Wind Turbine O&M (Operation and Maintenance) practices and optimization

Authors: Melethil, Tariq anwar and Pangerl, Marc

Table of contents

1. Abstract

As wind turbines stand as crucial contributors to sustainable energy, their operational efficiency depends on robust Operation and Maintenance (O&M) practices. This paper explores the strategic landscape of Wind Turbine O&M, emphasizing the shift from preventative to predictive maintenance strategies. The focus extends to specific challenges, such as the detrimental effects of icing on turbine blades, addressed through hydrophobic coatings applied by robots. Corrosion protection, particularly in offshore environments, is examined, utilizing coatings, cathodic protection, and corrosion allowance across distinct zones on the turbine tower. Phased Array Ultrasonic Testing (PAUT) emerges as a key tool for corrosion inspection.

The study delves into gearbox maintenance, highlighting temperature monitoring, vibration analysis, and early-warning methods to prevent failures. Different types of wind turbine gearboxes are evaluated, considering their advantages and drawbacks. Additionally, the paper explores advanced techniques like the 3σ criterion and Nonlinear State Estimate Technology (NSET) for gearbox fault prediction.

The importance of continuous gearbox monitoring through ICP® accelerometers is emphasized, providing insights into sensor mounting strategies. Gearbox oil change procedures are dissected, including methods like offline filtration, with an analysis of their impact on oil properties and wind turbine performance. The research incorporates real-world scenarios, presenting challenges and solutions in wind turbine maintenance.

The paper concludes with an exploration of a cutting-edge technology, the CMM-G Wind Turbine Gearbox Oil Changer, highlighting its versatility in performing multiple maintenance functions. Through a comprehensive analysis, this research aims to provide valuable insights for optimizing Wind Turbine O&M strategies, ensuring the longevity and optimal performance of wind energy systems.

2. Introduction

Wind turbines stand as sentinels of sustainable energy, but their continued operation hinges on robust Operation and Maintenance (O&M) practices. The field of Wind Turbine O&M is not just about addressing wear and tear; it's about the strategic interplay of ongoing care, technical troubleshooting, and the fine-tuning of processes to ensure peak performance. As the demand for renewable energy sources intensifies, optimizing these practices has become pivotal. This not only maximizes energy output but also extends the lifespan of the turbines, thereby increasing the efficiency of the investment. The evolution of O&M strategies, from preventative to predictive maintenance, underscores a commitment to innovation and sustainability in harnessing wind power.

3. Maintenance Strategies

There are multiple strategies for maintaining wind turbines, with Preventive Maintenance and Corrective Maintenance being two of the most common approaches. Preventive Maintenance is proactive, involving scheduled and planned tasks to prevent breakdowns. Corrective Maintenance, on the other hand, is reactive; it is employed when a component fails, which can occur if Preventive Maintenance is neglected or if a breakdown happens despite regular preventive efforts.

4. Icing on Wind Turbine Blades

Icing on wind turbine blades can have several detrimental effects. Ice shedding from rotating blades can present a safety risk to the surrounding area, increase the structural load on the blades, and reduce the power output of the turbine [1]. As illustrated in the power curve of Figure 2, the reduction in power due to icing on the blades is significant and should not be ignored.

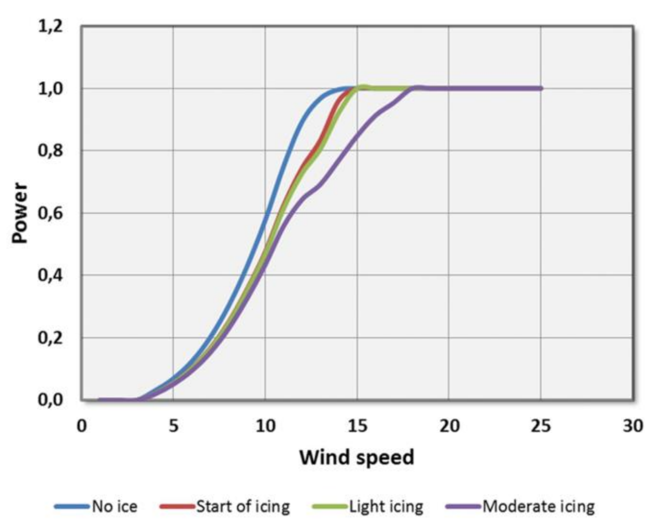

Figure 1: Power curves of each icing cases and a clean wind turbine (no ice) as reference. [2]

Consequently, icing on blades needs to be addressed as a maintenance and operational subject.

