Delivering Wind Turbine Drivetrain Reliability Through Enhanced Fluid Cleanliness

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Introduction

Over the last 20-30 years, wind power has evolved from a fledgling industry generating less than 1% of total US domestic power in 1990 to more than 7% in 2019. In Europe, government incentives to drive the adoption of clean energy have seen an exponential increase in both offshore and land-based wind farms, while in Asia countries such as China and India are driving their economic growth on a foundation of green power.

As the wind energy industry has evolved, so too has the sophistication of the technology used to deliver reliable wind power. From sub-1 MW turbines in the early 1990s to over 10 MW offshore turbines today, both the physical size and the power output of wind turbines has grown over the last few decades. To keep up with this growth, drivetrain components, and in particular wind turbine gearboxes, have also had to evolve from little more than modified industrial gearboxes to sophisticated planetary and parallel shaft gear drive technologies that can handle the often severe, transient loading experienced during all phases of a wind turbine's operation.

Unlike in the past, where basic gearbox maintenance practices were adopted, today's modern wind turbine gearboxes require a far higher degree of precision maintenance to ensure that gearboxes can get close to their 20-year design life. In doing so, more progressive OEMs and owner-operators have realized that addressing fundamental root cause failure modes through a proactive maintenance strategy is the only reasonable way to deliver asset reliability.

Operating a wind turbine gearbox at the typical levels of cleanliness found in a gearbox *without* enhanced contamination control can result in

ONLY 40-60% of the related design life being achieved,

which is one reason why many wind turbine gearboxes fail to reach even a ten-year service life.

What Causes Gearboxes to Fail?

There are many possible causes of poor gearbox reliability, from design, manufacture and installation, through operation and maintenance. However, while not always the root cause, lubrication can be a leading factor driving gearbox reliability, making the health, cleanliness and condition of the lubricant a critical proactive element in reliable wind turbine operations and maintenance.

When it comes to gearbox lubrication, there are two component types to consider - gears and bearings - and while both have different lubrication requirements; either can cause premature gearbox failure. For gear teeth, the dominant lubrication-related failure modes are adhesion (scuffing) and contact fatigue caused by a combination of heavy loads and poor lubricant condition, while for main and intermediate shaft bearings, fatigue and particle-induced 3-body abrasion play a significant role.

The reasons for this are fundamental to how a wind turbine operates. Wind turbine gearboxes operate at a range of speeds from slow speed on the input shaft to high speed at the generator, they are exposed to a wide range of operating temperatures and conditions and experience numerous cycles of high transient loads during start-up, emergency stops and grid connections. This means that bearings and gears are often operating under boundary lubrication conditions where the oil film thickness is typically less than the average surface roughness of the lubricated component. For this reason, most wind turbine gearboxes use an ISO VG 320 synthetic gear oil, fortified with extreme pressure additives.

Where boundary lubrication conditions prevail. Fluid cleanliness becomes critical. According to modern bearing life calculations such as ISO 16281, in all cases but particularly under boundary lubrication conditions, stress factors caused by contamination can result in a significant reduction in overall component life. Similar life calculations such as those found in the ISO 6336 series standards serve to predict fatigue life for different gear geometries taking into account lubricant condition and cleanliness.

The reason why cleanliness is so important relates in part, to how contact fatigue is manifest in rolling contacts such as those found in the load zone of rolling element bearings or the pitch line of gearing. Under slow speed and/or heavy loads where the oil's viscosity alone is unable to create hydrodynamic separation, mating components undergo an elastic deformation caused by the effects of elasto-hydrodynamic lubrication. Under these conditions, components are constantly being loaded and unloaded, resulting in Hertzian stress waves that propagate throughout gears and bearings. It is the magnitude and frequency of cyclical Hertzian stress that ultimately determines the fatigue life of a bearing or gear tooth.

