Significance of Effective Lubrication in Mitigating System Failures – A Wind Turbine Gearbox Case Study

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Abstract

The effectiveness of lubrication in machines mainly depends on the physical and chemical properties of lubricating oil, like quantity, level of suspended particles, effect of external load / shear forces, temperature amongst others. Periodic inspection of lubricating oil for its grade of viscosity, H_2O content, fuel content, amount and nomenclature of suspended particles etc. assists maintenance personal in assessing the quality of oil and its residual life. Such assessments are also useful in determining health of the system in which the lubricating oil was used. This work discusses about industrial Wind Turbine Gearbox lubrication, its importance, applications, oil analysis method and lists constituents found in the oil. Results lead us to the conclusion that additives in the oil protect the gearbox from wear and tear during initial years of operation. Analysis also suggests that re-lubrication process should be performed every 18 months time interval to optimise the life of gearbox components. Other results and advice for lubrication are also listed.

Keywords: Lubrication, Oil analysis, Wind Turbine, Maintenance, Gearbox

1. INTRODUCTION

The moving parts of machines undergo wear and tear which upon prolonged usage can fail without effective maintenance. The primary reasons for failures are generation of localised heat due to friction, debris contamination, corrosion and stress variation during operation. An effective preventive maintenance scheme, like lubrication, can circumvent many of such adversities and enhance the productive life of a machine.

Lubrication is a technique where load specific hydrocarbon liquid (lubricating oil) is used as a cushion between moving parts of the machine. Lubricating oils being a fluid easily percolate between the moving parts and provide the cushion effect. Such effect reduces the wear and tear of moving parts and helps reduce failure of moving and rubbing parts. Lubricating oil is also useful in reducing friction, absorbing heat, reducing corrosion and washing away of particulate contaminants from the oil [1]. Lubrication is done by using lubricating oil, a fluid, or a lubricating grease, a semi solid. Their application depends upon the purpose and place of lubrication. For example oil is used in instances where it fluidity tends to assist in the automatic replenishment of oil between moving parts to enhance cooling effect and washing away of suspended particles, whereas grease is generally used at places which needs to be sealed from external agencies [3].

Modern lubricating oils are hydrocarbon compounds consisting of a native base element, called a “BASE”, and an additive compound that is additionally mixed with the BASE element to provide it with special properties. This chemical addition is known as the “ADDITIVE”. It provides BASE oil with enhanced properties to act as anti-oxidant, detergent, friction jabber, wear resistant and heat dissipater [2]. These capabilities assist the BASE oil perform better in its function. These ADDITIVES hence assist in prolonging the operational life of BASE oil consequently of the machine in which the oil is being used. Some industries where lubrication plays vital roles are shipping, precision machineries, transformers, gearboxes, generators, automobile engines and airlines industry to name few.

2. ANALYSIS OF LUBRICATING OIL

Both online and offline oil analysis methods are being used in industries that are usually more cost effective and require less skillsets as compared to many other condition monitoring techniques. This method is hence an invaluable technique for large machines installed in offshore / onshore locations where hindered access and costly time bound activities are major concerns for maintenance planners. As lubricating oil analysis can identify particles in the oil which can assist in identifying wear and tear, a periodic study into level of machine wear and tear can assist in arranging maintenance that can reduce probability of failure and hence cut down upon downtime and costly servicing. As such economical and low skill techniques reduce the need for costly inspection methods it also assists in cutting down the time for inspection and its analysis. Modern oil analysis techniques (online/offline) do not require transportation of heavy instruments and hence assist in simplifying the overall maintenance cycle.

This work provides an introduction to lubricating oil, its constituents, external factors that affect the quality of oil, failures in lubricating oil and its usefulness in Wind Turbine Gearbox. It discusses about the usefulness of lubricating oil in Wind Turbine Gearboxes with aid of case studies involving many industrial Wind Turbine gearboxes. In the next section, classification techniques for lubricating oil are discussed.

