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STRUCTURAL FAILURE ANALYSIS OF THE HIGH-SPEED SHAFT COUPLING ARM IN WIND TURBINE

B N Nathish Sanjay, PG Student, Department of Engineering Design, Government College of Technology, Coimbatore, 641 013. Tamil Nadu, India. nathishcool444@gmail.com
T Sekar, Professor, Head of the Department, PG-Manufacturing Engineering, Government College of Technology, Coimbatore, 641 013. Tamil Nadu, India.
Daniel Antony Arokiyasamy, Full time PhD scholar, Government College of Technology, Coimbatore, 641 013. Tamil Nadu, India.

Abstract:
This study investigates the frequent damage to the high-speed shaft coupling arm in a 750 KW wind turbine. Initially, the damaged arm was modelled using a 3D scanner for future reference. SolidWorks 2023 was employed to design an accurate and feasible 3D model of the high-speed shaft coupling. The loading data corresponding to the wind turbine's various operating conditions are further simulated using ANSYS R19 software for carrying out a structural study of this high-speed shaft coupling design. The three-loading condition represents the operation scenarios of a wind turbine while the wind velocity is 16 m/s, the wind velocity is 25 m/s, and the sudden brake is applied at a maximum angular velocity of 158 rad/s. The simulations aimed to identify potential causes of damage under these conditions. The result indicates the highest stress experienced by the high-speed shaft coupling arm when a sudden brake is applied. This stress may have been caused by the reactive force produced during abrupt braking, which could be a potential reason that could cause damage to the high-speed shaft coupling arm. This issue could possibly be reduced by implementing a change in the braking module or by altering the current module with an alternate braking system.

Keywords: high-speed shaft coupling, structural analysis, total deformation

1.INTRODUCTION

The uneven heating of the atmosphere by the sun and the inequalities on the earth's surface generate winds. Wind turbines are one of the most efficient ways to harness wind energy. The components of a wind turbine system consist of a blade, coupling, power generator, tower, rotor shaft, gearbox, and several controllers for wind power generators, high-speed shaft couplings should be able to perform the same functions as general industrial couplings namely, absorbing potential axial and radial displacements and reliably transmitting power as well as acting as an insulation to prevent high current from flowing from the generator into the speed increaser. One of the main parts of a wind power generator is this kind of coupling, and IEC 61400 and the GL Guideline cover issues related to its design, operation, and verification It must continue to be durable for at least 20 years even in the event that the gearbox or generator experiences concentricity misalignment, or a change in the distance between the shaft ends [1, 2]. Products with a minimum 20-year lifespan are anticipated, thus only highly reliable products are allowed to hit the market [3, 4]. Although natural wind is a free resource, construction and maintenance are the primary expenses associated with the generation of wind power. However, like any complex machinery, wind turbines are susceptible to component failure, which can lead to downtime, reduced energy production, and increased maintenance costs. While world energy demand continues to increase at an average annual rate of about 2%, most of that demand (around 80%) is being met by fossil fuels (IEA 2018). In India, total wind power operational capacity is 46162 MW (April 2024), and renewable energy sources (excluding large hydro) currently account for 30.08% (125160 MW) of India’s overall installed power capacity of 416059 MW (March 31, 2023) [IWTMA 2024]. The high-speed shaft coupling is a power delivery component that facilitates the delivery of high torque from the gearbox in wind turbines. It also maintains effective power generation by accommodating the distance between the gearbox and generator and preventing shaft misalignment

[5–7]. This study intends to find the potential reason for the cause of the 750 KW wind turbine high-speed shaft coupling arm. The structural analysis was carried out under the conditions of wind velocity of 16 m/s where torque applied is 11,500 [Nm], wind velocity of 25 m/s where torque applied is 44,500 [Nm], and applying a sudden brake with 120 bar pressure at a maximum angular velocity of 158 rad/s.

2.DESIGN OF THE HIGH-SPEED SHAFT COUPLING

First, the damaged high-speed shaft coupling arm from a 750 KW wind turbine was modelled using a 3D scanner (Figure 1). This model provides a detailed and accurate preview of the deformation, capturing even the smallest imperfections and wear patterns. This comprehensive depiction is invaluable for future reference, enabling precise analysis, comparison, and repair planning. It ensures that any recurring issues can be accurately identified and addressed.

