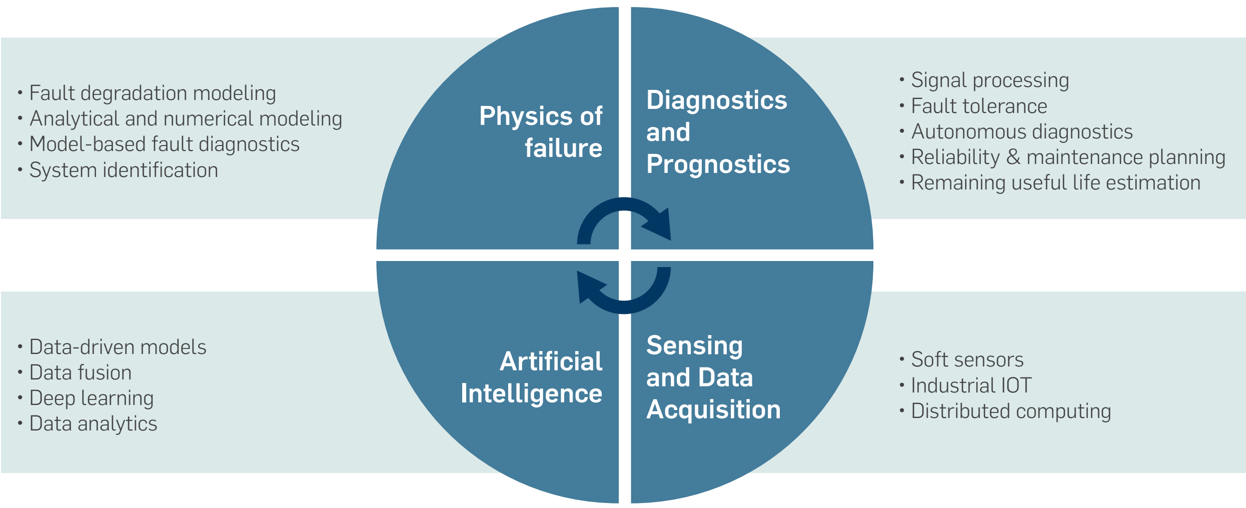
2016 – 2017

ADVANCED MAINTENANCE ACTIVITIES AT TEKNOVA AND UNIVERSITY OF AGDER

UNIVERSITY OF AGDER teknova

THE NEED FOR ADVANCED INDUSTRIAL MAINTENANCE STRATEGIES

At Teknova and the University of Agder, research is focused on providing end-to-end solutions for predictive maintenance and health management of high-value equipment in energy, oil & gas, mining and process industries. The objective is to improve reliability and availability while reducing unplanned downtime and maintenance costs.



Maintenance is, by many, associated with a mental picture of a mechanic holding a wrench repairing machineries. A task often seen by organisations as a necessary evil in order to keep the business running as usual.

With the recent progresses on sensors and data analytics, the field of maintenance is undergoing a complete revolution. The old picture of a mechanic is fading and a new picture of a machinery data interpreter is emerging whilst organisations will rely on maintenance groups to deploy new business models and survive in the digital world.

Indeed, with the deployment of sensors and data analytics on assets, the current business models of "selling machine packages" to owners can be confronted. Instead of selling machines, advanced maintenance strategies based on the asset health can enable equipment manufacturers to sell the function that the hardware supports; e.g. number of litres pumped, or number of tonnes lifted per day with some guarantee of availability.

In these new business models, asset owners transfer some responsibility for achieving the performance and reliability to the manufacturer in return for financial compensation. This sharing of accountability is of benefit to all as it pushes manufacturers to reduce consumption of resources by only replacing parts that need to be replaced. It also improves quality of services as both the customer and the supplier will share the same objectives: that is performance, reliability and cost reduction.

At Teknova and the University of Agder research is focused on providing end-to-end solutions for predictive maintenance and health management of high-value equipment in energy, oil & gas, mining and process industries.

Our objective is to improve reliability and availability while reducing unplanned downtime and maintenance costs. Research into condition monitoring, diagnostics and prognostics, can provide real-time assessment of asset health and help in planning inventory, logistics and maintenance actions. The team's research is focused on rotating machinery components that are ubiquitous in various industries as well as non-dynamic components such as ropes, which are a challenge for the industry.

Through a combination of classical signal processing methods with the novel industry 4.0 technologies, the team aims to provide solutions for large-scale deployment of health management systems for digital and connected industries of the future.

Kjell G. Robbersmyr

Profesor Kjell G. Robbersmyr is the Head of the Dynamics Research Group and of the ISHM lab at The University of Agder (UIA). The ISHM lab at UiA is focused on providing end-to-end solutions for predictive maintenance and health management of high-value equipment in energy, oil & gas, mining and process industries. He received his M.Sc. (1985) and Ph.D. (1992) degrees in Mechanical Engineering from the Norwegian University of Science and Technology, Trondheim.

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Thomas J.J. Meyer

Born in France in the 80s, Meyer started his career in the nuclear industry with an associated physico-chemistry education. He moved to England in 2003 to pursue a BSc, a Master and a PhD in the field of optoelectronics.

In 2010, Thomas relocated to Norway, switched focus to predictive maintenance and worked as physicist and later as a business development manager for Teknova, the youngest research institute in Norway. Meyer leads the task force on maintenance within the SFI Offshore Mechatronics project and coordinates the advanced maintenance activities at Teknova.

As an aside to this position, and in order to stay in touch with the academic world, Meyer also works part-time for the University of Agder as an associate professor in the department of Mechatronics.