4.1. Prevention of Icing

Several methods are available to prevent ice formation on turbine blades, with one effective approach being the application of a hydrophobic coating on the leading edge of the blades. These coatings create a surface that makes it more challenging for water droplets to freeze, often complemented by a blade heating system [3].

Applying the anti-icing coating to the leading edge of the turbine is primarily accomplished with the assistance of robots. As depicted in Figure 2, Aurones, a robotics company, utilizes robots to apply anti-icing coatings on wind turbine blades.

Figure 2. Robot applies coating to the leading edge of a blade [4].

Using robots significantly enhances safety measures, eliminating the need for humans to scale the turbine using ropes. Although humans oversee the setup and operation of the robots, approximately three technicians are required to manage this task [4].

Due to UV exposure, abrasion, and weathering, coatings gradually wear off and require reapplication. Typically, the lifespan of these coatings is approximately 4 years, necessitating a renewal thereafter [5]

5. Corrosion Protection of Offshore Wind Turbines

In 2016, the National Association of Corrosion Engineers (NACE) released its impact report estimating the global cost of corrosion to be around US$2.5 trillion [6]. This underscores corrosion as a significant financial factor requiring mitigation efforts. Implementing maintenance and correct operational methods to protect Offshore Wind Turbines (OWTs) from corrosion can lead to a substantial positive financial impact.

Corrosion is a significant issue in maritime environments across industries. Like oil and gas rigs, wind turbines face constant exposure to severe environmental elements. The gas and oil sector has grappled with prolonged exposure of their structures to such harsh conditions for decades. This experience provides the wind industry with valuable insights that it can utilize to its advantage to mitigate the effects. [7]

There are three specific zones on the tower of the wind turbines that require careful attention for corrosion monitoring: the Atmospheric zone, the splash zone, and the submerged zone. Figure 3 illustrates these distinct zones.

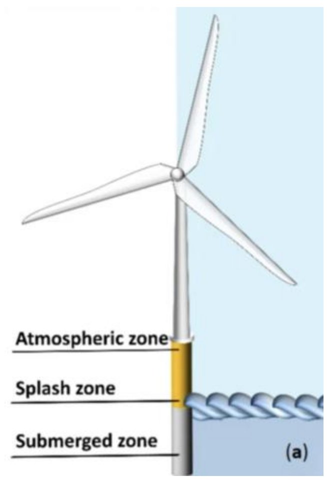

Figure 3: The different corrosion zones in an offshore wind turbine [8]

All three zones need to be controlled and maintained for corrosion in different ways. Corrosion protection can be categorized into three types: Corrosion-protective coatings, Cathodic Protection (CP), and Corrosion Allowance (CA) [7].

5.1. Corrosion-protective coating

To prevent metal surface oxidation, which causes material degradation and loss, a protective film or barrier is applied over the metal surface. Figure 4 illustrates the process of coating application on an Offshore Wind Turbine (OWT). These barriers often comprise paints or polymer coatings [9].

However, challenges arise with coatings when they are improperly applied or affected by external factors, resulting in surface scratches that expose the metal to the environment, compromising its protection. Moreover, coatings degrade over time due to harsh environmental conditions and typically have a lifespan of approximately 10 years [7] .Consequently, damaged, or degraded coatings require restoration.

Figure 4: Worker puts protecting coating on OWT [10]

Restoring degraded or defective coatings, particularly in offshore environments, constitutes a highly challenging, hazardous, labor-intensive, and consequently expensive maintenance task.

5.2. Cathodic Protection (CP)

Another method of protecting the OWT (Offshore Wind Turbine) structure from corrosion is Cathodic Protection (CP). There are two approaches to achieve this. One is the Galvanic anode method. In this method, the structure intended for protection is linked to an anode (sacrificial anode), transforming the structure into a cathode Figure 4. The sacrificial anode, composed of a reactive material, releases electrons. Instead of corroding the cathode, it shields the structure by sacrificing itself and corroding in place of the structure. [11] The second method is impressed current cathodic protection (CCP). As seen in Figure 5 an external DC power source supplies the necessary electrons to protect the structure.