3. CLASSIFICATION OF LUBRICATING OIL

Lubricating oils are classified using various techniques, such as:

- Origin – Artificial or Natural
- Viscosity – Different usage requires different oil viscosities, like heavy machinery like gearbox requires high viscosity oil, oiling of manual sewing machine requires low viscosity oil, etc.
- Application Area – Areas involving heavy stress and strain requires heavy duty oils
- ADDITIVES - Lubricating oils are also classified according to the types of ADDITIVE in the

BASE oil. It also determines its area of application

- Percentage of ADDITIVE – The percentage of ADDITIVE to original BASE in the oil also classifies various lubricating oils.

The grade of lubricating oil is defined by its Viscosity. Viscosity of oil is measured in either CGS system (centistokes (cSt)) or SI system ($10^{-6}m^2s^{-1}$). Viscosity of lubricating oil is measured at either 40 or 100 ^{0}C.

4. LUBRICATING OIL – EFFECT OF EXTERNAL AGENTS

The physical and chemical properties of lubricating oil assists maintenance planners decide upon its intended usage. However such properties tend to change due to affects of external agents. For example it has been known that the viscosity of lubricating oil changes with variations in temperature (Walther and Vogel equations relating change in viscosity with changing temperature) and high temperature environments induce tendencies of greater failure in lubricating oils [5]. The property of lubricating oil also changes with rising content of water and residual fuel contents (shoot) when its viscosity and anti-oxidation properties are affected. Hence due care is necessary, especially in offshore locations, to prevent growth of moisture content in oil. The presence of many acidic and basic compounds formed in the oil as a result of erosion or corrosion of various moving elements results in the changing acidic and alkaline values of the oil. Such numbers are represented as Total Acidic Number (TAN) and Total Base Number (TBN) for lubricating oils. The formation of alcoholic compounds i.e. glycols are also recorded for oils and it gives an indication regarding the quality of lubricating oil. The amount of debris or non neutralised dissolved particles in the oil, such as Silicon, assists in enhancing erosion in the lubricating oil. Such non required particles often contaminate the oil by being carried by air or gusts of wind and hence proper insulation methods should be exercised to prevent the build up of such concentration.

A higher level of particulate contaminants in oil not only reduces its efficiency in carrying away heat from localised contact areas, but generates additional dispersed particles. It also reduces the fluidity of lubricating oil and hence such levels of particulate build up should be avoided.

National Aerospace Standard (NAS) and International Organisation for Standardisation (ISO) are organisations who have benchmarked and proposed the acceptable quality levels for oils used in industrial applications. Based on the grading provided by these organisations, oil filtration, oil change or other suitable actions can be planned for action. A technique, by use of ADDITIVES such as Temperature and Viscosity Index improvers, can assist in prolonging the utility of industrial lubricating oil, however in that instance also periodic inspection is recommended to check abnormalities in oil. Use of filters can also help oil remain clean for utility. Use of moisture resistant breathers at suitable openings of the machine can assist moisture in oil and is hence recommended.

Hence in Table 1 some useful properties for industrial lubricating oil have been compiled. As seen, an industrial grade oil should be able to retain its viscosity within operating temperature range, it should have high levels of anti-oxidation potential, its affinity towards moisture should be low and its' chemical constituents should not enhance corrosion or chemical reaction with machine surface.

Table 1 Special properties of Industrial Lubricating Oil

Property	Description
Viscosity	Should maintain the correct level of viscosity over wide temperature range
Oxidisation Potential	Should have high level of oxidation potential
Affinity towards Moisture	Should exhibit low affinity towards moisture
Anticorrosion	Should be corrosion resistant and non reactive with machine surface

Some reasons of lubricating oil failure are: high concentration of contaminants, over heating of oil during operation, long intervals between oil change, oxidation of oil particles, inherent problem with lubricating film, use of wrong additives and non- standard maintenance policies [6]. Inherent changes in lubricating oil refers to circumstances when change in temperature and pressure can changes effect of lubrication and hence the likelihood of failure. Hence some practices, like periodic monitoring of lubricating oil, oil change at correct intervals, use of oil filters and the use of the correct grade and quantity of oil during servicing can assist in offsetting many of the failures in lubricating oil.

