Owner-Led Offshore Wind Gearbox Replacement

Equinor’s strategy at Sheringham Shoal

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Summary

In 2014, condition monitoring analytics and subsequent endoscope inspections revealed the need for two gearboxes to be replaced at Sheringham Shoal offshore wind farm. This case study explores the drivers for, and the result of, the operations team leading on the heavy lift jack-up operations and refurbishing the faulty gearboxes.

Lessons Learned

- Ensure there is a comprehensive strategy in place for managing all of the faulty components that will build up in the post-warranty phase.
- Carry out root cause analysis where possible with faulty components. This leads to much greater transparency and knowledge of component reliability. It worked to start small and show that this engineering approach works for less critical sub-components before applying to a major system component.
- To achieve the commercial and technical benefits made possible by root cause analysis of faulty components, it is critical to have a robust project management and evaluation process and buy-in from across the organisation. Openness and understanding of the project across the team is important, from understanding stakeholder risk assurance to implementation and execution of the project.
- Acting on condition monitoring system (CMS) warnings is important to avoid failure, but judging the right time to intervene is extremely difficult. Two gearboxes were replaced before anything catastrophic occurred at site in this case. However, through this activity the Sheringham Shoal team has learned a lot about interpreting CMS warnings. In particular, one of the gearboxes could have been safely run for longer before replacement – however, that would have ultimately required an additional jack up campaign at much higher overall project cost and should be considered when interpreting condition monitoring data.
- Finding a storage facility for multi-megawatt wind turbine gearboxes can be challenging, with a lack of suitable facilities on the market.

Introduction

Sheringham Shoal is an offshore wind farm situated 17 km off the north Norfolk coast as shown in Figure 1. The wind farm has 88 Siemens 3.6 MW turbines, making up a total installed capacity of 316.8 MW. The wind farm was originally a 50:50 joint venture between Statkraft and Equinor (then known as Statoil), but in November 2014 a 20% stake was sold to the Green Investment Bank (GIB) and now ownership of the wind farm is a 40:40:20 split. The farm was commissioned in December 2012 and came out of warranty early in June 2014. Siemens, as the original equipment manufacturer (OEM), continued to provide wind turbine servicing until December 2017. Statkraft was the lead operator of the site following commissioning, but in summer 2016 handed over responsibility as lead operator to Equinor.

Figure 1: Location of Sheringham Shoal Offshore Wind Farm

The 3.6MW Siemens wind turbine model is the workhorse of UK offshore wind, making up 3.6GW of the 5.3GW operational capacity in UK waters.

The turbines at Sheringham Shoal employ Winergy gearboxes that weigh approximately 40 tonnes each. Their purpose is to step up the slow rotational speed of the rotor to a rotational speed that is more efficient for generation of electricity. The particular design that has been adopted at Sheringham Shoal is a three-stage planetary gearbox as illustrated in Figure 2. Two stages are planetary and one stage is helical. A planetary stage consists of planetary cogs known as wheels, with teeth that mesh with both an inner cog and an outer ring.

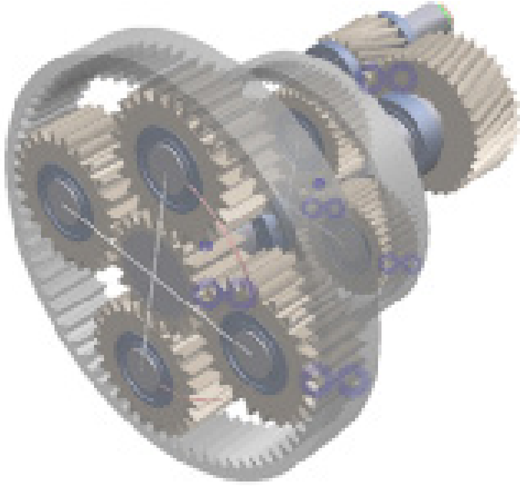

Figure 2: Diagram of the three-stage gearbox design as adopted at Sheringham Shoal Offshore Wind Farm

Moventas is a Finnish gearbox manufacturer. In addition to supplying components, it also offers engineering services. The company has a test facility in Jyväskylä, Finland that can be used to strip down gearboxes and identify and analyse the root cause of failed components.