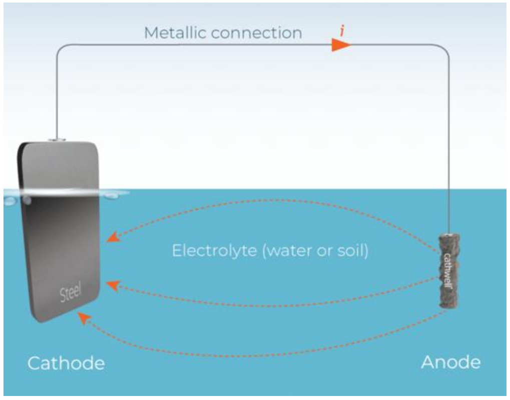

Figure 5:concepts of sacrificial cathodic protection [12]

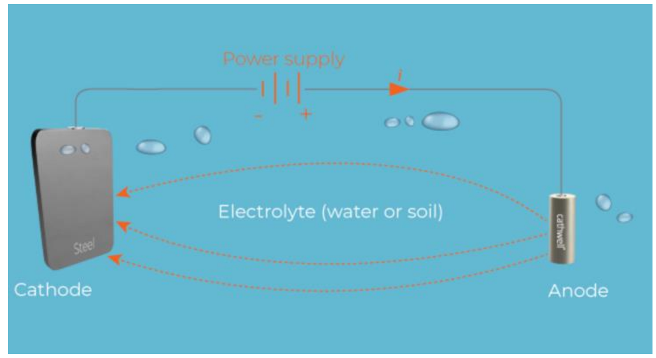

Figure 6:ICCP – impressed current cathodic protection [12]

The anode in this method does not need to sacrifice itself and therefore does not need to be replaced. Part of Operation and Maintenance is to replace sacrificed anodes when using the galvanic system or in the case of ICCP to monitor the process.

5.3. Corrosion Allowance (CA)

While coating the material or protecting it with CP actively tries to stop corrosion, Corrosion Allowance takes a different approach. In this method, a certain amount of extra thickness is added to the material, which can corrode without significantly affecting the structural integrity. It serves as a buffer, allowing some corrosion to occur without compromising the structure. Corrosion Allowance is used in conjunction with the other protective methods. [7] Regular monitoring and inspection of the structure's thickness is essential. This can be effectively accomplished using Phased Array Ultrasonic Testing (PAUT), a technique that will be elaborated upon in the following chapter.

5.4. Zone-Based Corrosion Defense

Because of the distinct zones and their varying levels of exposure to the environment, diverse types of protection are required.

In the *Atmospheric zone*, where the structure isn't directly exposed to seawater, applying a protective coating is suitable for protection. The *splash zone* is the most severe area. The structure is intermittently exposed to both seawater and air, leading to significant material stress, and making maintenance challenging, often resulting in infrequent upkeep. As this zone isn't continuously submerged, Cathodic Protection (CP) isn't feasible. To safeguard the Offshore Wind Turbine (OWT) from corrosion in this zone, a combination of coating and corrosion allowance is typically employed. In the *submerged zone*, where the structure remains underwater, employing Cathodic Protection (CP) is recommended to prevent corrosion. [8]

5.5. Corrosion control with Ultrasonic phased array (PA)

Phased Array Ultrasonic Testing (PAUT) serves as an exceptionally efficient method for inspecting corrosion and assessing the wall thickness in wind turbine foundations and towers. This technique utilizes multiple ultrasound beams to effectively penetrate the material for examination. The sensors can be operated manually (Figure 8) or with the assistance of remotely deployable robotic scanners (Figure 9).

Figure 7: Corrosion Mapping with a robotic scanner [13]

Figure 8: Manual scanning of WT Tower [13]

By connecting these sensors to the structure, variations in surface ultrasound reflection enable the detection of irregularities within the material's structure and facilitate wall thickness measurement. Consequently, this approach not only identifies corrosion but also expedites its timely remediation. [13]

6. Gearbox Preventive maintenance

The gearbox of the wind turbine is regularly submitted to random variation of stress due to the variable wind speed that can sometimes reach 80 kms/h. It frequently happens that the gearbox temperature increases dramatically. This increase of the temperature is correlated with an accentuated degradation of the gearbox components. For that reason, the current maintenance strategy of the gearbox consists in monitoring its state through its temperature. As soon as the latter exceeds a predefined threshold level, the wind turbine is slowed down reducing consequently the energy production rate, and the gearbox is cooled during a certain period before returning to the desired output rate. As this incident becomes more frequent with time causing additional production losses, the wind turbine operators will decide to renew the gearbox by a new identical one or perform an overhaul leading to as good as new state. The timing of the renewal is based on the judgement of maintenance operators. [14]