5. WIND TURBINES

Wind Turbines are machines that convert wind energy into electrical power. In performing this conversion a wind turbine uses many moving mechanical parts, like bearing, shaft, rotor, gears etc. Lubrication is hence done to reduce degradation of turbine parts and reduce friction during motion of parts. Different grades and qualities of lubricating oil and grease are hence applied to different parts of Wind Turbine. This paper takes special consideration of studying the importance of lubrication in Wind Turbine Gearboxes since gearbox is amongst the most frequent failing assemblies in a Wind Turbine. Hence this paper aims at identifying oil related causes of failure in wind turbine gearboxes.

6. GEARBOX LUBRICATING OIL – SOURCE OF SUSPENDED PARTICLES

Lubricating oils during course of their operation gets contaminated with many elements. The concentration of these particulate elements accumulates with time and amongst the primary sources of these elements are the machine parts and oil constituents that degrade due to corrosion and erosion and become suspended in the oil. A list of such elements and their corresponding sources for lubricating oil in a Wind Turbine gearbox has been compiled and provided in Table 2. The table has been later used during the analysis of the case study. As seen in the table, the particulate concentration of elements can arise from either the machinery components or the Additives used in oil.

Table 2 Suspended particles in lubricating oil of Wind Turbine Gearbox and their potential sources [4]

Wear Elements from Components	
Silicon	Dirt Contaminants, Seal, Oil, Coolant, Grease
Iron	Gears, Shaft, Bearings, Housing, gears, bearings, shaft, housing
Copper & Alloys	Bearings, Bushings, Retainers, Thrust Washers and Plates, Cooler Tube
Aluminium Alloys	Bushings, Thrust Washers
Chromium Alloy and Plating	Bearings, Shaft, Seals, Roller Bearings
LEAD and TIN Overlay or Flashing	Bearing, Bushings, Grease Contamination
Nickel Alloy (with Iron)	Gears, Shafts, Bearings
Silver Plating	Bearings, Bushings, Oil Coolers, Solder, Seals
Molybdenum Alloy and Plating	Bearing
Magnesium Alloy	Cases and Housing
Titanium Alloy (with Lead and / or Tin)	Journal Bearing Overlays
Zinc Alloy	Brass Fittings, Galvanised Surfaces
Tin	Bearing cage metal, lube additive
Wear Elements from ADDITIVES	
Molybdenum	Extreme Pressure Additive, Corrosion Inhibitor
Magnesium	Detergent, Dispersant, Alkalinity Increaser, Airborne Contaminant
Sodium	Corrosion Inhibitor in Oils, Salt Water, Air Born, Coolants
Boron	Detergent, Dispersant, Anti-Oxidant in Oils, Coolant inhibitor, Grease
Barium	Corrosion and Rust Inhibitor, Detergent, Anti-Smoke Additive in Fuels
Phosphorus	Anti-wear, Corrosion Inhibitor in coolants, Excessive Pressure Additive
Potassium Compounds	Corrosion Inhibitor, Trace element in Fuels, Mineral Salt in Sea Water
Calcium	Detergent Dispersant, Alkalinity Increaser, Airborne Contaminant, Contaminant from water
Zinc	Anti-Wear, Anti-Oxidant, Corrosion Inhibitor
Lithium	Coolant inhibitor, airborne contaminant, lithium complex grease
Antimony	Anti-wear, Anti-oxidant

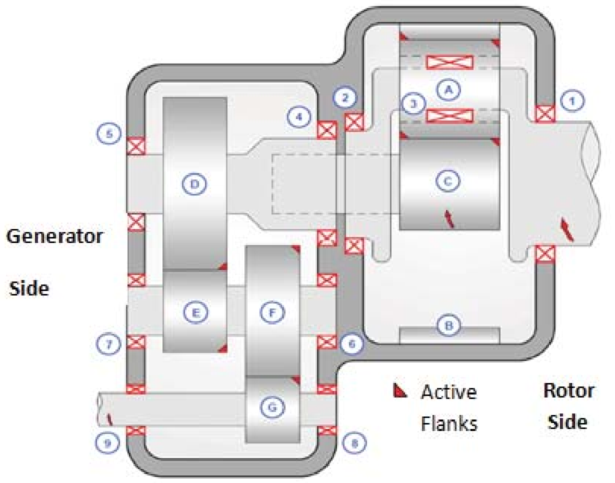
7. CASE STUDY – WIND TURBINE GEARBOX

Wind Turbine Gearbox is energy transmission machine that enhances the rotational speed of input side and feeds it into the generator. The generator then converts the rotational energy into electrical power. A schematic diagram of a 3 stage planetary gearbox used in wind turbines used in this case study is shown in Figure 1. The figure shows gearbox with many gears, bearings and shafts that during operation rub against each other. Hence to circumvent failure in the gearbox lubrication in the gearbox is proactively done.