The Challenge

In the post-warranty period, Sheringham Shoal's operator had an ongoing agreement with the OEM to provide vibration monitoring of the wind farm's gearboxes. In the third quarter of 2014, based on this information, the OEM flagged a potential reliability issue with one of the gearboxes at the wind farm. The operator then sub-contracted the OEM to carry out an endoscope inspection on that gearbox.

The inspection revealed a crack in a tooth of the planetary wheel in the first stage of the gearbox: the exact fault that the condition monitoring system had suggested. The decision was taken by the wind farm's operator that the gearbox would have to be replaced. To mitigate any further damage, it was also decided to curtail this turbine and operate below full power until a replacement could be carried out.

Subsequently, in December 2014, a second gearbox issue was identified – this time flagged by a third-party vibration monitoring system provided by Romax. The turbine OEM was able to confirm that this was a risk using their condition monitoring systems, and its analysis suggested that it appeared to be the same issue as had already been identified on the other turbine earlier in the year. Ultimately, the OEM recommended an endoscope inspection.

An inspection of the second gearbox was carried out in January 2015 by Romax. It found indicators of a problem such as debris – however, no actual cracks or broken gear teeth were found. It was concluded that this gearbox had suffered from very similar damage as in the other turbine, but it may not have been as severe. The wind farm operator decided to replace this gearbox, but a risk-based analysis concluded that it could run the turbine at full power until the replacement.

The decision to replace two gearboxes is a significant undertaking for any offshore wind farm in any phase of its lifecycle. Given the weight of this particular component, it is classified as a heavy-lift operation that requires a jack-up barge. These are extremely expensive vessels with typically extensive lead times, and the replacement operation can be expected to require significant turbine downtime. However, the costs of replacing faulty major components far outweigh the risks of not addressing the problems. Delaying a repair can exacerbate some types of damage and significantly increase the complexity of repair or refurbishment of that component. There can be longer-term integrity issues for the other components in the turbine. In the worst case, an unaddressed issue could lead to the catastrophic failure of the turbine, which can put human life at risk.

Given that Sheringham Shoal had come out of warranty, the operator faced a variety of options for how to proceed. The first main decision involved the party that would lead on the work: should it be contracted to a third party (likely the OEM), or should the wind farm operator take ownership and lead on planning and delivery of this heavy lift operation?

Furthermore, should the operator purchase new or refurbished gearboxes for the replacement? And finally, what should be done with the two faulty gearboxes?

The Approach

Heavy Lift and Gearbox Replacement

The wind farm operator chose to lead the major component replacement campaign rather than subcontract the work. The operator was aware that replacing a major component would be a significant challenge for the organisation, but it was keen to be in control of the operation and improve on its internal capability.

Two refurbished Winergy gearboxes were purchased from Siemens, and the heavy-lift operation was planned and delivered using only the Sheringham Shoal operator technicians and contracted technicians from two service providers: 3sun and SeaJacks.

Prior to this one, there had been two other jack-up campaigns during the operational phase of Sheringham Shoal. Both times, the wind farm was under warranty with Siemens and while the wind farm's operator took responsibility for sourcing a jack-up, the Siemens heavy-lift team planned and carried out the lifts. Therefore, this was the first heavy-lift operation at the wind farm where the operator was fully responsible for planning and delivery.

To alleviate any apprehension that the Sheringham Shoal technicians may have had about this new level of responsibility, the technicians were involved in the very early stages of planning the campaign and there were comprehensive walk-throughs of the work.

Planning was an engaging and collaborative effort, whereby clear work instructions were based on shared knowledge between the wind farm's operator as project manager, 3sun's experienced technicians and jack-up provider SeaJacks.