Different types of wind turbine gearboxes have been investigated in terms of technology, Mechanical planetary gearboxes are used in large wind turbines, they have a variety of drawbacks including high maintenance costs, a relatively high failure rate, and reduced dependability. Gearboxes with Continuously Variable Transmission (CVT) are used only in small and medium-sized wind turbines because of the material strength and manufacturing problems associated with them. Magnetic gearboxes are employed by both small and large wind turbines. Their advantages include the fact that there is no physical contact between the input and output shafts, which reduces the probability of failure, they also have the advantage of generating low acoustic and vibrational noises. The Variable Ratios Gearboxes (VRGs) may operate at a variety of rotor speeds to accommodate wind speed fluctuations under full or partial load conditions, respectively. In terms of tracking dependability, this type of gearbox performs very well. [15]

When it comes to preventing failures, it is of great practical significance to use reasonable and efficient methods to early-warning [16]. Both the scientific community and the wind business have made significant efforts to reduce early failures through a variety of design changes, and the development of optimal preventive maintenance strategies. Igba J. et al provided a method for determining the ideal PM period required to maintain the desired reliability of a typical module or subassembly by using historical failure data. This demonstrates how history in-service failure data may be used to choose PM tasks with the lowest possible maintenance cost and the highest possible availability. [17] The monitoring of the failure data is executed using the Supervisory Controlled Data Acquisition System (S.C.A.D.A), there are a large number of abnormal values in the data monitored by SCADA, the existence of these abnormal data has a serious impact on the fault warning of the gearbox. [16]

To overcome these abnormal values, these data can be preprocessed using the 3σ-median combination method and then the nonlinear state estimate technology (NSET) method is used to predict the gearbox temperature of wind turbine. When the gearbox works abnormally, the residual error between the predicted value and the actual value increases, and an alarm message is sent out when the gearbox exceeds the preset threshold value. [16]

6.1. PRINCIPLE OF 3σ CRITERION

The 3σ criterion is also called PauTa criterion, which assumes that a group of data obeys or approximately obeys the normal distribution and only contains random errors. The standard deviation of this set of data is calculated and an interval is determined according to a certain probability. It is considered that the error outside this interval is a gross error rather than a random error, which should be eliminated. A set of data is $x_i(i = 1, 2, \cdots, n)$, and calculate its average value x and deviation

$v_i = x_i - x(i = 1, 2, \ldots, n)$. If the deviation $v_b(1 \le b \le n)$ of a certain data x_b satisfies:

$|v_b| = |x_b - x| > 3\sigma$ (1)

It is considered that x_b is an abnormal data and should be eliminated. [16]

6.2. NSET MODELING PRINCIPLE

NSET is a data-driven method The basic idea of applying NSTE method to wind turbine fault early warning is to normalize the relevant data generated by the unit in the normal operating state to form a memory matrix, and then use the NSET model to achieve prediction. The operation state of wind turbine is determined according to the residual size, range, change and other information. [16]

7. Gearbox Vibration and Monitoring

Vibration monitoring has become a crucial method for identifying and diagnosing faults in gearboxes, utilizing vibrational patterns emitted by these systems to gain insights into the condition of internal components. Proactive maintenance measures can then be implemented based on the information obtained through vibration analysis, helping to mitigate the risks associated with unexpected breakdowns. This narrative delves into a wide spectrum of potential gearbox faults. Before selecting sensors and addressing their mounting on a gearbox, it is essential to revisit the characteristics of the vibration signature expected from common gearbox faults.

For instance, if there is a crack in a gear, it is likely to introduce a slight speed change when the defective tooth enters the load zone, resulting in impact every time that tooth assumes its load-carrying responsibility (typically once per revolution of that gear) [18] .The process of selecting and mounting sensors onto gearboxes is emphasized as a crucial step to ensure the acquisition of precise and reliable data. Real-world scenarios in various industrial landscapes, such as cooling tower gear systems, multi-drill head gear assemblies, crusher gear mechanisms, and precision tension bridle gear setups, are examined to provide tangible examples of diagnostic processes and decision-making based on vibrational insights.