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UNDERSTANDING THE ‘ROPE OF THE FUTURE’

Condition Monitoring of Large Fiber Ropes

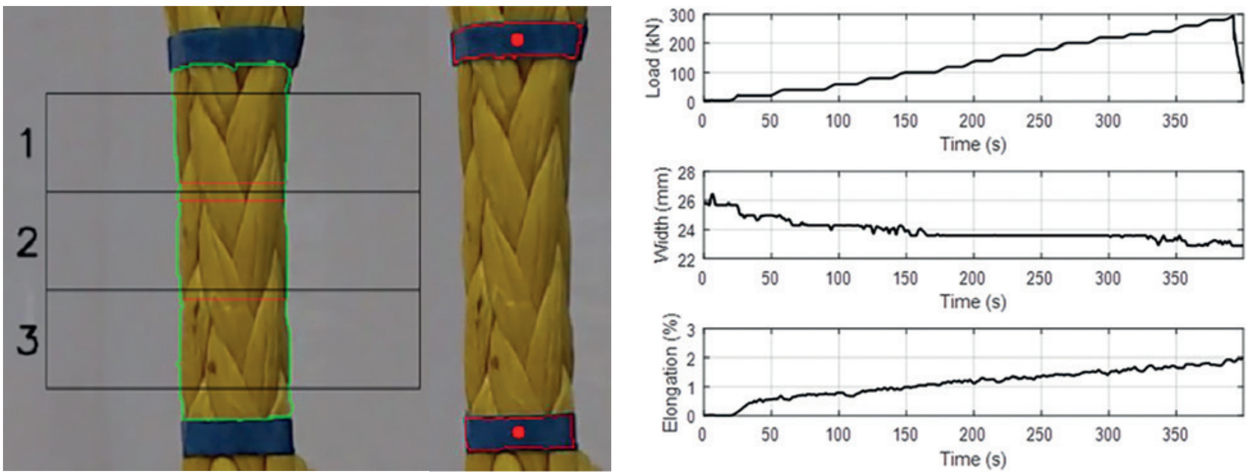
Superior qualities have dubbed fiber ropes as ‘rope of the future’. There is however a lot to learn about how fiber ropes perform over time and during intense use.

"The aim of this project is to research condition monitoring technologies that can better predict the remaining useful life (RUL) of large diameter fiber ropes used in subsea construction cranes during offshore operations," explains Shaun Falconer, PhD Research Fellow at the University of Agder, explains Shaun Falconer, PhD Research Fellow at the University of Agder, working for the SFI Offshore Mechatronics project work package 5, led by Teknova..

Fiber ropes have been shown to be stronger and have superior mechanical properties than their steel counterparts of the same diameter. While steel ropes must account for their own weight when determining the maximum depth a payload can be deployed, fibre ropes are considerably lighter and almost neutrally buoyant in water, meaning that smaller crane structures utilizing less offshore vessel deck space and weight can be implemented to reach greater depths. However, due to temperature build up in the fiber rope through the Cylcic-Bend-Over-Sheave (CBOS) motion, creep is an issue as HMPE (High-Modulus Polyethylene) fiber rope has a maximum safe working temperature of 65º to 70º centigrade.

Understanding the impact active heave compensation motion can have on deterioration of fiber ropes used in cranes during deep sea construction is of key concern for safer offshore lifting operations. Supported by recent experimental studies in the project SFI Offshore Mechatronics, the use of computer vision as an extension of visual inspection for condition monitoring purposes has been demonstrated. An improved understanding of condition indicators of fiber ropes during offshore lifting operations will lead to advances in the application of condition-based maintenance. This will be realised through improved RUL estimates, greatly reducing premature retirement of fiber rope.

R&D activities:
Experiments were performed by recording automatic width and elongation measurements of discrete sections of fiber rope through computer vision algorithms developed using OpenCV. Fiber ropes were subjected to tension-tension testing, the fiber rope was shown to reduce in width by around 10 per cent and elongate by around 2 per cent at the point before rupture, indicating that these measurements are suitable condition indicators for monitoring purposes. For more detailed results,



Diameter measurement algorithm (left), elongation measurement algorithm (middle) and experimental results correlating width and elongation measurements to tension data (right). From Falconer et al. (2017)

Shaun Falconer performs tests on fiber ropes at the rope-testing machine at Mechatronics Innovation Lab in Grimstad.

experiment set up and specific features of the computer vision algorithm, please read Falconer et al. (2017). As an example, the left and middle images in the figure on page 5 illustrate the application of the automatic width and elongation measurement algorithms. The right image displays the results from one of the experiments run on a fiber rope, where the width measurements and the elongation of the discrete rope section are correlated against the tension applied by the tension-tension machine.

Outlook:
Future research will extend the computer vision algorithm for automatic width and elongation measurements to monitor the condition of fibre ropes during CBOS motion through testing until failure. A CBOS test machine operated by Teknova, the University of Agder and the Mechatronics Innovation Lab will be used to simulate the motion of fibre rope during offshore active heave compensation. Additionally, thermal models for fiber rope due to CBOS motion are being developed to allow the implementation of IR cameras to give more reliable estimates of the temperature inside the rope. Ultimately several monitoring techniques (sensor fusion) are to be combined into a single approach to allow the condition of the rope to be gauged and create the best estimate of RUL.

Publications:
"Preliminary Results on Condition Monitoring of Fiber Ropes using Automatic Width and Discrete Length Measurements", *S.Falconer, A.Gromsrud, E.Oland and G.Grasmo,* Annual Conference of the Prognostics and Health Management Society 2017, FL, USA, October 2017

"Condition monitoring technologies for synthetic fiber ropes – a review", *E.Oland, R.Schlanbusch and S. Falconer,* International Journal of Prognostics and Health Management Society 2017

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SFI OFFSHORE MECHATRONICS

Shaun Falconer

Shaun Falconer holds an MEng in Mechanical Engineering with Aeronautics from the University of Glasgow, Scotland. As part of his studies he spent a year on Erasmus study placement at the Technical University of Madrid, Spain. He later completed his Master's thesis, again as part of the Erasmus programme, in conjunction with the University of Navarra and the CEIT research centre in San Sebastian, Spain, where he researched the use of extended finite element modelling techniques in simulations of aeronautical materials under fatigue testing.

