WHITE PAPER

The vicious cycle running silently in your fleet, and how to break it

Sensing360 GearUp | White Paper for Wind Farm Operators

How unequal load distribution drives gearbox failure and reduces turbine lifetime, and how real-time monitoring enables reliable operations and planned intervention.

Prepared by: Sensing360 , Date: April 2026, www.sensing360.com

The mechanism behind most of your gearbox costs

Wind turbine gearboxes account for 25-35 percent of all wind turbine failures. Within the gearbox, the planetary stage dominates. Bearings and gears together cause 96 percent of gearbox failures (NREL data: 76.2 percent bearings, 17.3 percent gears). These failures share one root cause that most operators have never directly observed: unequal load distribution among the planet gears.

In a planetary gearbox stage, input torque splits across multiple parallel planet paths. Each planet should carry an equal share. In reality, manufacturing and assembly tolerances (carrier pinhole position errors, gear tooth thickness variations, bearing clearance differences) cause unequal load sharing.

There is load sharing inequality after manufacturing, resulting in one planet carries excess load from day one and there is load sharing degradation during operation, caused by wear, unfavoured operating conditions, etc... The physics are severe: gearbox and bearing fatigue life scales with load to the power of approximately 3.3. A planet carrying 20 % excess load sees its life halved. NLR (former NREL) field testing documented planets carrying 46-47 % excess load in gearboxes that passed all standard commissioning checks.

> *Inequality drives wear, and wear feeds inequality, until failure.*

This self-reinforcing cycle prevents most gearboxes from reaching their 20-year design life. They typically require major intervention after six to ten years. It runs silently, invisible to SCADA and vibration sensors on the housing, until it produces a sudden, expensive, unplanned event.

Condition monitoring: the P-F curve and load sharing.

Predictive maintenance is to detect failure modes and schedule intervention just in time. This strategy depends on the ability to monitor assets continuously and track developing failure modes. Existing monitoring technology comes with limitations. Temperature sensors respond to thermal overload but offer almost no lead time. Up-tower inspections with endoscopy assess internal condition but are labour-intensive and typically only happen after an incident or on a regulatory schedule.

Current industry standard is vibration monitoring identifying evolving failure modes in bearings and gears through characteristic frequencies. Unfortunately, it works only well at higher rotating frequencies, at the higher stages of a gearbox. However, at the slow speeds of the Low-Speed Shaft and first planetary stage (5-20 RPM), sensitivity drops off. So, failures in the component with the highest torque develop unnoticed, and once detected, time to intervene is short. In the whitepaper we introduce adding load and load sharing as condition monitoring parameter to gearbox monitoring – detection before the failures start.