Figure 1 Model of damaged high-speed coupling arm

The 3D model of the high-speed shaft coupling from the 750 KW wind turbine was designed using SolidWorks. This model shows a detailed view of how the high-speed shaft coupling looks and helps to stimulate the operating conditions of the wind turbine. This model consists of a flange, brake disk, arm, and shaft. The arm is made of cast iron, and the flange, brake disk, and shaft of the high-speed shaft coupling are made of carbon steel 1040. Table 1 shows the material properties of the cast iron, carbon steel 1040, which is used as input data for the structural analysis.

Table 1 Materials Properties

Components	**Material**	**Elastic Modulus [GPa]**	**Poisson's Ratio**	**Yield Strength [MPa]**	**Tensile Strength [MPa]**
Flange	Carbon Steel 1040	210	0.3	655	965
Brake disk	Carbon Steel 1040	210	0.3	655	965
Arm	Cast Iron	185	0.3	400	700
Shaft	Carbon Steel 1040	210	0.3	655	965

The high-speed shaft coupling epitomizes engineering precision, relying on meticulously selected materials to ensure seamless power transmission. The 3D model of high-speed shaft coupling. Within its structure lie critical components, each chosen for its unique properties and contribution to operational integrity. From carbon steel 1040 flanges to cast iron arms, the material specifications weave a narrative of strength, resilience, and efficiency. In the high-speed shaft coupling lie several vital components, each fulfilling specific functions crucial for effective torque transfer and system stability. The flanges, brake disks, and shaft, crafted from carbon steel 1040, serve as the interface between driving and driven shafts. With an elastic modulus of 210 [GPa], these components endure high-speed rotations with ease, backed by a yield strength of 655 [MPa] and a tensile strength of 965

[MPa], ensuring durability under intense conditions. The arm, essential for stabilizing the system and dampening vibrations, is made of cast iron. Despite a slightly lower elastic modulus of 185 [GPa] compared to carbon steel 1040, cast iron compensates with a yield strength of 400 [MPa] and a tensile strength of 700 [MPa]. This material choice optimizes the arm's ability to absorb shocks and maintain stability, which is crucial in high-speed applications where vibrations pose significant challenges. The meticulous material selection for the high-speed shaft coupling underscores a commitment to engineering excellence. Each component is tailored to withstand the demanding conditions of modern machinery, where efficiency and reliability are paramount. carbon steel 1040's superior properties of strength and resilience, combined with cast iron's damping capabilities, create a coupling system that excels in performance and durability.

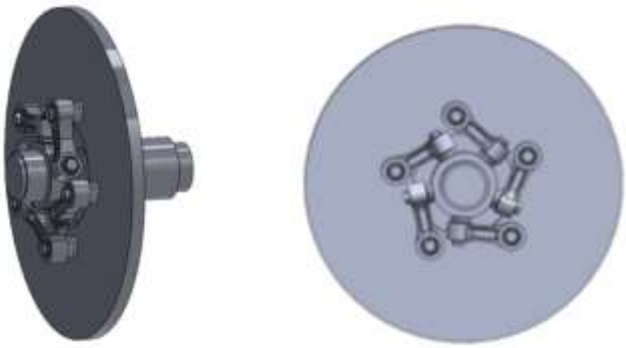


Figure 2. Model of high-speed shaft coupling

Figure 2 shows a meticulously designed 3D model of a high-speed shaft coupling arm, created using SolidWorks 2023. SolidWorks, known for its precision and advanced modelling capabilities, has facilitated the creation of this detailed and complex component. The high-speed shaft coupling arm is an essential part of a 750 KW wind turbine, responsible for transmitting power from the gearbox to the generator. This component also plays a critical role in minimizing axial and radial displacements that occur during the turbine's operation, thereby ensuring the efficiency and reliability of the power transmission process. The 3D model showcases the coupling arm attached to a disk, likely representing the brake disk in the wind turbine's mechanical system. The coupling arm's design includes several intricate elements, such as bolts and structural supports, which are crucial for its functionality and durability. Using SolidWorks for the modelling process ensures that the design is both accurate and feasible for real-world applications. SolidWorks allows for the creation of highly detailed models that can be easily adjusted and tested under various conditions, making it an ideal tool for designing complex mechanical components like the high-speed shaft coupling arm. The ability to visualize the component in 3D helps engineers identify potential issues and optimize the design before physical production, reducing the risk of failure and improving overall performance.