Under ideal circumstances where no foreign particles are present, bearings and gears are engineered to withstand fatigue stress, yielding gearbox theoretical design lives of twenty years or more. However, in the real world where less than ideal lubrication conditions prevail and where particle and moisture contamination are common, many gearboxes struggle to even last half that time.

The reason why particle-enhanced, early onset contact fatigue is so common is illustrated in ***Figure 1***. In a completely clean fluid, when the oil enters the load zone between a rolling element and the raceway or between two meshing gears, the pressure increases due to the localized force. In rolling element bearings, the pressure at the load zone can easily meet or exceed 200,000-500,000 psi while in meshing gears pressures can be even higher. Because of the increase in pressure, the viscosity of the oil increases based on the oil's pressure-viscosity coefficient. Even at pressures as low as 40,000 psi a standard mineral oil will undergo a phase change from a liquid to solid. At several hundred thousand psi, pressures are enough to cause a sudden phase change in the oil, causing the elasticity of bearing elements or gear teeth to deform due to elasto-hydrodynamic lubrication. As the surfaces deform, the contact area between the two components increases, reducing overall contact pressures reducing the sub-surface Hertzian stress on the components.

However, when particles are present as shown in ***Figure 1***, the particles serve to localize the force to a specific area, which can cause surface denting resulting in stress waves propagating through the material. This is similar to the force generated when body weight is concentrated on a small surface area such as a stiletto shoe, causing hardwood floors to damage. In a bearing, as material is displaced from the "crater", the displaced material can cause a surface irregularity known as a stress-riser to form on either side of the dent, which further exacerbates contact loading and Hertzian stress within the bearing or gear tooth.

It is important to understand the size of particles that contribute to particle-induced fatigue. The most damaging particles are those that meet or slightly exceed the typical oil film thickness under operating loads, speeds, and temperatures. Too small and they will pass through with little to no effect, too large and they simply will not be able to migrate between the contact points. In practical terms, this means anywhere from 0.1 to 5 microns, or less than one-twentieth the thickness of a human hair!