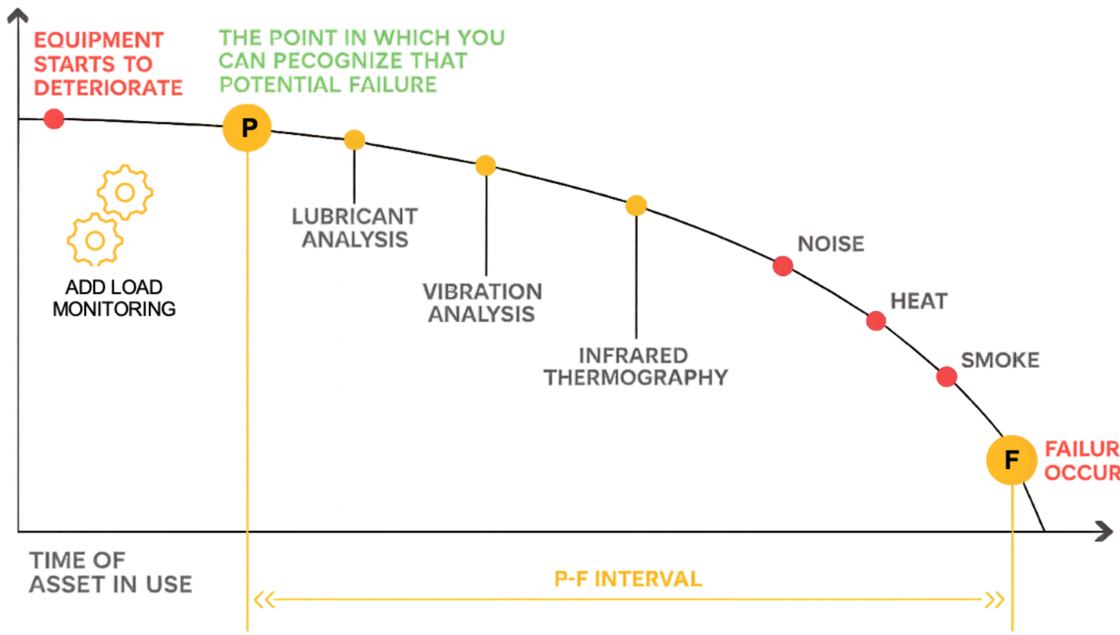

Figure 1: The P-F curve with the position of load monitoring

The cycle follows a predictable progression on the P-F curve as shown in figure 1. Load sharing inequality rises gradually as bearing clearances increase with wear. This progression is measurable months before any vibration signal appears and eventual failure. That intervention window determines whether you pay EUR 50,000 or EUR 500,000 plus

What GearUp measures

Sensing360 LumiSens GearUp mounts a string of optical strain sensors, fiber bragg gratings, directly on the outside of the ring gear of the gearbox as seen in figure 3. The sensor body is then connected optically to an edge computing device. Each sensor measures the strain exerted on the housing which scale with the torque of the passing planet. Speed is derived from the frequency of planet passes. Together with speed and torque these sensors also measure the transmitted load by each gearbox planet, basically looking "inside" the gearbox of the loads are balanced and how wear and stiffness is changing over time.

This measurement, other than for instance the electrical power measured by the SCADA system, discriminates between parallel transmission paths within the gearbox and determine the **LSII (Load Sharing Inequality Index)**. LSII tracks load sharing inequality per planet which is a prerequisite input to calculate the **CDI (Cumulative Damage Index)** tracking actual fatigue life consumed per component.

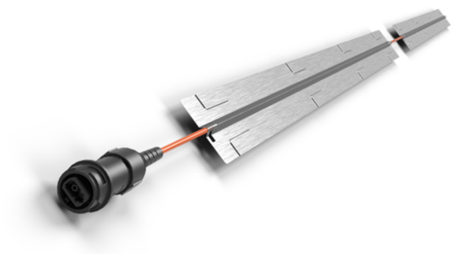

Figure 3: The LumiSens GearUp fiber optical sensor strip and the direct implementation on the outside of the planet ring gear.

LumiSens GearUp gives the following measurements:

- Main shaft torque
- Planet Load sharing
- Speed or rotation
- Strain based vibrations
- Temperature

Measuring both exact operation and condition of the gearbox in one sensor solution looking "inside" the gearbox.

Load Sharing Indication Index (LSII) in three cases

Exact "used" life as input to Smart derate to maintain production

When the exact load and load sharing (LSII) exceeds threshold, fatique life of the gearbox is reduced by the power 3+, meaning that 20% load is 50% less life. If measured at high frequencies, also events like start/stop and the resulting high torques can be captured, which allows for accurate lifetime predictions based on what is really happening. Give much better lifetime and gearbox status information compared to SCADA from the generator 1 Hz torque input from the blades, this is illustrated in figure 3.