2.1. SPECIFICATIONS

The wind turbine in question boasts a rated power output of 750 KW, making it a significant contributor to renewable energy production. It begins operation at a cut-in wind speed of 4 m/s and reaches its rated power at a wind speed of 16 m/s. To protect the turbine from damage, it shuts down at a cut-out wind speed of 25 m/s, but it can withstand survival wind speeds of up to 60 m/s. The turbine features a rotor diameter of 48.2 meters, which covers a swept area of 1,824 m^2, capturing wind energy efficiently. This turbine is equipped with three blades, a standard configuration for maximizing aerodynamic efficiency. The maximum rotor speed is 22 RPM, and the tip speed can reach 56 m/s, ensuring optimal energy capture from the wind. The gearbox employed is of the spur/planetary type, offering a gear ratio of 1:68, which effectively steps up the rotor speed to match the generator requirements. Consequently, the maximum generator speed is 1,500 RPM. Electrical specifications include a voltage of 690 V and compatibility with a grid frequency of 50 Hz, ensuring seamless integration with the power grid. Figure 3 shows the power curve of the 750 KW wind turbine. These specifications collectively highlight the turbine's robust design and capability to efficiently convert wind energy into electrical power while ensuring durability and operational safety across a range of wind conditions.

Figure 3. Power curve of 750 KW wind turbine [8]

In mechanics, torque is a basic notion that describes the rotating force exerted on an object. It is crucial in the operation of wind turbines, as it directly influences the conversion of wind energy into mechanical energy by causing the rotor blades to spin. Understanding torque is essential for optimizing the performance and efficiency of wind turbines. A wind turbine's torque is directly correlated with the speed of the wind. More kinetic energy is transferred to the turbine blades at higher wind speeds, which increases torque.

$$T = \frac{P_{mech}}{\omega}$$

$$\omega = \frac{2\pi \times RPM}{60}$$

T – Torque

ω - Angular velocity (rad/s)

Table 2. Loading data

Wind velocity (m/s)	**Air density (kg/m³)**	**Swept area (m²)**	**Wind Force (N)**	**Mechanical power (W)**	**Torque (Nm)**
16	1.225	1824	286,003	1,830,420	11,500
18	1.225	1824	361,972	2,606,204	16,600
20	1.225	1824	446,880	3,575,040	22,800
22	1.225	1824	540,724	4,758,378	30,400
24	1.225	1824	643,507	6,177,669	39,500
25	1.225	1824	698,250	6,982,500	44,500

3.ANALYSIS OF HIGH-SPEED SHAFT COUPLING

Structural analysis is a critical aspect of engineering, focusing on the assessment of structures to ensure they can withstand applied loads and forces. In the context of wind turbines, structural analysis evaluates the mechanical strength and stability of various components, such as blades, towers, nacelles, and high-speed shaft couplings, under different operating conditions. This analysis is essential for optimizing design, enhancing reliability, and preventing failures. Structural analysis is carried out in the high-speed shaft coupling under the following operation conditions: Case 1: simulating the condition when the wind velocity is 16 m/s, which is the rated wind speed where the power generation is maximum. At this operating condition, the maximum torque experienced in the high-speed shaft coupling is 11,500 Nm. Case 2 simulates the condition when the wind velocity is 25 m/s, which is the cut-out velocity at which the wind turbine operates. At this condition, the maximum torque experienced is 44,500 Nm. This is a rare operating condition. Case 3: simulating the conditions while applying the brake where the high-speed shaft coupling operates at its maximum angular velocity of 158 rad/s.

3.1 CASE 1-WIND VELOCITY 16 m/s

In this case study, we will perform a structural analysis of a wind turbine operating under a specific wind velocity. This analysis will focus on understanding the impact of wind velocity on the structural integrity and performance of the high-speed shaft coupling arm, a critical component that often experiences damage. we consider a wind velocity of 16 m/s, which is a common operational wind speed for many wind turbines. This velocity is within the typical range for efficient energy generation but can also exert significant forces on the turbine components.