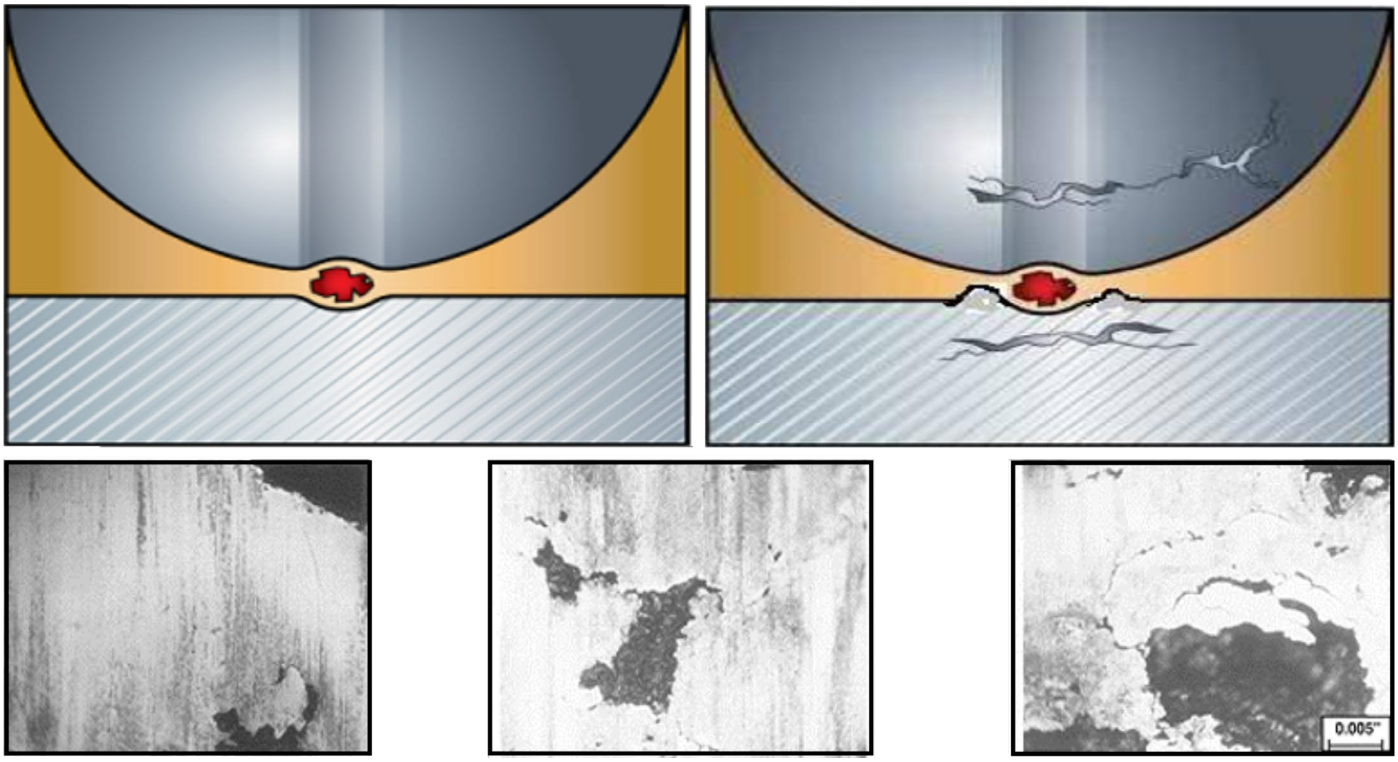


Figure 1: Progression of Particle-Induced Contact Fatigue

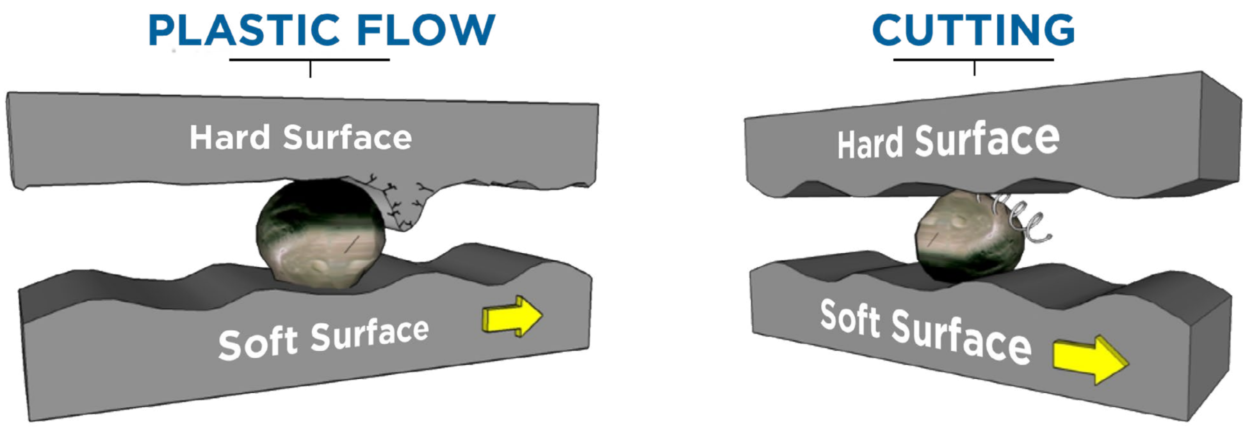
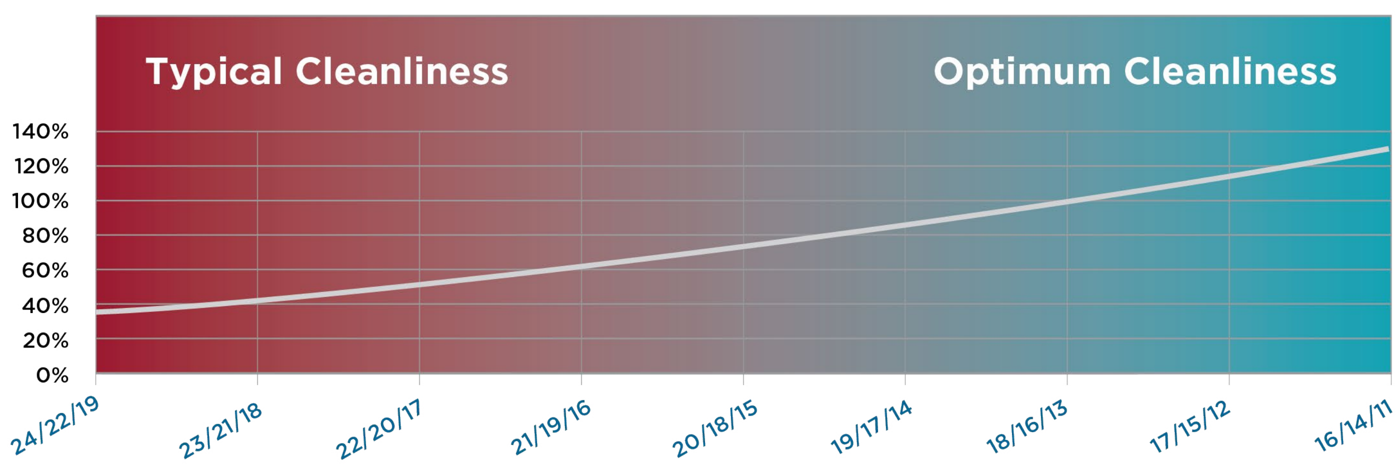


