initial selection of critical system components, which were entered into the working sheet of the FMECA method, the following subsystems were selected: tower, generator, yaw system, and gearbox. The reason for choosing these parts of the wind turbine system is that they represent general events in the FTA (Fault Tree Analysis) which can directly lead to the failure of the entire wind turbine system (Novaković et al, 2023). The FTA analysis of the wind turbine system was addressed in the paper “Evaluating wind turbine power plant reliability through fault tree analysis,” Novaković B., 2023, Applied Engineering Letters, 8(4), pp. 175–182. Therefore, it can be freely stated that this research is a continuation of the aforementioned study.

Pal Kour et al. (2019) report that industries have acknowledged the importance of wind turbine system reliability. Reliability analysis can reduce the number of hazardous events by lowering the failure rate. There are various methods for performing reliability analysis of wind turbine systems, among which are Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA). These two are analytical techniques that can

be applied to analyze the reliability of a system and its related features (Pal Kour et al, 2019).

For a detailed and more objective analysis of the wind turbine system, FMEA and FTA methods are suitable. FTA is based on deductive logic that assumes failures and their likelihood of occurrence, while FMEA investigates the behavior of system components during failure. FMEA involves the evaluation of indicators such as severity, occurrence, and detection. FMEA identifies failure modes and the effects (consequences) they leave on the system or other components (Tazi et al, 2017).

FMEA is used to identify and prevent problems, focusing primarily on preventing issues and improving safety. The Risk Priority Number (RPN) is used to assess the risk of a specific failure. This number is the product of occurrence, severity, and detection ratings. The main reason for conducting FMEA is to prevent the possibility that a new system or process may fail to meet proposed requirements under certain conditions and within defined purposes and boundaries. Additionally, the purpose of the method is to eliminate failures and improve the system. When used during the design phase, the goal is to prevent future failures. When used during operation, the aim is system control and monitoring. Key advantages of using FMEA include: cost reduction, shortened time from design to commissioning, improved quality, increased reliability, and enhanced safety (Dev Sharma & Srivastava, 2018).

The Failure Mode and Effect Analysis (FMEA) method is one of the best analyses for assessing reliability during the design phase. FMEA is a specific but subjective analysis used to identify potential causes and failure modes and to evaluate their consequences. The main goal is to detect and identify failures, then mitigate and reduce their risk. Therefore, it can be concluded that this analysis increases system reliability, quality, and safety (Tavner et al, 2010).

FMEA is an inductive method based on analyzing failures and their impact on the system, with the aim of acting preventively to avoid them. It anticipates risks, reduces them, or eliminates them. Its ease of application is one of its greatest advantages. A drawback of FMEA is that it focuses more on individual failure states than on their combinations. FTA compensates for this limitation (Arabian-Hoseynabadi et al, 2010).

However, for this research, the FMECA method, an extended version of FMEA, is of interest. FMECA includes risk ranking related to failure modes, allowing prioritization of solutions (Catelani et al, 2020). Each failure may have several causes, which must be documented in the FMECA report. Furthermore, the consequences of each failure for the system must be recorded. Failure effects are classified as local and global.

Local effects refer to the impact of the failure on the observed subsystem, while global effects represent higher-level consequences.

Therefore, the Failure Mode, Effects and Criticality Analysis (FMECA) is a logical extension of the FMEA method, encompassing both failure mode analysis and criticality assessment. Criticality analysis is the process of evaluating the degree of component criticality relative to the system. Criticality refers to the severity of failure consequences. Quantifying criticality and the probability of failure helps in making decisions about corrective actions and their priorities, as well as in determining clear boundaries between acceptable and unacceptable risk. Each observed failure effect is classified by its criticality in terms of the entire system's functionality. Table 1 provides an overview of criticality categories for each failure effect, according to the failure effects criticality scale (Gardijan, 2001).

Criticality analysis is performed using a method known locally as the critical elements method. The level of failure criticality in this method can be determined using criticality factors:

- Factor  $R_1$  – the probability of occurrence of a potential failure, determined according to Table 2,
- Factor  $R_2$  – significance of potential failure, determined according to Table 3,
- Factor  $R_3$  – probability of detecting a failure and preventing its manifestation, determined according to Table 4.