After graduation he worked with the Structural Monitoring Division of Fugro GEOS in Glasgow, Scotland between 2014 and 2016 where he gained knowledge in the design and data analysis of structural monitoring systems on offshore and subsea structures in the oil and gas sector. In addition to this, he has offshore installation experience in a variety of locations, including Norway, UK, Nigeria, Azerbaijan, Qatar, Congo and Angola.

Since October 2016, he has been a PhD Research Fellow at the University of Agder (UiA) as part of the SFI Offshore Mechatronics WP 5.3 investigation into condition monitoring technologies for large diameter fiber ropes, in collaboration with Teknova. He is currently supervised by Prof Geir Grasmo (UiA), Dr Ellen Nordgård-Hansen (Teknova) and Dr Thomas Meyer (Teknova).

WHEN WILL IT BREAK?

Condition Monitoring of Large Steel Ropes

Sensor technology is used to monitor the condition of large steel ropes. The goal is to prevent accidents, extend rope lifespan and challenge regulations.

"More precise knowledge of the rope's health will enable us to make better and safer decisions. Sensor technology is superior to the human inspections we rely on today for determining the condition of ropes," says Rune Schlanbucsh, Senior Researcher at Teknova.

Subsea construction operates at increasingly lower depths, lifting heavier payloads, thus requiring larger steel wire ropes.

Modern ropes have complicated construction for avoiding payload rotation up to 3-4000 meters, and have diameter up to 180 mm. As such offshore environment are harsh, several degradation mechanisms are seen such as lubrication protrusion due to high pressure, severe corrosion, and fatigue due to continuous bending during active heave compensation.

Moreover, traditional human inspection of such ropes is not very productive as about 80 per cent of the wires are hidden below the rope visible surface, and the outer wires are obscured by a thick layer of grease. It is difficult to keep up concentration for effectively inspecting and assessing long lengths of rope within a time frame not hampering operations.

As the cost of modern subsea steel wire ropes increases with their size, it is important to research robust condition monitoring technologies for being able to assess the current health of the steel wire rope in near-real time,

Rune Schlanbusch adjusts the rope-testing machine before continuing tests.


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along with robust prognostic models for enabling optimal replacement planning. Thus, the objective of this work is to provide enough scientific evidence for rope users and classification companies to change the maintenance regime and discard criteria of steel wire ropes.

R&D activities:
The work is focusing on combining the most suitable sensing technologies for assessing the steel wire rope in real time. At the time beeing we are looking into combining the following three monitoring technologies for feeling (magnetically, internal wire breaks and corrosion), hearing (acoustic, real-time wire breaks) and seeing (optic, external wire breaks and mechanical damage).

The main priority throught the first part of the project has been to acquire and develop all sensing technologies and a continuous bend over sheave (CBOS) test rig.

Outlook:
The equipment is now in place and the test rig was set up during June 2017 and is now ready for substantial testing during the next project phase. The test rig has a capacity of 15 tonnes line pull, sufficiently for fatiguing ropes up to 30 mm diameter. The results so far can be found in the publications mentioned below.

The really big offshore steel ropes are much thicker than the ropes we are able to test on our current machine. It is unclear whether our findings on smaller ropes can be extrapolated to bigger ropes.

Publications:
Schlanbusch, R., E. Bechhoefer and T. J. J. Meyer (2017). Low Computation Acoustic Emissions Structural Health Monitoring Through Analog Signal Pre-Processing. In: *Proceedings of the Annual Conference of the Prognostics and Health Management Society,* St. Petersburg, FL.

Schlanbusch, R., E. Oland and E. Bechhoefer (2017). Condition Monitoring Technologies for Steel Wire Ropes – A Review. *International Journal of Prognostics and Health Management,* vol. 1, 14 pages.

Acknowledgement:
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SFI OFFSHORE MECHATRONICS

Rune Schlanbusch

Rune Schlanbusch received his MSc in Space Technology from Narvik University College (NUC), Norway in 2007, and a PhD in Engineering Cybernetics from NTNU, Norway in 2012. He currently holds positions as Senior Researcher at Teknova, Norway and Associate Professor II at the Faculty of Science and Technology, The Arctic University of Norway (UiT).

His major research interests include nonlinear control theory and stability analysis, Multiphysics modeling and simulation, intelligent sensor technologies, unmanned technologies and condition monitoring. He is currently a member of the IEEE Control System and Robotics and Automation Societies, and leads the Research and Development group of the Norwegian national drone organization UAS Norway.

EXPLORING THE ART OF SMART LISTENING

Contition Monitoring of Bearings in Low-Speed Machines

The ability to listen is valuable – especially when it comes to bearings experiencing serious stress.

All rotating machinery need roller-element bearings to function smoothly and effortlessly. Bearing faults can result in serious machine damage and costly down-time for the operator.

In the laboratory at UiA, PhD Research-Fellow Andreas Klausen is busy destroying bearings. He measures the vibration signals coming from the rotating bearings as they gradually wear down and break. The vibration signature changes during the degradation process, and reveals the state of the bearing.

"My research is focused on developing reliable methods for detecting faults in slowly rotating bearings by processing and analyzing the bearing vibration signal. When a bearing roller spin over a local defect, a distinct vibration signal is generated, and this can be picked up by a vibration sensor. The exact location of the damage can be identified by the fault impact frequency, and the severity by the magnitude of the vibration, Klausen says."

Bearings operating under low-speed and high loads can be found in for example winches, windmills, and oil-rig top drives. By analyzing data from the machine and comparing them to signals from a healthy bearing, a computer can automatically detect faults and warn the operator at an early stage to avoid break-down of these machines.