Figure 2: Particle-Induced 3-Body Abrasion

Aside from contact fatigue, particles also cause abrasive wear to occur ***(Figure 2)***. Particle-induced 3-body abrasion is found wherever sliding motion occurs such as the tip to root contacts in gearing or bearing cage to roller contacts in element bearings. Like particle-induced fatigue, 3-body abrasion occurs when particles similar in size to the oil film thickness are present between two surfaces.

Figure 3 shows the combined impact of particle-induced fatigue and 3-body abrasion on the life of gears and element bearings. Not surprisingly, cleaner oil results in longer component life. Operating a wind turbine gearbox at the typical levels of cleanliness found in a gearbox without enhanced contamination control can result in only 40-60% of the related design life being achieved, which is one reason why many wind turbine gearboxes fail to reach even a ten-year service life. Some wind turbine gearboxes have smaller orifices through which oil flows. In some instances, excess contamination can cause these critical clearances to become plugged, preventing sufficient oil flow rates. Left unaddressed, this can result in failure due to the effects of lubrication starvation, another reason to maintain optimum fluid cleanliness in wind turbine gearboxes.

While particle-induced wear is the most common form of contamination related failure, water can also play a role in gear and bearing failure. In addition to rust and corrosion, water in oil can result in a micro emulsion of water droplets within the oil causing the fluid to behave as a non-Newtonian fluid. Unlike clean dry oil, where increased pressure causes the oil's viscosity to increase, heavily moisture contaminated oil will start



DIRTY		CLEAN		VERY CLEAN
22/20/17	20/18/15	18/16/13	17/15/12	16/14/11

Figure 3: Impact of Particle Contamination on Gearbox Life

to yield viscosity as shear forces increase. Since oil film thickness is closely tied to an oil's viscosity, any reduction in dynamic viscosity due to non-Newtonian behavior will cause the dynamic viscosity to drop, reducing overall oil film thickness thereby increasing the likelihood of scuffing and contact fatigue. ***Figure 4*** shows the impact that water contamination has on the life of a rolling elements bearing. Controlling water is of particular concern since white etching cracking, a leading cause of bearing failure in wind turbine gearboxes, is believed to be due, in part, to hydrogen embrittlement from hydrogen radicals generated from moisture at tribochemical surfaces.*

Because of the insidious impact that particle and moisture contamination play in gearbox failure, controlling contamination at all phases of the oil's life is critical to maximizing gearbox life. Based on the criticality, loads and speed associated with turbine drivetrain gearboxes, most OEMs recognize that gear oils need to be maintained at cleanliness levels at or below ISO 17/15/12 and less than 200 ppm of moisture.