A case study is elaborated here where oil analysis results of 49 different Wind Turbine Gearboxes were investigated. Since not all the Wind Turbine Gearboxes were from Wind Turbines in the same Wind Farm, these Wind Turbines were grouped according to their geographical location. In one geographical location a Wind Farm contained Wind Turbines of similar model and their operating age were also similar. Hence these Wind Turbines were grouped into seven different groups for the purpose of analysis. These groups along with their age are shown in Table 2. The individual wind turbines in a wind farm have been numbered to uniquely identify them. Since two groups of Wind Farms were found to have similar ages, they were given the group names as Group 3A and Group 3B. This is shown in Table 2.

Table 3 List of Wind Turbine Groups

Groups	Age	WT IDs	Groups	Age	WT IDs
Group 1	2	WT1 - WT17	Group 4	5	WT36–WT39
Group 2	3	WT18 – WT23	Group 5	6	WT40–WT44
Group 3A	4	WT24 – WT26	Group 6	8	WT45–WT49
Group 3B	4	WT27 – WT35	———	———	————



A = planet gear (3x)
B = ring gear
C = sun gear
D = gear, low-speed shaft
E = pinion, intermediate-speed shaft
F = gear, intermediate-speed shaft
G = pinion, high-speed shaft

1 = planet carrier bearing, RS
2 = planet carrier bearing, GS
3 = planet gear bearings
4 = low-speed shaft bearing RS
5 = low-speed shaft bearing GS
6 = intermediate-speed shaft bearing RS
7 = intermediate-speed shaft bearing GS
8 = high-speed shaft bearing RS
9 = high-speed shafts bearing GS

Figure 1 Schematic diagram of a 3 stage planetary gearbox of wind turbine (Reproduced with permission from Stork Technical Services, Aberdeen, UK)

8. RESULTS

It was observed during the analysis of lubricating oil data that within a particular group of Wind Turbines a very high level of co-resemblance existed between the concentration level (ppm) of elemental particles. This was also justified by the high value of positive covariance between these concentration level data. This in turn indicates that within a group, gearboxes exhibited similar amounts of erosion with time and hence our pre assumption into grouping such gearboxes was correct for the purpose of analysis. This can also be observed in Figure 2 where a uniformly high level of Phosphorous (P) and small traces of other elements were present in all the lubricating oils of Group 1 gearboxes. Taking the aid of Table 1, we can see that the originating source of P in the oil is Anti-Wear and Excessive Pressure handling ADDITIVES. For the wind turbines considered here it is hence inferred that during first two years of Wind Turbine Gearbox operation, the lubricating oil is able to effectively protect the gearbox against erosion and other causes of malfunction.

A similar type of plot was also observed for Group 2 gearbox lubricating oil, in which case the wind turbine gearboxes were in operation for three years. A relatively high level of Magnesium (Mg), Zinc (Zn), Phosphorous (P) and Molybdenum (Mo), and relatively small levels of all other elements suggests degradation of ADDITIVES in the oil or degradation in Brass Fittings, Galvanised Surfaces, Casing/Housing and Bearing of a gearbox. So for Group 2, it is difficult to identify the source of elements in the oil.