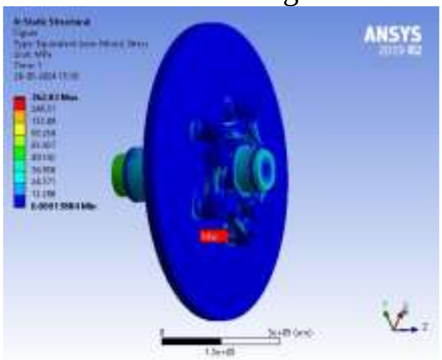


Figure 4 Case1- High-speed shaft coupling

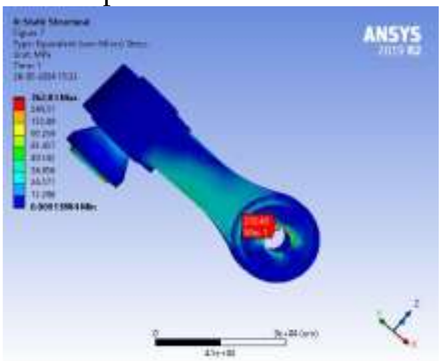


Figure 5 Case1- High-speed shaft coupling arm

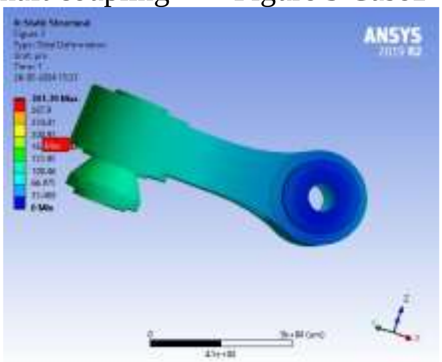


Figure 6 Case2-Total Deformation of high-speed shaft coupling arm

Under the rated wind velocity condition of 16 m/s, the high-speed shaft coupling experienced a maximum von-Mises stress of 238.49 MPa (Figure 4,5). This stress level is within the material's yield strength, indicating that the coupling can operate safely under normal conditions. The stress distribution shows that the highest stress concentrations are located near the points where the shaft connects to the gearbox and the generator. These areas are critical because they are subjected to both torsional and bending stresses. The deformation under this condition was 301.39 µm (Figure 6) which is minimal, indicating that the coupling maintains its structural integrity during normal operations. Indicating that normal operating conditions do not significantly contribute to arm damage.

3.2 Case 2 – WIND VELOCITY 25 m/s

In this case study, we will perform a structural analysis of a wind turbine operating under a specific wind velocity. This analysis will focus on understanding the impact of wind velocity on the structural integrity and performance of the high-speed shaft coupling arm, a critical component that often experiences damage. we consider a wind velocity of 25 m/s, which is a rare operational wind speed for many wind turbines. Stable wind flow at this velocity is rare.

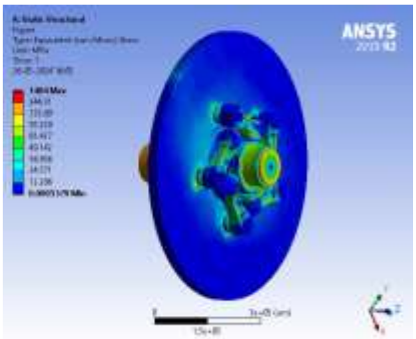


Figure 7 Case 2- High-speed shaft coupling

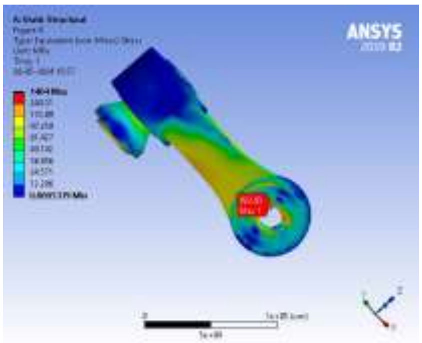


Figure 8 Case2-High-speed shaft coupling arm

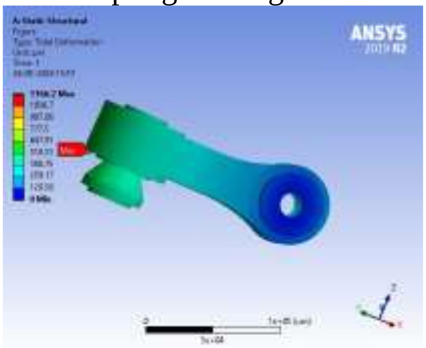


Figure 9 Case2-Total deformation of high-speed shaft coupling arm

When simulating the cut-out wind velocity condition of 25 m/s, the maximum von-Mises stress on the coupling increased significantly to 922.83 Mpa (Figure 7,8). This wind speed is considered rare and is typically experienced during extreme weather conditions. The substantial increase in stress is due to the higher aerodynamic forces acting on the turbine blades, which are transmitted through the gearbox to the coupling. At this condition the total deformation was about 1166.2 µm (Figure 9). The stress distribution under this condition showed that the areas near the connections and the mid-span of the coupling experienced the highest stresses. The deformation was also more pronounced compared to the rated wind velocity condition. However, since these conditions are infrequent, they are less likely to be the primary cause of arm damage.