Achieving this level of cleanliness and dryness is not easy and requires a holistic approach to fluid cleanliness. Even new oil in an unopened barrel is several ISO cleanliness codes too dirty for the intended application meaning that all new oils should be pre-filtered prior to filling the gearboxes. Ideally, new oils should be filtered using a minimum β_3>200 filter to obtain fluid cleanliness 1-2 ISO codes cleaner than the 17/15/12 target level. In humid environments, or where new oils have been stored in less than ideal conditions, use water removal elements containing a hygroscopic super-adsorbent polymer to keep moisture levels in the 100-200 ppm (or lower) range.

Once filled with clean, dry fluid, it is important to continue to protect wind turbine gearboxes from particle and moisture ingression. Unlike industrial gearboxes that often run continuously inside heated buildings, wind turbine gearboxes experience a far broader array of operating conditions from high ambient temperatures in the summer months to low winter temperatures particularly in northern locations. Because of the way that wind turbines operate, gearboxes are often left idle for long periods during low wind season, adverse weather conditions or during routine maintenance activities. As a result, thermal syphoning in wind turbine gearboxes is far greater than in most industrial applications.

Thermal syphoning is an important consideration in wind turbine reliability. When the gearbox is operational, oil temperatures may fall in the 120°-140° F range. However, as soon as the gearbox stops turning and cools down, the air inside the gearbox will also cool causing it to contract. In order to equalize ambient pressure, gearboxes will breathe in air from the outside; air that is often laced with particles and moisture. Based on the ideal gas law, a gearbox that cools from 140° F to just 50° F will ingest approximately 18% of the total headspace volume. That is 18% of dirty, humid air!