In the presence of a fault generating stress wave activity on a set of meshing gears, that energy will be transmitted to the outer housing via the shafts where the gear set is attached through the bearings (assuming they are rolling element bearings). An accelerometer attached to the outer surface in the proximity of that bearing would capture the stress wave activity, provided the accelerometer has sufficient bandwidth and sensitivity. If the bearing is a sleeve bearing, significant attenuation will occur to the stress waves in coupling across the gap from the inner race to the outer race and may not be sufficient for capture by the sensor. A proximity probe lacks sufficient sensitivity for the relatively high-frequency stress wave activity. Besides the relatively high frequencies present in the stress wave packets generated by friction and impacting, the lower frequencies generated by faults such as misalignment, looseness, and balancing issues must also be captured and analyzed. These stress wave packets contain frequencies in one of the following two ranges. [18]

- About 0.3 times running speed to about 3.25 times the gear meshing frequency.
- About 0.3 times running speed to about 50 times running speed. [18]

The analysis of the low-frequency band involves capturing a time waveform and transforming it into spectra data, on which most of the diagnostics are performed. For the high-frequency band, the common procedure is to run the signal from the sensor through a high-pass filter followed by full-wave rectification. The rectified signal is then demodulated to extract any periodic or random activity that is occurring. If periodic or random activity is present, the analyst needs to know the periodic rate as well as the amplitude of the activity. [18]

Let's delve into the impact of sensor mounting strategies on frequency response, with a specific focus on ICP® accelerometers. Gearbox predicaments such as eccentric gears, cracked teeth, and fatigue-induced issues in bearings and gears are thoroughly examined to underscore the importance of continuous monitoring as a preemptive strategy against catastrophic failures. The ultimate goal is to promote equipment reliability and prolong the lifespan of gearbox components.

7.1. ICP® Accelerometer

The most common sensor type employed in vibration analysis on gearboxes are ICP® accelerometers with a sensitivity of 100 mV/g, a resonant frequency in the 25 kHz range and a noise floor of approximately 100 μg/√Hz at 1 Hz (or less). [18]

8. Gearbox Oil Change

The main functions of the lubricant include: separating from the tread surfaces, reducing wear, ensuring machine cooling, improving the dissipation of heat, reducing friction and increasing efficiency, propitiating energy savings, protecting the bearing, both from corrosion and from contamination and absorbing wear particles, that is, cleaning the system. [15]

To meet these objectives, the oil needs to preserve its properties during its useful life. These properties should ideally be:

- resistance to aging and oxidation
- low foaming
- good air separation capacity
- high load carrying capacity
- neutrality to materials (ferrous, non-ferrous, joints, paints)
- ability to withstand high and low temperatures
- good viscosity—temperature behavior
- detergency (i.e., the ability to clean and dissolve dirt in the hydraulic circuit).

To check that the oil keeps the aforementioned properties in an optimal state, oil analyses are carried out providing information on the condition of the lubricant, the operational environment (environment in which the machine operates), and the condition of the gearbox (internal wear of the equipment).

The state of the oil is determined by checking its contamination and degradation [19] specifically, the loss of lubricating capacity caused by variations in its physical and chemical properties, especially those of its additives. The contamination of the oil can be determined by quantifying the content of metallic particles, the proportion of water, carbonaceous materials, and insoluble particles in a sample of the lubricant—everything that is in the fluid and does not belong to it. The degradation can be evaluated by measuring viscosity, detergency, acidity, and dielectric constantthe loss of lubricating capacity caused by a variation of its physical and chemical properties (especially those of its additives). The contamination of the oil can be determined by quantifying in a sample of the lubricant the content of metallic particles, proportion of water, carbonaceous materials, and insoluble particles, i.e., everything that is in the fluid and does not belong to it. The degradation can be evaluated by measuring the viscosity, detergency, acidity, and dielectric constant. [20] .Not only the oxidation, but also the additive depletion forms deposits that can restrict the flow to bearings, producing an increased bearing and gear teeth wear and eventually gearbox failure. When the sediments or metallic particles become bigger, damage in the bearings and gears of the gearbox can occur. These particles can erode the external layer of these elements, creating a weak point and possible future greater damage. The reason is that it is the hardest layer and provides hardness (the rest of the material inside is more ductile). The wear of the additives reduces the capacity of the oil to protect the bearings and gears.

Del Álamo et al [15] Five different tests have been conducted in a total of 30 wind turbines across three independent wind farms. The five tests with high relevance include leakage and oil filling, brand (and features) oil replacement, installation of a portable off-line filter, high-temperature oil, and replacement of thermostatic valves and the position from which the sample has been taken is also considered.