3.3 Case 3 – APPLYING BRAKE AT MAXIMUM ANGULAR VELOCITY (158 rad/s)

At this case, the simulation was carried out on the condition of applying sudden brake at the maximum angular velocity of 158 rad/s. Under this scenario, the maximum von-Mises stress on the coupling soared to an alarming 4637.8 Mpa (Figure10,11). This stress level far exceeds the typical yield strength of most materials used for shaft couplings, indicating a high likelihood of material failure if the coupling were subjected to such conditions. The stress distribution revealed that the highest stress concentrations were located at the points where the braking force was applied and near the arm connected to the shaft. The extreme stress levels suggest that the braking mechanism and the coupling design must be robust enough to handle emergency braking scenarios. The deformation under this condition was maximum of 5965µm (Figure 12).

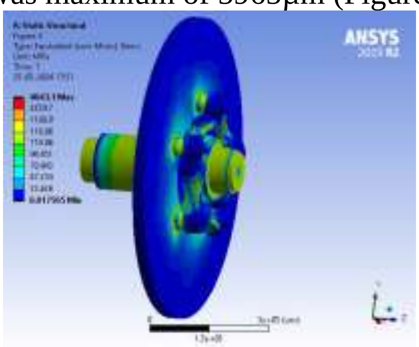


Figure 10 Case3-High-speed shaft coupling

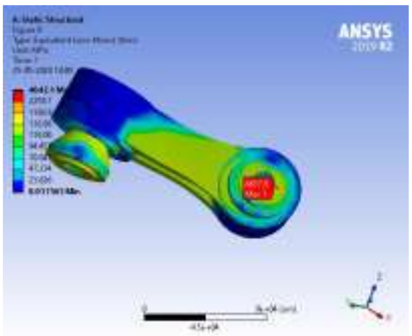


Figure 11 Case3-High-speed shaft coupling arm

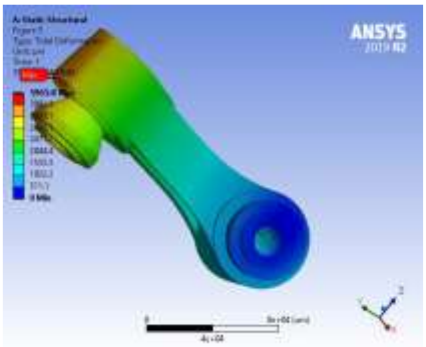
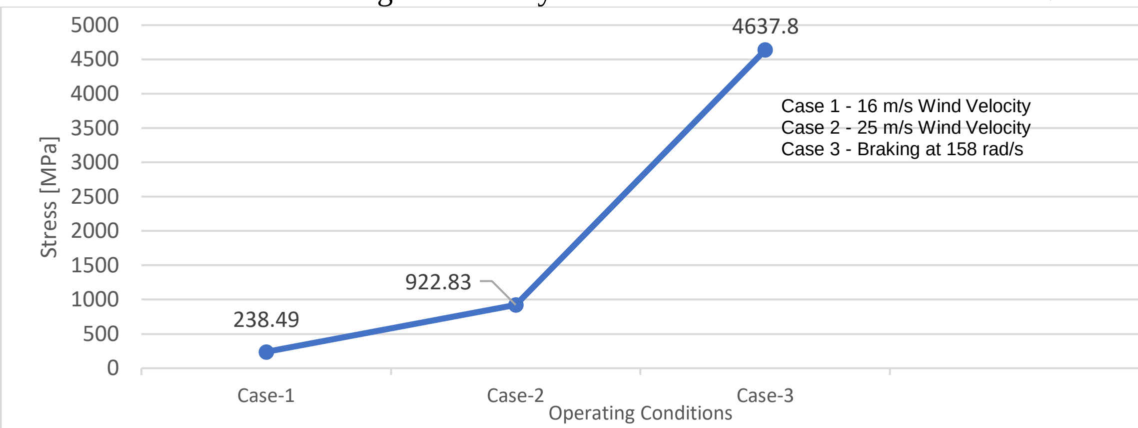