One of the most significant barriers to overcome in the planning phase was the challenges around demonstrating sufficient mitigation of health and safety risks. The collaborative team addressed this by producing comprehensive work instructions, method statements and risk assessments. Regular, scheduled communication was key, including a kick-off meeting with representatives from all stakeholders and weekly progress meetings.

Figure 3: Change-out of a Winergy gearbox at Sheringham Shoal in Q1 2015

The jack-up arrived on site at the end of the first quarter of 2015 as planned.

The procedure involved supporting the gearbox while technicians unbolted it from the main shaft. Most of the necessary lifting tools were available in the market, but the wind farm's operator had to manufacture some specialised instruments. The sea fastenings were provided with the two gearboxes purchased from Siemens.

All work instructions and procedures were fit for purpose and the change out of both gearboxes took 10 days.

In total, it took less than six months for the Sheringham Shoal operations team to identify a gearbox issue, plan a replacement campaign, mobilise a jack-up barge, and execute the change-outs. This can be regarded as a very efficient operation.

Pilot Component Refurbishment Scheme

Before becoming aware of the two faulty gearboxes, Sheringham Shoal's operator was already demonstrating a proactive approach to examining and refurbishing failed sub-systems. A representative from its operations team explained that one overlooked aspect of post-warranty operations was how to manage the stock of faulty components. Before long, there was a warehouse in the O&M base filling up with faulty turbine components. This necessitated a strategy for handling faulty components once they had been removed from the offshore assets and returned to the onshore base.

A pilot component refurbishment project was initiated to address this issue, the main aims of which were to:

- Increase/maintain the availability of (working) spare parts.
- Maximise the value of existing parts by extending their lifetime.
- Maximise turbine availability by minimising common faults associated with different components.
- Minimise the overall cost associated with the replacement of faulty components.
- Improve in-house knowledge and competence.

The process for investigating and repairing (or replacing) faulty components once they are removed from an asset is illustrated in the decision tree shown in Figure 4.

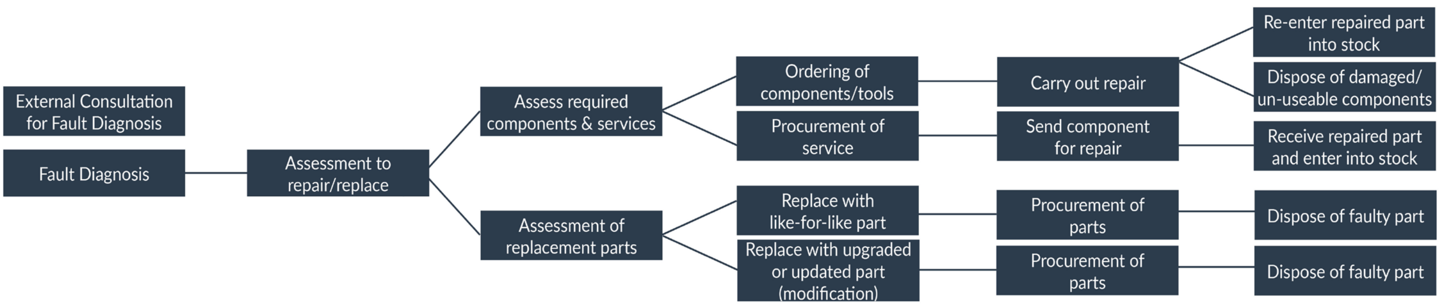

Figure 4: Decision tree to support the process for managing faulty components.

The project demonstrated cost savings and was well received internally. In particular, this approach facilitated improvements in the management of delta modules faults – a sub-component of the converter within the power electronics system. It was shown that a refurbishment of a delta module is 60% cheaper than purchasing a new one, and although a delta module can only be successfully refurbished following certain failure modes, overall, the component refurbishment project demonstrated a 40% cost saving for the maintenance of this sub-system. Another sub-system that demonstrated success was the automatic greasing system.