Criticality Level  $R$ , which is determined according to Table 5, is obtained as the product of these three factors:

$$R=R_1 \cdot R_2 \cdot R_3 \quad (1)$$

Table 1 - Categories of Failure Effect Criticality (Gardijan, 2001)

Failure Effect	Criticality Category (Criticality Level)
Insignificant loss of function	I
Partial loss of function	II
Loss of function after a certain period	II
Severe damage	III
Immediate function interruption with safety risk	IV

Table 2 - Probability of Occurrence of Potential Failure (Gardijan, 2001)

Evaluation Criterion $R_1$		
Probability of Occurrence	$R_1$	Possible Failure Rate
Very Low	1	0
Low	2-3	1/20000-1/10000
Measurable	4-6	1/2000-1/1000-1/1200
High	7-8	1/100-1/20
Very High	9-10	1/10-1/2

Table 3 - Significance of Potential Failure (Gardijan, 2001)

Evaluation Criterion $R_2$	
Significance	$R_2$
Negligible	1
Low	2-3
Moderate	4-6
High	7-8
Critical	9-10

Table 4 - Probability of failure detection (Gardijan, 2001)

Evaluation Criterion $R_3$	
Probability of failure detection	$R_3$
High	1
Measurable	2-5
Low	6-8
Very Low	9
Unlikely	10

Table 5 - Criticality Level (Gardijan, 2001)

Evaluation Criterion R	
Criticality Level	R
Low	<50
Medium	50-100
High	100-200
Critical	>200

The numerical values of factors R1, R2, and R3 are determined by comparing the established condition with the corresponding criterion for selecting parameter values, always considering the worst-case scenario. The values of all three factors range from 1 to 10, with each value having a specific meaning, as shown in the tables.

By multiplying all three factors, the criticality level is obtained, which represents the degree of system criticality. Criticality is low if  $R \leq 50$ , and "critical" if  $R > 200$ . When the criticality is "critical," i.e.,  $R > 200$ , certain corrective actions need to be defined to improve the condition or bring the system status back within acceptable limits.

The critical components of the wind turbine system identified are:

- Tower,
- Generator,
- Yaw system,
- Gearbox.

In the FMECA worksheet, tabularly presented in Figure 3, an overview of the failure modes, causes, and effects in the wind turbine system is provided. After this activity, a criticality analysis is conducted. The quantification of criticality and failure probability is carried out to assist in making decisions about corrective actions and their priorities, as well as in determining a clear boundary between acceptable and unacceptable risk.

Component	Function	Failure Type	R1	Failure Consequence		R2	Failure Cause	Failure Detection	R3	Criticality Level (Condition Rating) R	Corrective Actions	Remarks
				Local	Final							
1	2	3	4	5	6	7	8	9	10	11	12	13
Tower	Steel/Concrete Support	Structural Failure	3	Tower Failure	IV	7	Corrosion of Structure	Visual	1	21 (Low)	Anti-corrosive coatings	
Generator	Conversion of Mechanical Energy to Electrical	Rotor and Stator Failure	6	Generator Failure	III	9	Broken Bars	Visual	1	54 (Medium)	Bar Replacement	
		Bearing Failure	4	Generator Failure	III	8	Abnormal Vibrations	Vibroacoustic Method	5	160 (High)	Bearing Replacement	
Yaw System	Wind Direction Tracking	Yaw Motor Failure	1	Yaw System Failure	Loss of Function After Some Time	5	Wear	Mechanical Repair	9	45 (Low)	Yaw Motor Replacement	
		Meteorological Unit Failure	7	Yaw System Failure	Loss of Function After Some Time	4	Blade Damage	Visual	6	168 (High)	Meteorological Unit Replacement	
Gearbox	Acceleration of Rotor Speed from Low to the Speed Sufficient to Start the Generator	Poor Lubrication	9	Gearbox Failure	III	5	Presence of Contaminants in Oil	Spectrometric Analysis / Ferrography / Viscosity Measurement	4	180 (High)	Oil Replacement and Control	
		Poor Equipment	7	Gearbox Failure	III	7	Abnormal Vibrations	Vibroacoustic Method	3	147 (High)	Gearbox Replacement	

Figure 3 - FMECA Worksheet for Selected Components of the Wind Turbine System

## Conclusion

The aim of the research presented in this paper is to identify potential causes of failures in the wind turbine system components, which affect reliable and efficient operation, and to determine which component of the wind turbine system is most critical in terms of failure occurrence.

For these four subsystems, the criticality level was determined using the FMECA method, and it was concluded that the most critical part of the wind turbine system is the gearbox, with the failure cause being the presence of contaminants in the oil and a criticality level of 180, which represents a high criticality level.

It was concluded that component failures can lead to the failure of the entire wind turbine system, causing its downtime, which in turn reduces

reliability and increases maintenance costs. The FMECA method highlights the critical components of the system and provides an efficient method for system analysis. It also allows for the prioritization of problem-solving actions.

There are certain preventive measures and maintenance practices that can significantly impact the lifespan of the wind turbine system:

- Regular maintenance – inspection of all mechanical and electrical components, replacement of consumables, and monitoring of software systems,
- Real-time monitoring – modern monitoring systems that can detect and report irregularities or faults before they lead to more serious problems,
- High-quality staff training – personnel must be well-trained and familiar with all aspects of operation and maintenance.

With regular maintenance and proper monitoring, failures in wind turbines can be minimized.