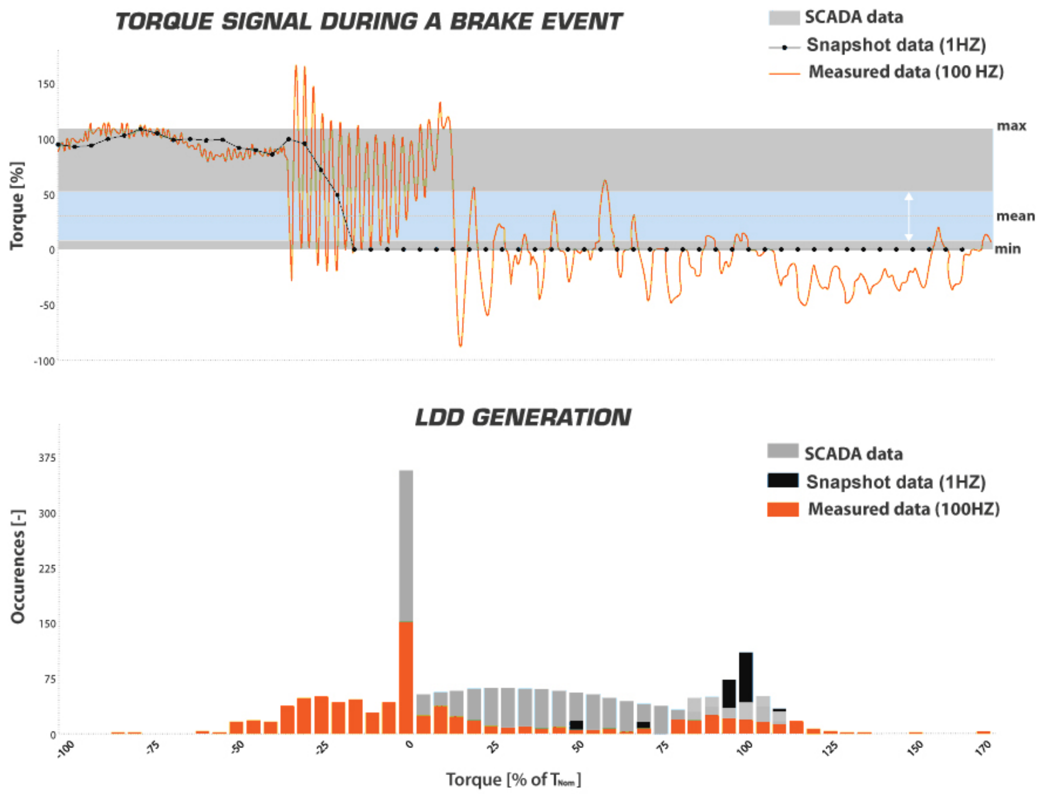

Figure 3: Brake event transient effect on Load Damage Distribution as input for "used" life. As one can see, more high load events are normally missed.

With this more accurate torque and addition of load sharing, one can decide to for instance reduce turbine output to approximately 1/LSII of nominal power, which brings the actual load on the overloaded planet back within design limits. As example this could mean that the turbine generates at 80% of nominal output with life consumption returns to the design rate, gaining time to arrange a planned repair.

On a 5 MW turbine, four months of derated operation at 80 percent instead of zero recovers EUR 200,000-400,000 in revenue. That alone pays for the monitoring system many times over, before counting avoided repair costs.

Scenario	LSII	Power	Life consumption	Energy harvest	Outcome
Undetected or late detection	1.1	Full	Approx 2x design rate	Approx 50% of nominal	Unplanned stop
Early detection + smart derate	1.1	90%	Design rate	Approx 90% of nominal	Planned maintenance

Plan the intervention, not the emergency

Load sharing captures 90% of the gearbox failure and not weeks ahead, but months ahead. The main reason is that load sharing at nominal operating condition will only chance when either tolerances become larger (wear) or stiffness changes (cracks, breaking). Meaning that trending the LSII parameter is on parameter to capture most of the gearbox failures, including planet bearings (also journal bearings), teeth issues of planet and the sun and excelling a slow rotation.

Measuring the start of failures 6-9 months ahead, allows for pre-ordering components (8-16 week lead times), book a crane during a low-wind window at standard rates rather than emergency rates (2-3x higher), and schedule the repair for summer rather than winter. A planned uptower bearing swap costs EUR 50,000-60,000. An emergency full gearbox replacement costs EUR 300,000-600,000, the difference comes down to advance warning.