In addition to cost savings, for both of these turbine sub-systems, the endeavour to refurbish sub-components opened up valuable channels of communication and direct relationships with sub-component OEMs. Therefore, Sheringham Shoal's operator was informed of new versions of delta modules under development, and creative ways to maintain auto greasers.

Applying the Pilot Scheme for Major Components

Given the success of the pilot scheme for refurbishment of sub-systems, the wind farm's operator was keen to apply this methodology for larger components. The operations team set out to consider its options for how best to refurbish the two faulty gearboxes.

With reference to the decision tree in Figure 4, the plan was to acquire two gearboxes to enable a quick replacement and minimise downtime at site, and in parallel carry out a repair of the faulty gearboxes once they had been brought back ashore.

With regards to the faulty gearboxes, the operator's strategy was to reduce operational expenditure (OPEX) through refurbishment if possible, and to create in-house knowledge by gaining a full understanding of the failure modes and mechanisms.

Tendering for Refurbishment of the Two Faulty Gearboxes

The wind farm's operator produced a scope of work for repairing the gearboxes and engaged with the open supply chain. The team was very pleased to find that a lot of third parties were interested in providing this service. However, the main barriers that excluded many gearbox manufacturers were the need for cranes with sufficient lifting capacity, and access to a testing facility where the gearboxes could be stripped to identify the root cause before being repaired and reassembled.

Option	Provider	Details
A	Winergy (component OEM)	Root cause analysis Two refurbished gearboxes Gearbox transport logistics UK storage solution 24-month warranty
B	Moventas	Root cause analysis Two refurbished gearboxes Gearbox transport logistics UK storage solution 24-month warranty
C	Siemens (turbine OEM)	Faulty gearboxes to be sold as scrap

Option C was not aligned with the operator's strategy of maximising value from faulty components, and out of option A and B, Moventas tabled the more competitive bid.

In addition to minimising cost, this decision to hire Moventas was driven by the intention to introduce competition to the market. The Siemens 3.6MW turbine is the most common turbine in the UK offshore wind fleet, making up 68% of all the operational wind capacity in the UK offshore wind fleet. Despite gearbox issues being one of the most common faults in the wind industry, to date there have been very few service providers that can offer full gearbox refurbishment. The work at Sheringham Shoal was seen as an opportunity to bring a new player into this market.

Root Cause Analysis of the Faulty Gearboxes

By the second quarter of 2015, the gearbox replacement project had been closed out. The refurbishment of the faulty gearboxes was managed as an independent project by the Sheringham Shoal team.

Initially, the gearboxes were stored at a facility in Lowestoft while logistics and contracts between Sheringham Shoal's operator and Moventas were finalised.

The plan involved transporting both gearboxes to the Moventas test facility in Finland, performing a root cause analysis (RCA) on both, transport back to UK, and finally a long-term storage solution at an appropriate facility in the UK.

Transport of the gearboxes from Lowestoft to Finland posed several logistical challenges. The biggest was creating load plans for trucks to carry the gearboxes on land. The wind farm's operator had to source a technically capable supplier and have confidence in their plans. Furthermore, the operator was responsible for heavy lift at the Lowestoft end, and finding out if the cranes were up to the job proved difficult.

The transit from Lowestoft to Finland took one week and the gearboxes arrived at Moventas' testing facility in July 2015.

Figure 5: The Moventas gearbox testing facility in Finland.

In January 2016, a representative from the wind farm's operations team travelled to Finland to walk down the stripped gearbox and review the RCA findings and conclusions. Both gearboxes had suffered from the same failure mode: a material defect of one of the planetary cogs. More details of the RCA findings are provided in the results section.

The gearboxes were shipped back to Sheringham Shoal's operator in July 2016. Gearbox storage requires an active facility and investment would have been required to keep the gearboxes at the Sheringham Shoal site. Instead, they are now being held in a suitable Moventas-owned storage facility in Huddersfield.