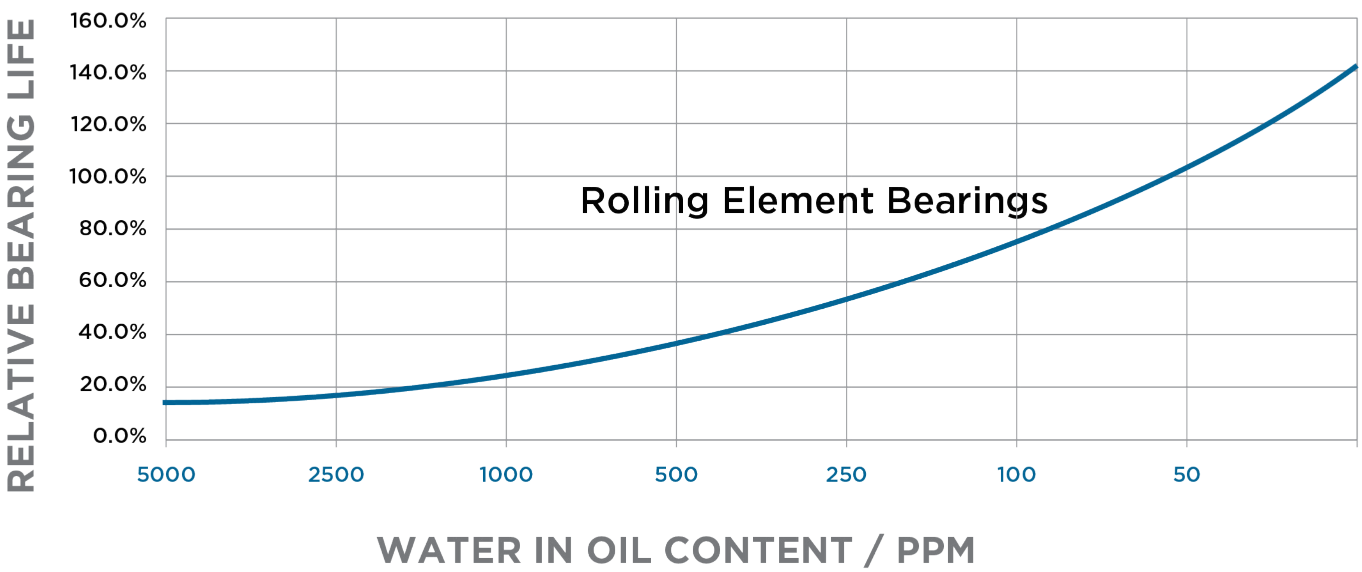


Figure 4: Impact of Water on Rolling Element Bearing Life

* (Ref https://www.global.mobil.com/-/media/project/wep/mobil/mobil-lubes-eame-sap-industrial-us/wind-wec-whitepaper/wec-wind-whitepaper-2020.pdf)

How to Maintain Oil Cleanliness

To control headspace cleanliness and by inference oil cleanliness, all wind turbine gearboxes should be equipped with a desiccant breather ***(Figure 5)***. Desiccant breathers contain a particle removal filter media rated at 3 microns absolute as well as silica gel desiccating media to reduce the relative humidity of the ingested air to less than 20% RH.

To maintain optimum headspace dryness, desiccant breathers should be changed before the blue desiccating media becomes completely saturated and turns pink. While in lower humidity environments this may take a year or more meaning that breathers can be replaced during routine, annual turbine services, in higher humidity locations, standard desiccant breathers may only last 3-6 months. Under these circumstances, using a vented breather with integrated check valves, which keep the breather sealed under steady-state conditions will help ensure that the desiccant remains effective without having to change maintenance services intervals.

In addition to desiccant breathers, filtration is a critical component in driving fluid cleanliness. All wind turbine gearboxes come equipped with full flow oil filters, designed to remove particle contamination. Many wind turbine gearboxes are specified with a 99.9% efficient 10-micron filter (β_{10c}>1000). However, due to the extended service intervals between filter changes and the need to maintain flow to the bearings and gears, full flow filters are often operating in bypass through either the filter housing bypass valve or an internal bypass valve incorporated into the filter. Once in bypass, the filter is doing nothing to protect gears and bearings exposing the gearbox to particle- induced failure. ***Figure 6*** shows the typical level of cleanliness found in a wind turbine gearbox without adequate filtration.

Figure 5: Desiccant Breathers help to keep the headspace clean and dry. In higher humidity locations, vented breathers that only open when the gearbox heats up or cools down help insure optimum service life.

Additional Tests

TAN (mgKOH/g)	OPC Code	OPC 4u Count	OPC 6u Count	OPC 14u Count
0.86	22/21/18	34548	10782	1339

Figure 6: Many wind turbine gearboxes operate at ISO cleanliness levels far above the optimum target of 17/15/12

To maintain high levels of fluid cleanliness, some new wind turbine gearboxes come equipped with off-line filtration systems. However, many are not equipped. These off-line systems, often called kidney loop systems, use a small pump and motor to pass oil from the gearbox sump through an external filter, returning clean fluid back to the sump. The benefits of off-line filtration are twofold. First, since the off-line unit is not directly supplying oil to the gears and bearings there is no fear of lubrication starvation, meaning finer filters can be used, often as low as 3 microns. Secondly, since the flow rate through an off-line filtration is usually very low (often <0.5 GPM) more efficient filtration and better fluid cleanliness can be obtained. Under optimum conditions, off-line filtration systems such as the one shown in ***Figure 7*** can maintain fluid cleanliness levels as low as 16/14/11, which based on the life extension charts shown in ***Figure 3*** would potentially increase gearbox life by as much as 60-70%.