Rotating machinery employ rolling element bearings to reduce friction between moving parts and stationary parts. A typical bearing consists of: an inner ring that is fastened to the shaft; an outer ring that is stationary inside a bearing housing; and rollers/balls that move between the two rings in their race-ways. Undamaged bearings are critical for smooth operation of the machine. Bearings wear out over time due to the cyclic stress induced from every revolution. After N number of cycles, the wear is so great that metal particles detach from the race-ways, or the rollers. This leaves irregularities like gaps or holes in the bearing.

As the machine continues to rotate, the rollers hit these irregularities, causing shocks of vibration, which accelerate further wear in the bearing. If the bearing is not replaced in time, the internal damage gets so great that the bearing may cause complete machine shutdown. Determining the exact machine bearing life-time in cycles, N, is difficult due to the complex modeling required to include all factors. An estimate can easily be calculated, but a huge statistical uncertainty is included.

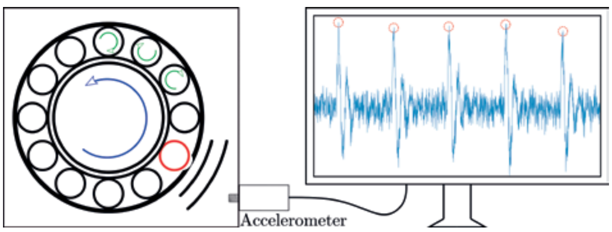

Figure 1: The bearing vibration is monitored using an accelerometer attached to the bearing housing.

Instead of relying on replacing the bearing before it fails, the machine may be monitored using sensors to detect early signs of faults. A schematic is shown in Figure 1 where a bearing is monitored using a vibration accelerometer. As the shaft rotates, the rollers hit a small gap in the outer race, causing the bearing to vibrate.

This vibration is captured by the accelerometer, and the raw data is displayed on the screen. Analyzing this data using signal processing methods allows for detecting this fault early in process, allowing for maintenance to be scheduled. In this example, the vibration peaks are easy to detect due to a high impact energy, as can be seen from the red-circled peaks.

Machines operating in a low-speed condition emit much lower impact energy due to slower bearing velocity. Examples are large winches, wind-mills, top drives, and output shaft of gearboxes. In these cases, it is a challenge to detect these faults early, however they are just as critical as in other machines. The machine vibration is often a combination of several sources including: Bearings, motor, gearbox, shaft, and external sources. In addition, the vibration travels from the bearing to the accelerometer, causing extra distortion of the signal. To detect the bearing vibration during low-speed conditions, it is necessary to separate this component from the other sources. The vibration caused by the motor, shaft unbalance, component misalignment, and gearbox teeth meshing, are all synchronous to the shaft rotation; i.e. the vibration caused by these sources are occurring in cycles correlated to the shaft. The vibration caused by impacts in the bearing, however, are slightly random due to the dynamics of roller slip and internal clearance.

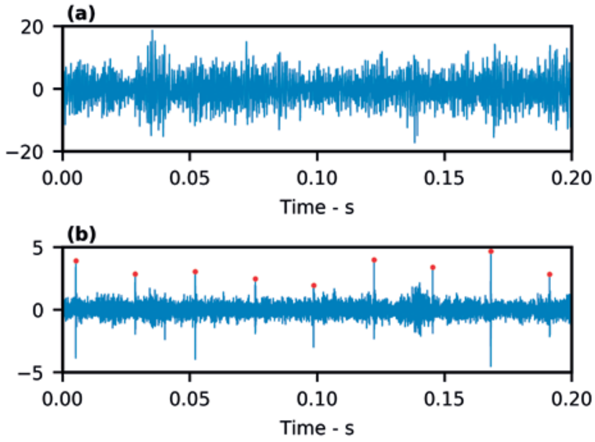

Figure 2: The raw vibration signal is filtered using an autoregressive model to highlight bearing faults. (a) The raw signal. (b) The filtered signal with red dots signalizing the bearing impact vibration.

This randomness allows for separation of the bearing vibration component from the rest using an Autoregressive model (ARM) filter. An ARM learns to predict the vibration dataset based on previous values. The vibration components originating from the synchronous sources are predictable by this ARM. Bearing impact vibration on the other hand, is not predictable due to the rollers random nature, and becomes part of a residual error. By preserving this residual, the vibration signal is less noisy and easier to analyze. An example of this filter is given in Figure 2: (a) shows the raw vibration signal, and (b) indicates bearing fault vibration after the ARM filter is applied.

After retaining the residual containing the bearing fault vibration, it is necessary to determine the fault type by analyzing the signal. This analysis is often performed in the frequency domain because the fault impacts happen at a certain cyclic frequency. This cyclic frequency is determined by the geometry of the bearing. The bearing in Figure 1 has an outer-race fault. Using the radius of each roller, the number of rollers, and the distance from the center of the shaft to the center of a roller, it is possible to calculate how often a roller should pass a certain point on the outer-race for each shaft revolution. The same philosophy can be used to find the cyclic frequency for how often a point on the inner-race is passed, or how often a roller spins around its own axis. Knowing these cyclic frequencies of the bearing, the remaining task is to identify impacts occurring at these cyclic frequencies in the vibration signal. If there is any correspondence, it is very likely that there is a damage in the bearing.

The residual signal is analyzed in the frequency domain to identify high energy peaks at the three cyclic frequencies

Andreas Klausen at work in the lab.