8.1. Leakage and Oil Refilling

When a leak appears in a gearbox, there is a loss of oil volume, which generates an increase in temperature and oil degradation due to a high level of stress [21].When the oil is at minimum levels, a warning alarm or even a stoppage of the wind turbine occurs in order to avoid working in risky conditions that might damage the equipment. To avoid this situation, the usual practice is to increase the level of filling with new oil, obviously with intact properties, which produces contamination (positive in this case) that alters the evolution of the previous oil analysis results. [15]

8.2. Oil Brand Replacement

When replacing the oil of a gearbox for a different brand, the following steps are carried out:

- Withdrawal of the used oil.
- Wash” with new oil. This task is not usual and depends on the decision of the maintainer to-do so or not. This action seeks a better elimination of the remains of the former oil, since the configuration of the gearbox with many gears and bearings (with small holes of difficult access) makes the full elimination practically impossible.

- Oil filter replacement.
- Flushing to remove all traces of the retired oil. This operation seeks to remove the maximum amount of oil and remains of dirt with compressed air.
- Filling with new oil.

Although most components of oils for gearboxes are the same, the percentage of additives may vary or may even have some differences. [15]

8.3. Installation of Off-Line Filters

most gearboxes of multi-megawatt wind turbines have an oil filter. In addition, there is a second piece of equipment called an off-line filter, which is more effective and provides higher quality filtering. The scheme for the gearbox off-line oil filtration equipment is shown in Figure 9.

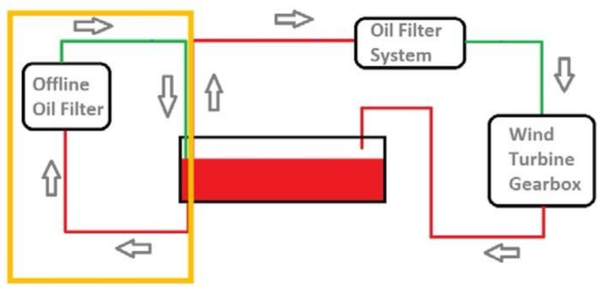

Figure 9:Gearbox offline oil filtration. [15]

This type of filter can be installed permanently or temporarily to improve oil properties. The purpose of the offline filter installation is to reduce: the humidity level to around 50%, the ppm of copper (Cu) and iron (Fe) by 30%, the ppm of Silicon (Si) particles (not in the case of silicon joints), the level of particles around two ISO classes Table 1 and the PQ index level (ferromagnetic particles) and small particles of wear [22].

Table 1:ISO 4406/99 Max. Number of Particle/100 mL

From	To	Class
250000	500000	19
130000	250000	18
64000	130000	17
32000	64000	16
16000	32000	15
8000	16000	14

Table 1 was excerpt from international standard ISO 4406:1999 code that establishes the relationship between particle counts and oil contamination (quantifying levels of particulate contamination of fluid per milliliter in three sizes: 4µ, 6 µ, and 14µ and coding the contamination level with three numbers (example: 17/15/12). [15]

8.4. High temperature of oil and Replacement of Thermostatic Valves

Continuous monitoring of oil temperature is imperative to ensure it remains within designated temperature bounds, mitigating potential deterioration originating from thermal processes. Utilizing thermostatic valves facilitates precise fluid temperature control, thereby ensuring the oil temperature is consistently maintained within predetermined operational parameters. [15]

The thermostatic valves are in the oil cooling circuit, and their internal components are in permanent contact with the oil. When these components undergo degradation and are replaced, the new ones contain higher levels of iron and copper in their composition. Consequently, the oil indirectly experiences an increase in the levels of these wear components. [15] Sometimes it is necessary to replace one of these devices that are in contact with the oil because some components undergo degradation, and the operation of the component becomes consequently deficient. [15]

8.5. Position of Sample Taking

The position of the sample taking is usually determined by: the procedure of each maintainer, the design of the gearbox, and its own know-how [23]. The sample should be taken in the same position, but due to different circumstances, this does not always hold true. Figure 10 shows different options for sampling positions.