The impact of maintaining cleaner oil through off-line filtration can best be illustrated by the data presented in ***Figure 8***, which shows how the fatigue life of rolling element bearings within a gearbox varies with filter rating. As the study shows, controlling coarse particle contamination in the 20-40 micron size range has very little impact on fatigue life. This is because these particle are simply too large to enter the dynamic clearances in gears and bearings. However, below 10 microns and in particular below 5 microns, there is an exponential increase in fatigue life as dynamic clearances sized particles are removed. This is the domain of off-line gearbox filtration.

Figure 7: This small, compact filtration system is ideally suited for installation on a wind turbine gearbox, with a low profile and overall footprint and particle filtration down to 3-µm absolute.

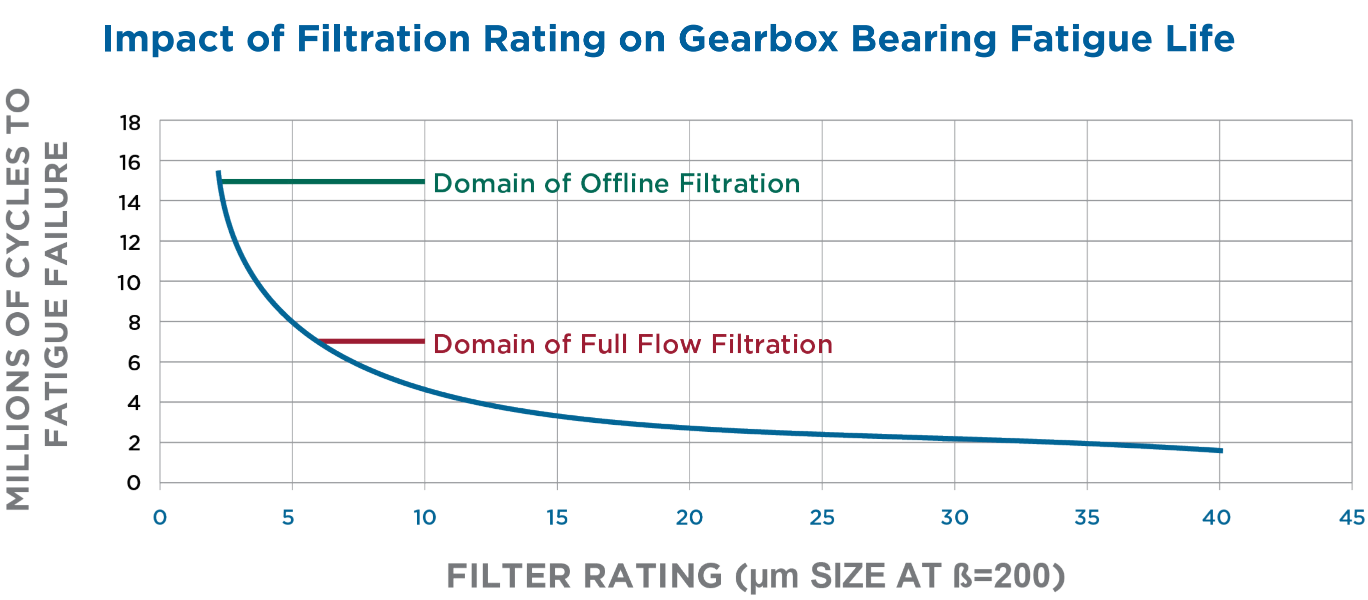


Figure 8: Impact of Filter Rating on Gearbox Bearing Fatigue Life Ref: Sayles, R. and Macpherson, P. (1982). Influence of Wear Debris on Rolling Contact Fatigue. Rolling Contact Fatigue of Bearing Steels. ASTM STP 771. p. 255-274