Prevent secondary damage

Th When a planetary stage fails catastrophically, metal debris travels through the entire lubrication system, contaminating the main bearing, oil coolers and potentially the generator bearings. Secondary flushing and component replacement add EUR 100,000 plus. Early months LSII detection stops the cycle before structural disintegration, keeping the replacement to the gearbox itself.

From predictive maintenance to smarter operations

Apart from advanced condition monitoring, LumiSens GearUp shifts the question from 'when will this gearbox fail?' to 'how do I operate this gearbox to maximize its productive life?

With exact damage accumulation available of the gearbox, it gives more insights in used and remaining "life" and giving probability of failure based on fatigue models. This allows for the implementation of risk-based operations strategy, and this requires a tailored control strategy for each gearbox in the farm. With the detailed insight into the internal state of each individual Gearbox available allows for improved calculated failure probabilities on internal gearbox components and complete drivelines. GearUp combines historic loads with scenarios for future operation to develop accurate prediction models, applicable at each lifecycle phase.

Lifecycle monitoring

The lifecycle approach covers five stages: design life (validated by design models and safety factors), build life (manufacturing tolerances and quality), service life (operational loading and maintenance), field inspection (condition assessment), and second life (life extension or refurbishment).

Torque and Load sharing data changes the conversation at each stage. Specifically for operations, it for instance distinguishes between stochastic risk (overload events during risky conditions that can be curtailed) and deterministic degradation (developing failure modes whose progression can be slowed). Smart curtailment during high-risk operating conditions (low wind, high turbulence) which reduces excess loads on critical components.

New developments

Ideally a new gearbox has an LSII of 1, the loads equally shared among its planets. But manufacturing quality is not constant and actual numbers in new gearboxes vary more than 10%. These gearboxes leave their factory with a reduced service life which is already one third less. The reason? Wear is accelerated, especially when a turbine is operating near cut-in speeds (due to underload events) and cut-out speeds (due to overload events).

Fleet level

Due to wake effects, loads are unequally distributed over turbines in a windfarm. The variations in loads and the variations in torque and mainly load sharing add up in the calculation of gearbox failure rates. And in older farms, after multiple gearbox replacements, also service life between gearboxes differs. The mean failure rate predicts the number of yearly gearbox replacements. Because of the broad distribution of failure rates, this rate is largely determined by the small number of gearboxes most at risk. LSII gives the opportunity to reduce the failure rate of the farm by a focused intervention on the 10-20% least reliable gearboxes. Thus, gearbox replacements can be reduced while overall annual production losses remain limited to 1-2%.

At fleet level, curtailment applies to roughly 10 percent of gearboxes, during 10 percent of operating time, at load conditions where electricity prices are low or negative 60 percent of the time. Net revenue impact is approximately 0.2 percent of fleet revenue. Avoided gearbox replacement costs at a 50 percent reduction in long-term failure rate on a 100-turbine fleet amount to multiple millions per year. Curtailment costs roughly EUR 200K per year. The ratio is clear.

The most urgent case: ten-year-old fleets with limited monitoring

A fleet approaching or past the ten-year mark with no or limited existing CMS represents the highest-risk profile in the operating wind industry. Load sharing inequality and peak torques accumulates gradually over years of operation. Ten years of unmonitored operation means ten years of invisible cycle progression. The "used" life (CDI) on these assets is almost certainly worse than the design model predicted, because the design model assumed average site conditions and perfect load sharing, and neither holds in the field.

On proposed way to implement GearUp is to retrofit during a scheduled maintenance visit with approximately two hours of installation work by your maintenance team, no crane, no specialist. A field-only CDI baseline is established from first operating data, secondly a retrofit health certificate documents LSII and CDI is made at installation. Then as example fleet rollout batched across your existing maintenance schedule, requires no separate site visits and no additional crane costs.