Turbine Gearbox Storage

A wind turbine gearbox cannot simply be stored in a standard warehouse. Instead, an active facility is required in which the gearbox can be connected to rotating shafts. This prevents "stand-still" marks, corrosion, and blackspots forming on the gearbox bearings.

The operator identified that this gearbox refurbishment operation could have been much more efficient and cheaper if Moventas was able to carry out the refurbishment in the UK-based storage facility.

The Results

Owner-led heavy lift and major component replacement

Sheringham Shoal's operations team has successfully demonstrated that it can safely and effectively carry out a heavy-lift operation without the supervision from, or experience of, a turbine OEM. This activity has helped the team develop significant in-house capability around heavy-lift operations.

Not only was the operation carried out with no health and safety issues, it was executed in an extremely efficient manner. It took less than six months for the operations team to identify a gearbox issue using condition monitoring, plan a replacement campaign, mobilise a jack-up barge, and execute the change outs.

The project demonstrates an excellent example of collaborative working between the Sheringham Shoal team, the contracted technicians, and the jack-up provider. Effective communication and thorough planning were key to the project's success.

Refurbishment over selling

It has been demonstrated that the refurbishment of one of a wind turbine's most important major components can be delivered in a cost-effective manner, and at the same time generating valuable knowledge and capabilities for the wind farm operator.

The operations team at Sheringham Shoal now has access to two fully-functional gearboxes whenever the need arises.

While the driver for selecting to refurbish was to develop in-house knowledge of the assets by better understanding the failures, the refurbishing option also proved more cost-effective.

Tendering the refurbishment highlighted the third party market for Siemens 3.6 MW turbine services. It was found that there was a healthy appetite in the market to offer the refurbishment work, but many organisations were unable to meet all of the requirements. This is a promising indicator of a maturing supply chain ready to provide complex engineering services to offshore wind farm owner and operators.

Gearbox Failure Root Cause Analysis

Moventas stripped down each gearbox to its constituent parts in order to carry out RCA on each gearbox. It was concluded that both gearboxes had suffered from the same failure mode. Material defects were found within the planetary wheels in the first stage of the gearbox.

The low rotational speed of the rotor end of a gearbox experiences relatively large torques. As the rotational speed is stepped up through the various stages, the torque is stepped down in proportion. Therefore, the first stage of the gearbox, at the rotor end, is expected to be the likely location of failures.
The gearbox that was inspected first in the field was significantly more damaged, with a crack running almost the entire length of the planetary wheel tooth. At one end of the tooth, the crack had developed into a fracture as shown in Figure 6.

Figure 6: Planet gear 3. Flank of sun pinion mesh. Fractured tooth. Rotor side end.

The damage on the second gearbox was more localised. A hole approximately 2cm in diameter had formed in a planetary wheel tooth as shown in Figure 7. This can occur when debris is trapped within the gearbox.

Figure 7: Ring gear (first stage): severe indentation

The Sheringham Shoal team was satisfied with the results of the RCA, which were detailed, well-documented, and well-presented. The team now understands a critical gearbox failure mode and mechanism much better.

The strategy at site is to run assets in the safest and most efficient manner. The RCA findings indicated that replacing the less-damaged gearbox might have been premature. However, letting the gearbox run could have ultimately required an additional jack-up campaign at much higher overall project cost, and should be considered when interpreting condition monitoring data. Being able to reconcile between the RCA findings and the information that had been gathered during operation of the gearboxes was an excellent learning experience regarding interpretation of CMS signals and endoscope information.

Costs

Thanks to the two consecutive and complementary projects, Sheringham Shoal's operator is in an excellent position to appraise the costs of acquiring this particular type of component.