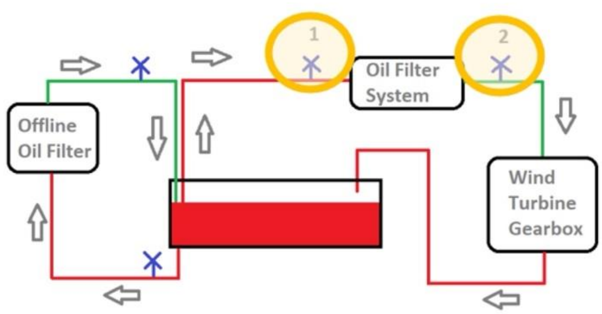

Figure 10:Sampling position options: option (1) when the sampling is done before the oil filter system, and option (2) when the sampling is performed after the oil filter system. [15]

If the sample is taken before filtering (option 1 in Figure 10), priority is given to understanding the gearbox state. Conversely, if it is taken after the filter (option 2 in Figure 10), the oil condition is prioritized. The condition of the filter is also important. Results should typically improve with new filters, but significant disturbances can be obtained if the filter is dirty [15]

Results

- Oil refilling significatively alters the concentration of additives (e.g., zinc, phosphorus, and Sulphur) in the oil analysis results.
- The change in oil brand can lead to false alarms since additives (e.g., molybdenum, magnesium, and zinc) can exceed the allowable limits.
- The installation of an off-line filter highly affects the concentration of wear particles and consequently, modifies oil analysis results.
- The replacement of the thermostatic valve alters the values of some additives (e.g., zinc and copper) due to contamination with the valve materials.
- The position of the sample taking causes modifications in the concentration of wear particles. [15]

8.6. CMM-G Wind Turbine Gearbox Oil Changer

Principle of Operation: The CMM-G (Figure 11) operates in six versatile modes, including filling gearbox with clean oil, pumping used oil, heating oil, draining used oil, flushing the gearbox, and transferring oil between tanks. Power is supplied either through a built-in generator or an external three-phase alternating current network. The unit is multifunctional, capable of heating and vacuum drying the gearbox.

Figure 11:CMM-G Wind Turbine Gearbox Oil Changer [24]

The aim is to delve into the effectiveness and efficiency of these advanced gearbox oil changers, considering their impact on wind turbine performance, longevity, and overall maintenance practices. Through a comprehensive analysis, we seek to provide valuable insights into optimizing gearbox maintenance strategies in the ever-evolving field of wind energy.

9. Conclusion

In conclusion, effective maintenance strategies play a pivotal role in ensuring the optimal performance and longevity of wind turbines, particularly in addressing critical components such as gearboxes. The comprehensive examination of various maintenance aspects, including icing prevention, corrosion protection, oil analysis, and gearbox vibration monitoring, underscores the intricate challenges faced in wind turbine operation. Addressing the impact of icing on turbine blades requires proactive measures, such as hydrophobic coatings and heating systems, to mitigate safety risks, structural load increases, and power output reduction. Corrosion protection strategies, encompassing coatings, cathodic protection, and corrosion allowance, emerge as crucial considerations for offshore wind turbines exposed to harsh environmental conditions.

Oil analysis serves as a valuable diagnostic tool for assessing lubricant condition, contamination, and degradation. The detailed examination of oil-related tests, including leakage and oil filling, brand replacement, off-line filter installation, high-temperature oil, and thermostatic valve replacement, emphasizes the significance of these procedures in maintaining gearbox health.

The integration of advanced technologies, such as the CMM-G Wind Turbine Gearbox Oil Changer, showcases the ongoing efforts to enhance maintenance practices. The application of the 3σ criterion and NSET modeling in predicting gearbox temperature demonstrates the importance of data-driven approaches in fault early warning systems.

Vibration monitoring emerges as a powerful method for detecting gearbox faults, necessitating careful sensor selection and strategic mounting to ensure precise and reliable data acquisition. The exploration of gearbox predicaments, such as eccentric gears, cracked teeth, and fatigue-induced issues, emphasizes the proactive role of continuous monitoring in preventing catastrophic failures.

In the evolving landscape of wind energy, optimizing gearbox maintenance strategies requires a holistic understanding of various factors. Collaborative efforts between the scientific community and the wind industry, as evidenced by research on ideal preventive maintenance periods and the use of SCADA systems, contribute to ongoing improvements.

In summary, the research underscores the multifaceted nature of wind turbine maintenance, emphasizing the need for a tailored, data-driven, and technologically advanced approach to ensure the reliability, safety, and efficiency of wind energy systems.