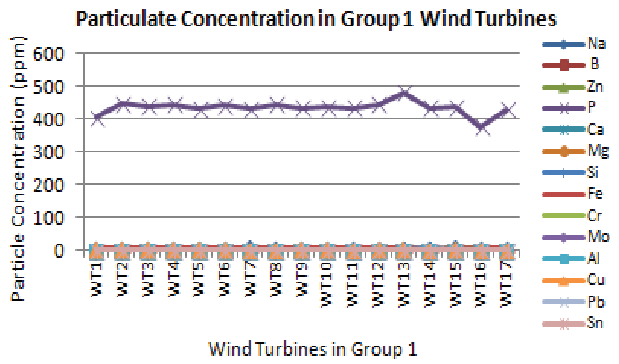


Figure 2 **Variation in particulate concentrations for Group 1 Wind Turbine Gearboxes**

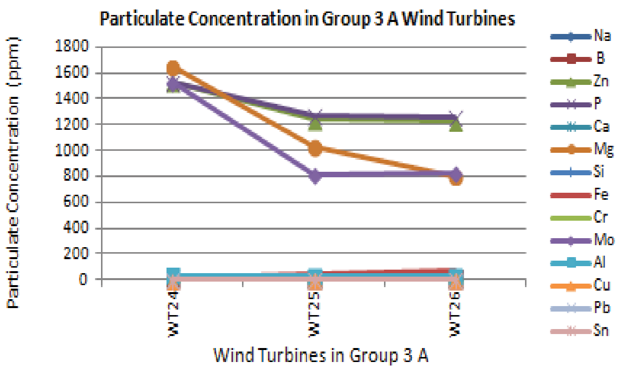


Figure 3 **Variation in particulate concentrations for Group 3A Wind Turbine Gearboxes**

A similar pattern of element concentration was also seen in Group 3B (Figure 4), which was also into its 3rd year of operation. Since this result was from a different Wind Farm, and the concentration level of elements (ppm) was between 800 ppm and 1600 ppm for Mg, Zn, P and Mo, it suggests that such a degradation pattern is universal. A low value for WT27 in Figure 4 indicates that either the lubricating was changed for this Wind Turbine Gearbox or the Gearbox had undergone recent maintenance. However since we do not have access to such maintenance data, such a conclusion is only indicative. Such high levels of elemental concentrations were also seen in Group 4 and Group 5. In Figure 5, a representation of the variation in particulate concentration in the lubricating oil of Group 6 Wind Turbine Gearboxes has been shown. This group of gearboxes have been in operation for 6 years. As can be observed from the figure, Zn, P, Mo and Mg have uniformly attained very high values between 1200 ppm to 1600 ppm. Such a high concentration levels of

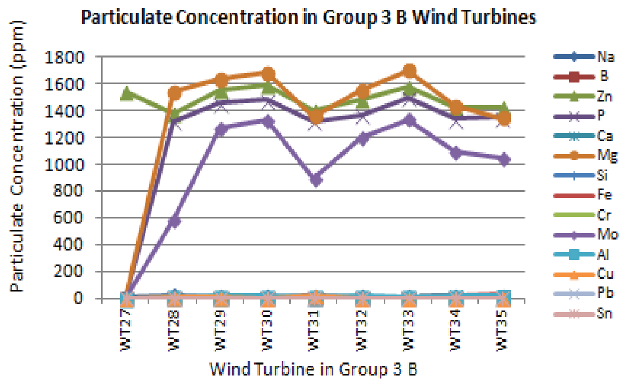


Figure 4 **Variation in particulate concentrations for Group 3B Wind Turbine Gearboxes**

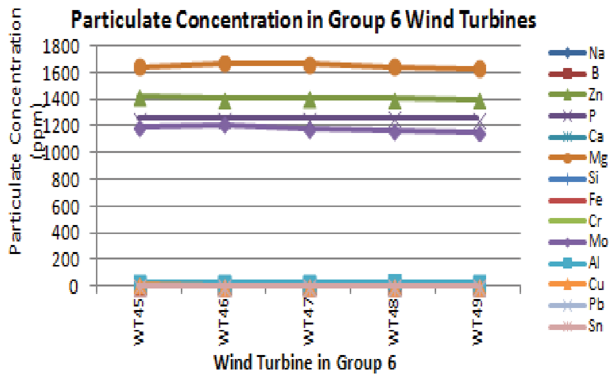


Figure 5 **Variation in particulate concentrations for Group 6 Wind Turbine Gearboxes**

particulates in the lubricating oil suggests that the lubricating oil needs to be changed as soon as possible. This is also in line with suggestions of NAS standard which has been plotted in Figure 6. It is highly likely that the oil in the Group 6 gearboxes would have been in operation for quite some time, however preassembly not for six years since the installation of the Wind Turbine. However since we do not have any related data about oil change, such a statement is purely logical. It is hence inferred that gearbox parts when once eroded, the chances of its erosion in spite of introducing new oil remains at a high level.