Figure 12 Case3-Total deformation of high-speed shaft coupling arm

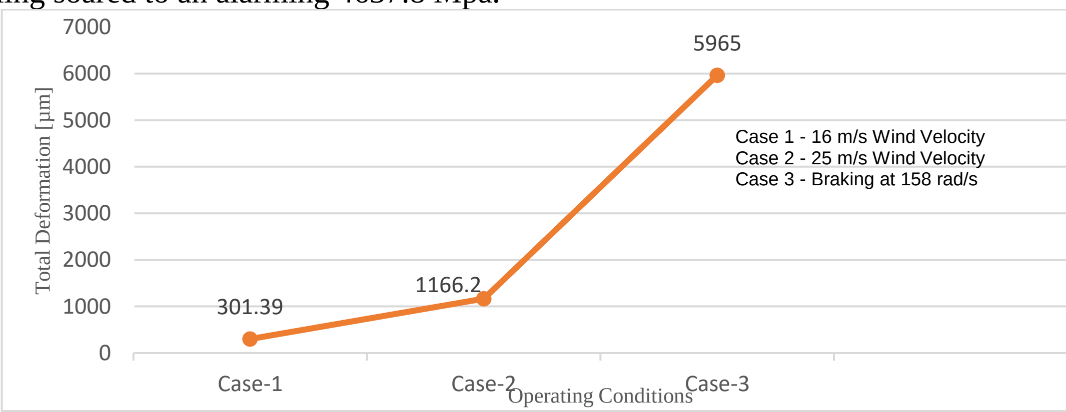
4.RESULT AND DISSCUSSION

The graph 1 illustrates the stress experienced by the high-speed shaft coupling arm under three different operating conditions of a 750 KW wind turbine. In Case 1, at a wind velocity of 16 m/s, the stress is relatively low at 238.49 MPa. As the wind velocity increases to 25 m/s in Case 2, the stress rises significantly to 922.83 MPa. The most dramatic increase occurs in Case 3, where the application of a sudden brake at a maximum angular velocity of 158 rad/s results in a stress of 4637.8 MPa.



Graph 1 Comparison of stress value of all three cases

The sharp rise indicates that the reactive force generated during abrupt braking exerts a substantial load on the coupling arm, potentially leading to damage (Graph 1). This substantial increase in stress in Case 3 indicates a considerably higher mechanical load or operational strain compared to the other two cases. The pronounced difference underscores the need for enhanced safety measures and more robust structural designs to accommodate the elevated stress levels encountered in Case 3. The most critical condition analysed was the application of the brake while the turbine was operating at its maximum angular velocity of 158 rad/s. Under this scenario, the maximum von-Mises stress on the coupling soared to an alarming 4637.8 Mpa.



Graph 2 Comparison of Total deformation of all three Cases

Shows the stress value while applying brake over the time period. This stress level far exceeds the typical yield strength of most materials used for shaft couplings, indicating a high likelihood of material failure if the coupling were subjected to such conditions. The stress distribution revealed that the highest stress concentrations were located at the points where the braking force was applied and near the arm connected to the shaft. The extreme stress levels suggest that the braking mechanism and the coupling design must be robust enough to handle emergency braking scenarios. The deformation under this condition was maximum of 5965μm.This condition could be the potential reason for the cause of arm damage.

5.CONCLUSION

The investigation into the deformation of the high-speed shaft coupling arm of a 750-kW wind turbine has revealed valuable insights through structural analysis under various operating conditions. Among these conditions, one standout scenario emerged where the application of the brake while the high-speed shaft coupling operates at maximum angular velocity likely contributes significantly to the observed damage. The structural analysis results point towards the reactive force generated during sudden braking could be the reason behind the deformation of the high-speed shaft coupling arm. This force, when exerted on the coupling system, has the potential to not only cause damage to the arm but also affect other components within the coupling mechanism. In light of these findings, it is imperative to address this issue to minimize damage and improve the efficiency of wind turbines while reducing maintenance costs. A potential solution lies in revisiting the design and functionality of the braking module. By implementing changes to the braking mechanism, such as incorporating gradual braking systems or enhancing shock absorption capabilities, the impact of reactive forces on the high-speed shaft coupling can be mitigated. Moreover, proactive measures such as regular inspection and maintenance of the braking module can also contribute to identifying and addressing potential issues before they escalate into significant damage. By prioritizing the optimization of the braking system, wind turbine operators can ensure the longevity and reliability of the high-speed shaft coupling, ultimately enhancing the overall performance of the turbine. In conclusion, the structural analysis results highlight the need for proactive measures to mitigate damage to high-speed shaft coupling arms in wind turbines, particularly under conditions involving sudden braking of force of 120 bar pressure on the brake disk. By implementing changes to the braking module and adopting regular maintenance practices, operators can minimize damage, improve efficiency, and reduce maintenance costs, thereby optimizing the performance of wind turbines in renewable energy generation.

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