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2 4 6 8 10

belonging to the bearing in question. Using the Fast Fourier Transform (FFT), the time-domain signal is transformed to the frequency domain where the signal is described using sine-waves with certain frequencies, amplitudes and phases. Before transforming to the frequency domain, the envelope of the residual signal is first identified, as it aids to describe each bearing impact as a single event.
The envelope of the signal is shown as a red line in Figure 3 (a), while the residual from the ARM filter is the blue line. The frequency spectrum gained after performing the FFT is shown in Figure 3 (b). Here, the x-axis is given in orders, which is a measure of cycles per shaft revolution. From the bearing geometry, a point on the outer-race is passed 5.12 times per shaft revolution. In the frequency spectrum shown in Figure 3 b), harmonics at 1, 2, and 3 times 5.12 are marked, indicating that there is an outer-race fault present in the bearing.

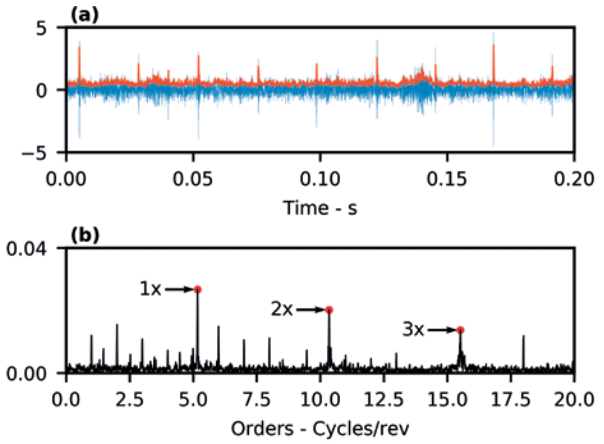

Figure 3: The envelope spectrum is analyzed to detect faults in the bearing. (a) Filtered vibration signal with the corresponding envelope. (b) The envelope frequency spectrum indicating an outer-race fault.

Hs procedure is typical for most applications where bearing fault identification is required. The biggest difference in low-speed conditions is the lower impact energy, which require more sophisticated algorithms to prepare the signal. The ARM is one such powerful method.

R&D activities:
In this article, the vibration generated by a damaged bearing operating at low-speed showcase the difficulty of fault detection during this machine condition. The signal is shown to be contaminated by noise, which makes the analysis difficult. By applying the Autoregressive model filter and the Hilbert envelope, it is possible to detect the fault before catastrophic failure occurs. The research project will continue research on low-speed bearing diagnosis by developing new methods for automatic fault detection.

Outlook:
To continue the research on low-speed scenarios, a test bench is built and used at UiA. Its main objective is to wear a bearing to failure by running it at high speed with heavy loads. During the life-time of the test bearing, the vibration signal is measured at lower speeds, down to 20 revolutions per minute. Using the available data, the goal of the project is to create algorithms that aid to perform early diagnosis of a damaged bearing.

Publications:
R. B. Randall and J. Antoni, "Rolling element bearing diagnostics - a tutorial," *Mech. Syst. Sig. Process.*, vol. 25, DOI 10.1016/j.ymssp.2010.07.017, no. 2, pp. 485–520, 2011.

W. Wang and A. K. Wong, "Autoregressive model-based gear fault diagnosis," *J. Vib. Acoust.*, vol. 124, DOI 10.1115/1.1456905, no. 2, pp. 172–179, 2002.

Klausen, A., Folgerø, R. W., Robbersmyr, K. G., Karimi, H. R., 2017. "Accelerated Bearing Life-time Test Rig Development for Low Speed Data Acquisition." *Modeling, Identification and Control* 38(3), pp.143-156.

Klausen, A., Robbersmyr, K. G., Karimi, H. R., 2017. "Autonomous Bearing Fault Diagnosis Method based on Envelope Spectrum." *IFAC World Congress,* 9-15 July, Toulouse, France.

Kandukuri, S.T., Klausen, A., Karimi, H.R. and Robbersmyr, K.G., 2016. "A review of diagnostics and prognostics of low-speed machinery towards wind turbine farm-level health management." *Renewable and Sustainable Energy Reviews*, 53, pp.697-708.

Acknowledgement:
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Andreas Klausen

Andreas Klausen was born in Norway in 1991 and lived in Vennesla before moving to Grimstad to study in 2010. He received the Bachelor's and Master's degrees in Mechatronics from the University of Agder, in 2013 and 2015 respectively.
His Bachelor thesis deal with the modeling of a hydraulic valve with a built-in closed-loop spool position controller, while his Master thesis concern modeling and control of a hydraulically actuated load circuit. He is currently working on his PhD in Mechatronics within the field of Condition Based Maintenance. His project deals with condition monitoring of slowly rotating roller element bearings. His research interests include the areas of signal processing, modeling, optimization, and condition based maintenance


Martin Hemmer displaying the kind of bearings that are part of his research.

DETECTING BREAK-DOWNS BEFORE THEY OCCUR

Contition Monitoring of Large, Slow-Rotating Bearings

Improved methods of signal analysis, can prevent costly machine failures and break-down in the energy sector.

"The average cost of downtime on a top drive in the off shore sector is about 1,5 million kroner per day. If we can find new ways of detecting imminent damage and failures to the equipment at an early stage and avoid equipment failure, it will be highly beneficial to the industry," explains Martin Hemmer, PhD Research Fellow at the University of Agder, working for the SFI Offshore Mechatronics project work package 5, led by Teknova.

Hemmers approach is to explore ways of improving listening systems that can "hear" trouble before it turns into a big problem.

– When machinery gets worn and fatigued, it generates signals that contains information about the fault. I´m using sensors that pick up these signals and I develop algorithms that can analyse them. We´re talking about improved usage of existing sensor technology and new ways of analyzing data, Hemmer says.

Today operator relies on strict routine inspection- and maitenance intervals to prevent failure and damage. This is a costly and often difficult task in a running facility. Yet break- downs of bearing and moving parts in heavy off shore and energy producing machinery occur from time to time.