10. References

[1] P. Roberger, J. Lemay, J. Ruel and A. Bégin-Drolet, "The effect of icing severity on wind turbine ice protection systems efficiency," Elsevier, Quebec, 2023.

[2] V. Turkia, S. Huttunen and T. Wallenius, "Method for estimating wind turbine production losses due to icing," VTT Technology, 2013.

[3] L. Hanxiang , J. Xingliang , Y. Zhou and S. Lichun, "Review on Anti-icing and De-icing Techniques of Wind Turbine Blades," 2022.

[4] "Aerones Engineering," 2023. [Online]. Available: https://aerones.com/services/coating/. [Accessed 3 12 2023].

[5] "Phazebreak Coatings," [Online]. Available: https://www.phazebreak.com/#:~:text=Long%20Lasting,for%20up%20to%204%20years.. [Accessed 3 12 2023].

[6] "NACE international," 2016. [Online]. Available: http://impact.nace.org/economic-impact.aspx. [Accessed 2 12 2023].

[7] R. Brjider, C. H.M. Hagen and A. Corttes, "Review of corrosion monitoring and prognostics in offshore wind turbine structures: Current status and feasible approaches," Frontiers, 2022.

[8] M. Nevena, A. Urbegain and P. Benguria, "Evaluation of Anticorrosion Coatings for Offshore Wind Turbine Monopiles for an Optimized and Time-Efficient Coating Application," MDPI, 2022.

[9] "EONCOAT," 2023. [Online]. Available: https://eoncoat.com/corrosion-prevention-methods/#:~:text=One%20of%20the%20easiest%20and,to%20create%20a%20thin%20film.. [Accessed 1 12 2023].

[10] M. AG, "Material Performance," 16 2 2016. [Online]. Available: https://www.materialsperformance.com/news/2016/02/research-project-focuses-on-offshore-wind-turbine-coating-maintenance. [Accessed 2 12 2023].

[11] "Institute of Corrosion," [Online]. Available: https://www.icorr.org/how-does-cathodic-protection-work/. [Accessed 2 12 2023].

[12] "Cathwell," 20 11 2023. [Online]. Available: https://cathwell.com/cathodic-protection-explained/. [Accessed 2 12 2013].

[13] "Eddyfi," [Online]. Available: https://www.eddyfi.com/en/application/phased-array-corrosion-mapping. [Accessed 3 12 2013].

[14] Y. Aafif, A. Chelbi, L. Mifdal and S. Dellagi, "Optimal preventive maintenance strategies for a wind turbine gerabox," 2022.

[15] J. del Álamo, M. Duran and F. Muñoz, "Analysis of the gearbox oil maintenance procedures in wind energy," MDPI, 2020.

[16] S. Wang, Z. Zhang, P. Wang and P. Tian, "Failure warning of gearbox for wind turbine based on 3σ-median criterion and NSET," 2021.

[17] J. Igba , K. Alemzadeh, K. Henningsen and C. Durugbo, "23.Igba J, Alemzadeh K, Henningsen K, Durugbo C. Effect of preventive maintenance intervals on reliability and maintenance costs of wind turbine gearboxes," 2015.

[18] "PCB," [Online]. Available: https://www.pcb.com/ContentStore/MktgContent/whitepapers/WPL_82_GearBoxWhitePaper.pdf. [Accessed 3 12 2023].

[19] J. Manyala and M. Atashbar, "Development of particle contaminants monitor system for gearbox lubricant prognostics," Orlando,FL, 2016.

[20] A. Raza and V. Ulansky, "Optimal preventive maintenance of wind turbine components with imperfect continuous condition monitoring," 2019.

[21] C. Sequeira, A. Pacheco, P. Galego and E. Gorbeña, "Analysis of the efficiency of wind turbine gearboxes using the temperature variable," 2019.

[22] J. Wright, "Understanding Filter Efficiency and Beta Ratios," 2008. [Online]. Available: https://www.machinerylubrication.com/Read/1289/oil-filter-effciency. [Accessed 1 12 2023].

[23] J. Manwell, J. MCGowan and A. Rogers, Wind energy explained, vol. 2, Wiley, 2009.

[24] "Globecore," [Online]. Available: https://globecore.com/. [Accessed 1 12 2023].

[25] R. S. Ehrmann, B. Wilcox and E. B. White, "Effect of Surface Roughness on Wind Turbine Performance," SANDIA REPORT, Albuquerque, New Mexico, 2017.