Comparing the cost of acquiring two functioning gearboxes from the change-out project, and the options available for the refurbishment project, (as set out in Table 1) spending the money to refurbish the faulty gearbox was approximately 15% cheaper than purchasing a refurbished gearbox from a supplier – even when the price for selling the faulty component was factored in.

Strategic Benefits

The proactive strategy adopted by Sheringham Shoal's operator had the following benefits:

- Improved in-house knowledge and competency – Leading on a heavy-lift campaign and the refurbishment of the faulty major component has developed valuable in-house competency.
- Ownership and control of campaigns. An active approach to leading campaigns puts the asset owner in charge of their own destiny, driving timescales and contractors.
- Introducing competition. The strategy provided an opportunity for a gearbox supplier to develop products and services for the offshore wind fleet. In turn this acts as an incentive for existing suppliers to improve, encouraging the industry to develop and mature more quickly.
- Cost reduction. Refurbishing a faulty gearbox is a more competitive option in terms of component costs and minimising downtime through more favourable lead times.
- Independent root cause analysis. This provides considerably more confidence, transparency and understanding of component reliability.
- Supply chain engagement. Engaging in root cause analysis of faulty components has facilitated better communication and collaboration between asset owner and the supply chain.

Lessons Learned

Sheringham Shoal's operator shared the following lessons learned:

- When Sheringham Shoal came out of warranty, the operator did not have a sufficient plan for managing all of the faulty components that would build up in the post warranty phase.
- It recommends carrying out root cause analysis where possible with faulty components. This leads to much greater transparency and knowledge of component reliability. It worked to start small and showed that this engineering approach works for less critical sub-components before being applied to a major system component.
- Collecting quality-checked maintenance data on components should not be overlooked. Development of a database to collect information on all repairs and any learning from root cause analyses serves as an excellent knowledge base. This can significantly reduce time wasted through planning campaigns and considering options by demonstrating what worked in the past.
- To achieve the commercial and technical benefits made possible by root cause analysis of faulty components, it is critical to have a robust project management and evaluation process and buy-in from across the organisation. Openness and understanding of the project across the team is important, from understanding stakeholder risk assurance to the implementation and execution of the project.
- Acting on condition monitoring system (CMS) warnings is important to avoid failure, but judging the right time to intervene is extremely difficult. The gearboxes in question were replaced before anything catastrophic occurred at-site. However, throughout this activity the Sheringham Shoal team have learned much about interpreting CMS warnings. In particular, one of the gearboxes could have been safely run for longer before being replaced.
- Actively reach out and engage with the full supply chain at an early stage in a wind farm lifecycle to ensure any potential future root cause analysis tenders can involve a broad range of suppliers.

- For replacement of major components, there are many alternative options. Ensure all options and suppliers are explored including the OEM. It is critical to make connections with many different suppliers, even if your turbines do not currently use their particular products.
- Try to build relationships with suppliers early in the wind farm lifecycle – In particular do not wait until the end of warranty to start making connections within the supply chain as there could be many competing issues to deal with in parallel.
- The Siemens 3.6MW turbine model is the most common in the UK offshore wind fleet. There is an opportunity for the supply chain to provide products and services for this turbine platform. In particular, the refurbishment and storage of gearboxes is a big opportunity.

Appendices

References

[1] Bonanomi, A. (2014) *Powerful Analysis of Wind Turbine Gearboxes.* Published in Power Transmission World.

Author profiles

Dr Conaill Soraghan is Team Leader for O&M Data Systems at ORE Catapult. He has a background in applied mathematics and completed a PhD in wind turbine design. Conaill's main area of interest is the management and optimisation of operational assets and he has extensive experience in the design and development of benchmarking systems and data/knowledge sharing for the offshore wind industry.

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This is one in a series of offshore wind O&M-focused case studies, supported by ORE Catapult's O&M forum and funded by The Crown Estate and the Offshore Wind Programme Board. These studies aim to highlight game-changing O&M projects, and promote the dissemination of knowledge among the offshore wind O&M community.

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