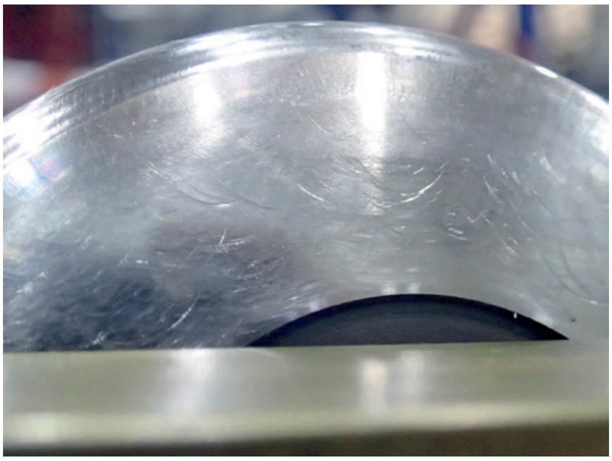
The focus of this projects is larger bearings, typically found in on offshore applications like top drives, wind turbines, cranes and winches. The consequence of failure typically increases with bearing size, with high cost of unplanned downtime and larger potential for hazardous situations. Condition Monitoring (CM) of large, slow-rotating REBs (Rolling element bearings) have challenges that are associated with both size and rotational speed of the bearing, making conventional, acceleration-based monitoring systems less suitable.

Localized faults in races, rolling elements and cage can be diagnosed by identifying peaks in the frequency- and envelope spectrum corresponding to the fundamental fault frequencies of the bearing, which are functions of bearing geometry and rotational speed. As acceleration is the second time-derivative of displacement, faults in low-speed applications will generate low energy vibrations that are easily masked by background noise. The signal transmission path also increases with bearing size, which further masks the signal of interest.
At low speeds, fault frequencies, sidebands and other forcing frequencies can be close in frequency domain. High frequency resolution is required for separation. Frequency bin width is inversely proportional to acquisition time, which makes measurements more prone to capturing speed variations, further smearing the frequency content.

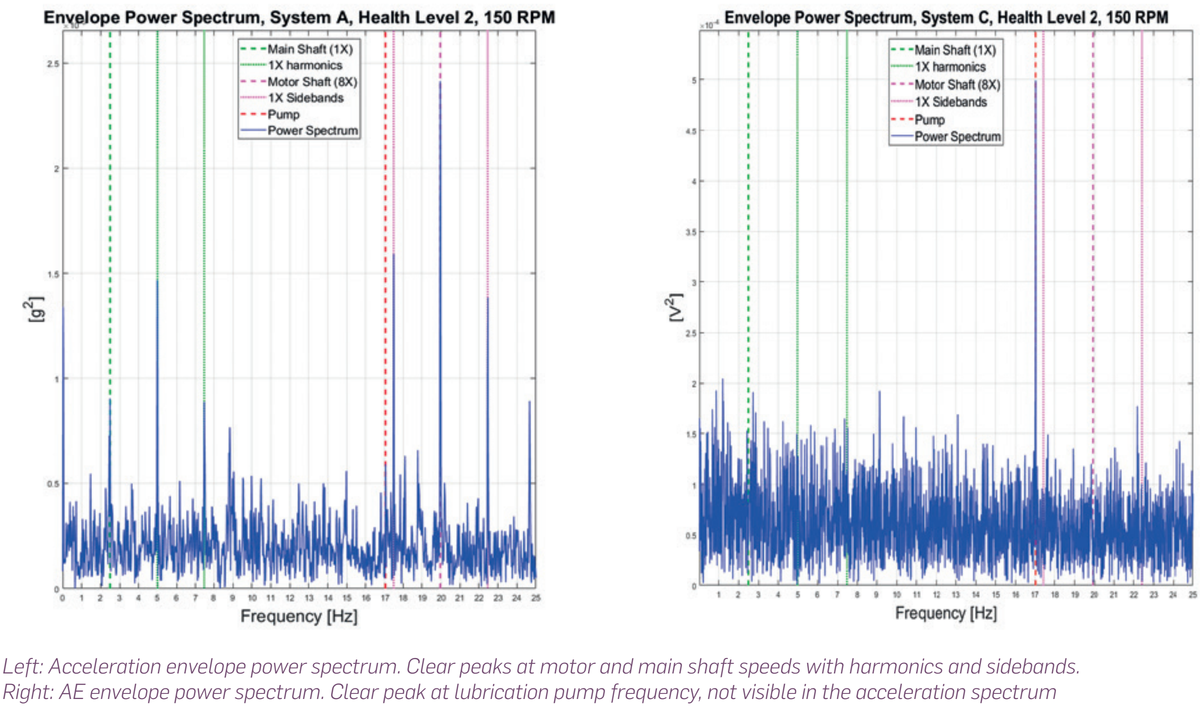
A study of downtime causes on offshore drilling rigs identified top drive bearing failure as a large contributor, with an average downtime cost of 1.4 MNOK. With this in mind, we have performed comparative tests on a top drive taken out of operation. The machine was tested using a main bearing axial bearing at three stages of degrading health over a range of speeds. A new bearing was tested for reference, before being replacing is with a worn bearing. The worn bearing was then tested under normal operating conditions, before artificial damage was applied the roller end and run under poor lubrication conditions.

Three different vibration systems and one Acoustic Emission (AE) system was compared. A purpose-built adaptor plate allowed simultaneous testing of all systems. It was found that AE RMS values correlated better with the bearing health degradation than acceleration RMS. Compared to the vibration measurement systems, AE had complementing forcing frequency identification abilities.

In applications with high axial forces or combined radial or axial load, tapered roller bearings are often used. These bearings suffer from other failure modes in addition to fatigue in the main load path. Due to tapering of the rollers, a seating force acts on the roller end. On the top drive, we observed arc-shaped scratches distributed on the roller ends. Similar wear is known to occur in other applications as well, often due to poor lubrication. The failure can be critical, but the non-periodic nature of this failure mode leaves Fourier-based analysis unsuitable for fault detection.