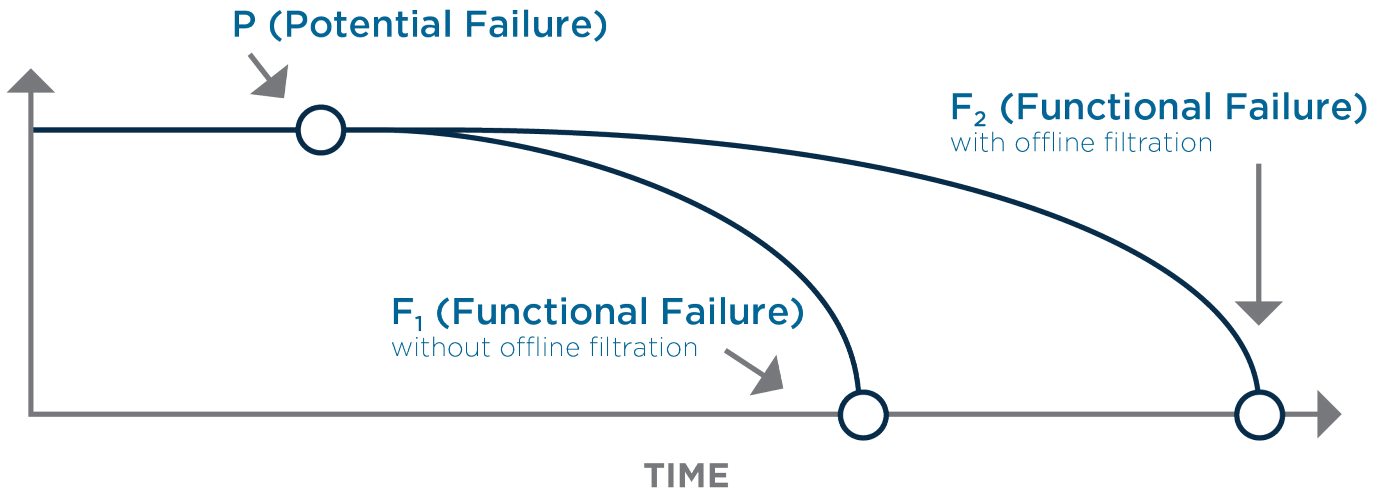


Figure 9: Off-line filtration can reduce overall wear rates, thereby extending the time between a problem becoming apparent and the machine failing.

Conclusion

Of course, not all gearbox failure can be attributed to particle contamination. In wind turbine gearboxes there are many other causative factors at play. However, even if the root cause of failure is not particle contamination, having off-line filtration can still be effective in extending gearbox life. To understand this concept, consider the progression of failure in a gearbox. Most failures do not occur instantaneously. Oftentimes, a single event or series of smaller events create failure initiation but the failure progresses insidiously for months or even years. In reliability theory, this process is often explained using the P-F curve ***(Figure 9).***

The P-F curve identifies two unique moments in time. Point P identifies when a failure first starts to occur and is observable and point F when the machine is considered to have functionally failed. While off-line filtration will have no impact on point P if the failure is unrelated to particle contamination, as the failure progresses, wear debris particles created by active wear will affect the rate of failure and hence the time to reach point P. By removing wear debris with off-line filtration, the P-F failure curve can be "flattened" thereby extending the timeline before which point F is reached. While flattening the P-F curve does not stop the failure, the extended timeline may be enough to plan and schedule corrective action, lowering the overall financial cost of an unscheduled failure.

Reliable wind turbine operation demands optimum drivetrain reliability. Central to this is the role that lubrication and contamination plays. Put simply, dirty oil causes gearboxes to fail. With many wind turbine gearboxes only reaching a fraction of their engineered design life it is time to do something different. Even a 20-30% increase in life expectancy has massive financial implications to annual O&M budgets; something that off-line filtration can easily deliver.■

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