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Primena FMECA metode za identifikaciju otkaza u vetroturbinskim sistemima

*Branislava Radišić, autor za prepisku, Ljiljana Radovanović, Borivoj Novaković, Jasmina Pekez, Slavica Prvulović, Eleonora Desnica*  
Univerzitet u Novom Sadu, Tehnički fakultet „Mihajlo Pupin“, Zrenjanin, Republika Srbija

OBLAST: mašinstvo  
KATEGORIJA (TIP) ČLANKA: naučni rad

**Sažetak:**

*U ovom radu prikazani su potencijalni uzroci otkaza komponenti vetroturbinskog sistema koji utiču na pouzdan i efikasan rad iste. Otkazi komponenti u vetroturbinama mogu dovesti do potpunog otkaza sistema, što rezultira zastojima, smanjenom pouzdanošću i povećanim troškovima.*

Zarad maksimalnog iskorišćenja potencijala energije vetra, bitno je potencijalne otkaze svesti na minimum. Primenom FMECA metode (Failure mode Effects and Criticality Analysis) utvrđene su kritične komponente vetroturbinskog sistema, čime se pruža mogućnost da se odrede prioriteta za rešavanje problema. Rezultati naglašavaju važnost održavanja i optimizacije dizajna radi smanjenja rizika od otkaza i maksimizacije iskorišćenja energije vetra.

Uvod/cilj: Pouzdanost vetroturbinskih sistema igra ključnu ulogu u obezbeđivanju stabilnog i efikasnog snabdevanja električnom energijom iz obnovljivih izvora. Otkaz bilo koje komponente može izazvati zastoj sistema, smanjiti njegovu pouzdanost i povećati troškove eksploatacije. U tom kontekstu, važno je prepoznati i analizirati potencijalne kvarove kako bi se poboljšala celokupna pouzdanost sistema. Cilj ovog rada je analiza pouzdanosti vetroturbinskog sistema primenom FMECA metode. Fokus je na identifikaciji najkritičnijih komponenti i razumevanju uzroka i posledica njihovih otkaza, kako bi se doprinelo unapređenju projektovanja, održavanja i rada sistema.

Metode: U ovom radu primenjena je metoda FMECA (Failure Modes, Effects, and Criticality Analysis), koja omogućava detaljnu procenu potencijalnih otkaza sistema, njihovih uzroka i posledica, kao i identifikaciju najkritičnijih tačaka sistema na osnovu kvantitativnih parametara. Metodologija obuhvata sledeće korake: identifikaciju ključnih komponenti vetroturbine, uključujući rotor, menjač, generator, sistem za upravljanje i druge podsisteme; definisanje mogućih načina otkaza za svaku komponentu, uz navođenje mehanizama koji mogu dovesti do kvara (habanje, pregrevanje, mehaničko oštećenje itd.); procenu posledica otkaza, kako na samu komponentu, tako i na celokupan rad vetroturbine; numeričku procenu rizika kroz dodeljivanje vrednosti za: verovatnoću pojave potencijalnog otkaza ( $R_1$ ), značaj potencijalnog otkaza ( $R_2$ ) i verovatnoću otkrivanja otkaza i sprečavanje njegovog ispoljavanja ( $R_3$ ); izračunavanje nivoa kritičnosti ( $R$ ) korišćenjem izraza  $R = R_1 \cdot R_2 \cdot R_3$ ; rangiranje komponenti prema  $R$  vrednostima, radi identifikacije onih koje najviše ugrožavaju pouzdanost sistema i zahtevaju prioritarno praćenje ili optimizaciju.

Rezultati: Rezultati FMECA analize pokazali su da su najkritičnije komponente vetroturbinskog sistema: menjač – najviši nivo kritičnosti ( $R$  vrednost), jer otkaz menjača može dovesti do potpunog zastoja sistema i iziskuje skupe popravke; generator – visoka ozbiljnost otkaza i srednji nivo mogućnosti otkrivanja problema; sistem za upravljanje vetroturbinom – iako su otkazi ređi, posledice mogu biti ozbiljne zbog gubitka kontrole nad turbinom. Na osnovu analize, komponente su svrstane u prioritete održavanja i praćenja, s ciljem pravovremene detekcije potencijalnih kvarova i prevencije havarija.

*Zaključak: FMECA metoda se pokazala kao efikasno sredstvo za identifikaciju i rangiranje potencijalno kritičnih komponenti vetroturbinskog sistema. Rezultati ukazuju na to da menjač, generator i sistem za upravljanje predstavljaju najosetljivije tačke sistema. Njihovo preventivno održavanje, uz uvođenje sistema za praćenje stanja i unapređenje dizajna, može značajno povećati pouzdanost i smanjiti operativne troškove. Ova analiza može poslužiti kao osnova za unapređenje strategija održavanja i povećanje efikasnosti rada vetroparkova.*

*Ključne reči: energija vetra, vetroturbinski sistem, otkazi komponenti, FMECA metoda, pouzdanost, preventivno održavanje.*

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