Arc-shaped scratches observed on the roller end of a worn axial tapered roller bearing from a top drive.



Left: Acceleration envelope power spectrum. Clear peaks at motor and main shaft speeds with harmonics and sidebands.
Right: AE envelope power spectrum. Clear peak at lubrication pump frequency, not visible in the acceleration spectrum

R&D activities:
Condition monitoring of rolling element bearings
Fault detection, diagnosis and prognostics Signal processing

Outlook:
Further investigation of condition indicators capable of diagnosing the failure mode is one of the main priorities of this project. Currently, visual inspection is the only reliable identification method.

An axial bearing test rig is currently being designed, made for both fatigue testing, seeded fault testing and replication of the failure mode observed in the top drive test. The rig is designed with versatility in mind, prepared to fit a wide range of sensors and instrumentation. Bearings up to 215 mm in diameter can be tested at axial loads up to 350 kN and speeds up to 2000 RPM. The test rig is planned to be operational in Q1 2018.

Publications:

M.Hemmer, T. I. Waag, K. G. Robbersmyr (2017). A Review of Methods for Condition Monitoring of Large, Slow-rotating Bearings. COMADEM Conference 2017

M. Hemmer, T. I. Waag (2017). A Comparison of Acoustic Emission and Vibration Measurements for Condition Monitoring of an Offshore Drilling Machine, PHM Conference 2017

Acknowledgement:
The research in this paper is 100% funded from the Norwegian SFI Offshore Mechatronics, a consortium with partners from industry and science, hosted by the University of Agder.

SFI OFFSHORE MECHATRONICS

Martin Hemmer

Martin Hemmer received his B.Eng in Mechanical Engineering from Oslo University College, and his M.Sc in Mechatronics from the University of Agder in 2014. He graduated with a thesis on implementing electric actuation in an offshore application, utilizing mathematical optimization methods for mechanical design problems. From 2014 to 2016 he worked for MHWirth as a mechanical engineer in the Technology and Innovation department and Crane department, gaining knowledge of applications in the oil and gas industry utilizing large rolling element bearings. In April 2016 he started his position as a PhD Research Follow, researching condition monitoring methods for large, slow-rotating bearings. His main research focus is development of processing and analysis methods for time-waveform data, with the purpose of improved fault detection, diagnostics and health assessments.

Tor Inge Waag

Dr. Tor Inge Waag is a Senior Scientist at Teknova AS. His background is in Technical Physics from NTNU in Trondheim, where he took his M.Sc and Ph.D in signal processing for laser light scattering. He has worked in Sintef Petroleum, and as a visiting scholar at Chevron Research in California. He also has experience from Sensorlink AS in Trondheim, developing sensor solutions for the offshore industry, and has been working with condition based maintenance at MHWirth AS. His work has been concentrated on the entire chain from sensor data via signal processing to decision support, mainly for the offshore industry in Norway, in various fields such as seismic acquisition and processing, ultrasonic imaging, electromagnetic sensors, wellbore surveying accuracy, condition monitoring and condition based maintenance.

EXPLORING DISTURBANCES IN ELECTRICAL SIGNATURES

Condition Monitoring of Pitch and Yaw Systems for Offshore Wind Turbines

Everything is more complicated offshore than onshore. Replacing even the simplest components could prove a huge challenge when you rely on short and infrequent maintenance windows at the mercy of good weather.

"Maintenance makes up for 30 per cent of all costs related to offshore wind farms. The percentage is much higher than onshore, due to transportation costs and the complexity of an offshore environment. Components that are quick to fix onshore, could take weeks or even months to fix offshore. Downtime is extremely costly, so offshore wind farm operators need a better understanding of and control over all components that are failure prone. By studying disturbances in the components electrical signature, we are looking for ways to predict failure before a shut down," says Surya Teja Kandukuri, PhD Candidate at the University of Agder.

Offshore wind energy is among the promising renewable energy resources that is gaining significant presence across the world. As the wind farms grow larger and farther offshore, it becomes necessary to adopt a farm-level maintenance strategy in order to ensure reliable and economic operation. Such a maintenance strategy should include expanding the scope of condition based maintenance (CBM) to the balance of systems that are known to be failure-prone.

Although pitch and yaw systems were often on the list of components with frequent failures, they were not a top priority for condition monitoring in the onshore wind turbines. This is due to the fact that they are easily replaceable in the case of onshore wind. However, in case of offshore wind turbines, any unplanned maintenance activity is expensive due to their location and challenging due to short weather windows. Therefore, it is worthwhile to evaluate the pitch and yaw systems for condition monitoring and remote health assessment. Through remote health assessment, the maintenance personnel can detect incipient faults and plan the maintenance ahead of failures. Such planning results in economizing on logistics, inventory and resources. However, health assessment of these systems poses significant challenges as they operate intermittently and at low speeds.

R&D activities:
At the University of Agder, the electrically operated pitch & yaw systems are being evaluated for condition monitoring and health assessment. The research is focused on answering the following questions:

a. What is the nature of the pitch and yaw system operations in typical wind conditions? Can the incipient faults be reliably detected under such operating profiles?
b. What methods and techniques are suitable for detection? Are they suitable for farm-level implementation?
c. Is reliable failure prediction (prognosis), that is sensitive to operating conditions, feasible?

In order to answer these questions a laboratory setup, shown in Figure 1, is built. It includes a multistage planetary gearbox and an induction motor controlled through a variable frequency drive while the blade root loads that are experienced by the pitch drive are generated using a load motor through a bevel-planetary-helical (BPH) gearbox. The objective of this setup is to simulate various seeded faults described in Table 1, in the pitch motor and the gearbox, and evaluate detection capabilities. In order to assess the feasibility of diagnostics in realistic conditions, the 5MW reference wind turbine is simulated in FAST tool (Fatigue Aerodynamics Structures and Turbulence) to generate pitch speed profile and blade root load profiles. The motor faults are diagnosed using motor current signature analysis (MCSA) and the planetary gearbox faults shall be diagnosed using vibration based methods.