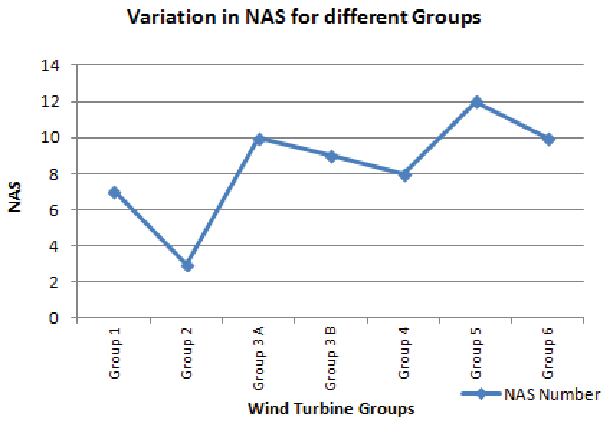


Figure 6 Variation of NAS number across different groups

However for a high value of NAS number, i.e. Group 3A, Group 3B, Group 4 and Group 6, it can be concluded that bits of some specific component may have broken down and become dissolved in the lubricating oil without leaving much trace of its original origin even if the filtration system was included.

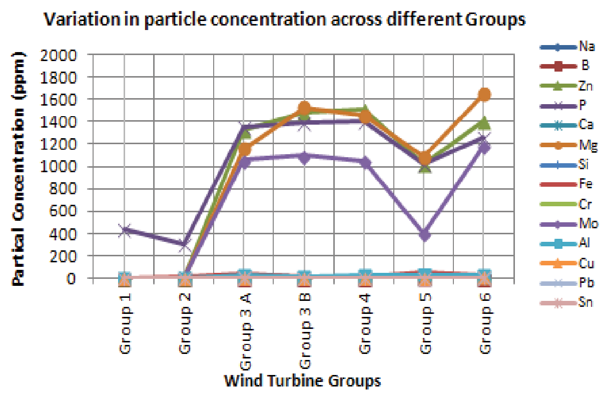


Figure 7 Variation in element concentrations across different groups

A look at Figure 7, suggests that with increasing group number, the concentration level of particulate elements in the oil increases. However for Group 5 the values are lower possibly due to maintenance, recent oil filter or lubricating oil change. The elements contributing most towards the concentration in lubricating oil comes from the ADDITIVES (Table 1) which means that they effectively protects the gearbox against failure due to seizure or other mechanical failures. The use of lubricating oil hence has a positive effect in prolonging the life of machines, in this case of Wind Turbine Gearbox.

9. Conclusion

This study confirmed our assumptions that lubricating oil assists in circumventing failures in Wind Turbine Gearbox and we conclude that during initial period of lubricating oil operation, ADDITIVES effectively protects the gearbox against any gradual failures. Based on results from Group 1 Wind Turbine Gearbox, we can say that re-lubrication of these Wind Turbines should be done after 18 months of operation. It is also concluded that to increase time between oil change, Gearbox parts, i.e. Brass Fittings, Galvanised Surfaces, Casing/Housing and Bearing should be strengthened against erosion by making use of more reliable and non-degradable elements, like Carbon Nanotubes. We have also identified the origin of particles in the oil, primary amongst them are ADDITIVES (Na, B, Mo, P, Ca), Gearbox Casting (Mg, Zn, Fe), Bearings and Washers (Cr, Al, Cu, Pb, Sn) and external agents like Silicon (Si).

10. Summary

The particulate concentration due to degradation in casting is amongst the main sources of high levels of concentration in the lubricating oil, apart from the ADDITIVEs that is used in lubricating oils. Hence enhanced versions of ADDITIVE and a more robust Gearbox casting along with some of its other components can improve the operational efficiency and longevity of Wind Turbine Gearbox and Lubricating Oil.

11. Acknowledgement

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