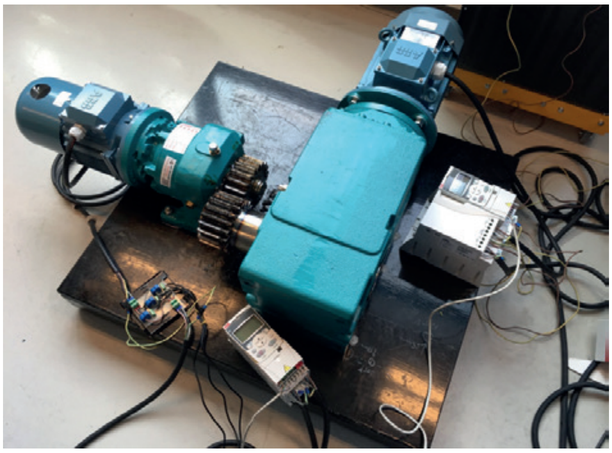


Figure 1: Laboratory setup with pitch drive (left) and load motor with bph gearbox (right)

The principle of MCSA is that any change in the motor's electrical or magnetic circuit will produce a periodic disturbance in the electrical fields. This disturbance is then detected using Fourier analysis on the supply currents. Common faults of induction motor drives, such as the stator turns fault, bearing fault and broken rotor bars fault are artificially seeded in the test motor and the current signatures are studied. Besides, the diagnostics is extended to include the gearbox faults utilizing vibration signature as well as their effects on the current signature analysis.

Subsystem	Component	Faulty type
Pitch Drive	Motor	Broken rotor bars
		Stator winding fault
		Worn bearings
	Gearbox	Planet gear fault
		High speed shaft bearing
		Sun gear fault

Table 1: Failure modes that will be seeded in the lab setup

Outlook:
While the physics-of-failure methods are extremely suitable for detecting incipient failures, to achieve large-scale utilization of diagnostics across a wind farm, artificial intelligence (AI) techniques may be leveraged. This has the advantage of bifurcating the diagnostics process into a preliminary analysis at the wind turbine level and then utilize AI methods for farm-level fault classification. Such bifurcation circumvents the necessity to replicate computationally expensive diagnostics at each wind turbine and also gives the ability to utilize plant-level knowledge.

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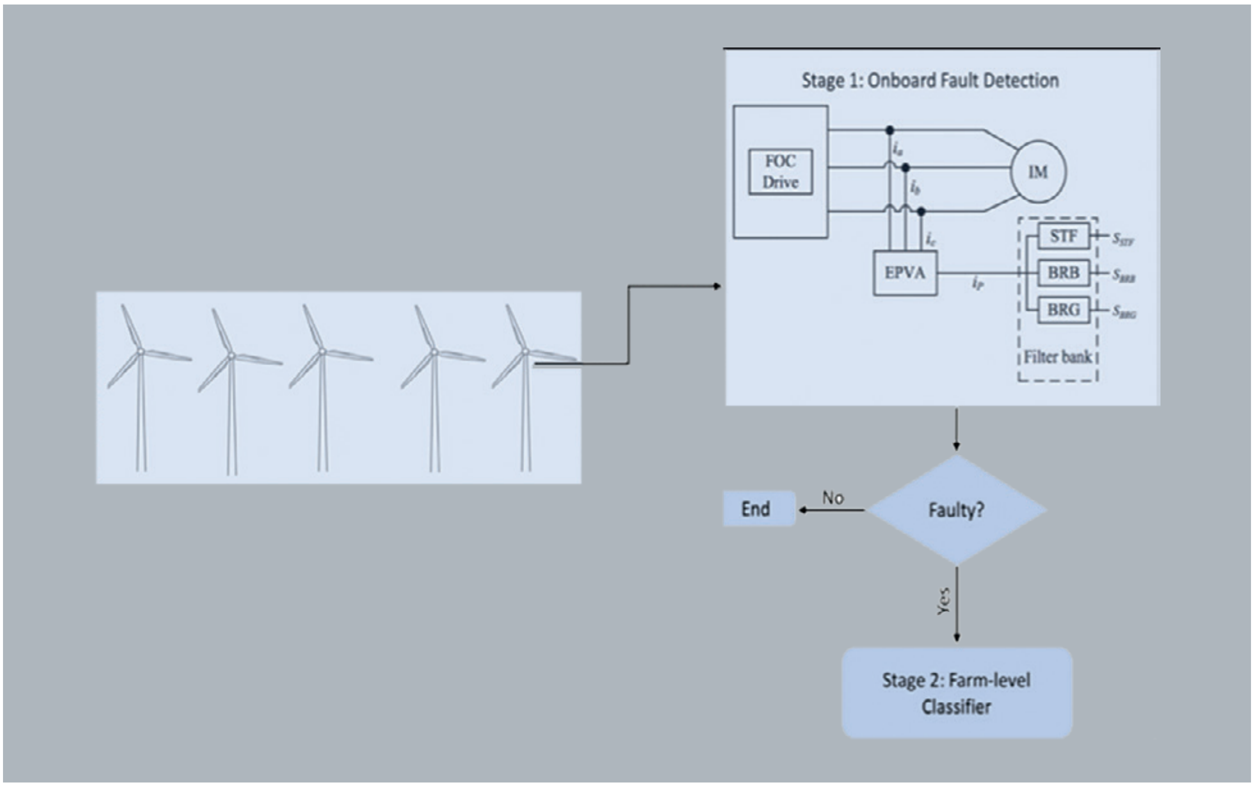
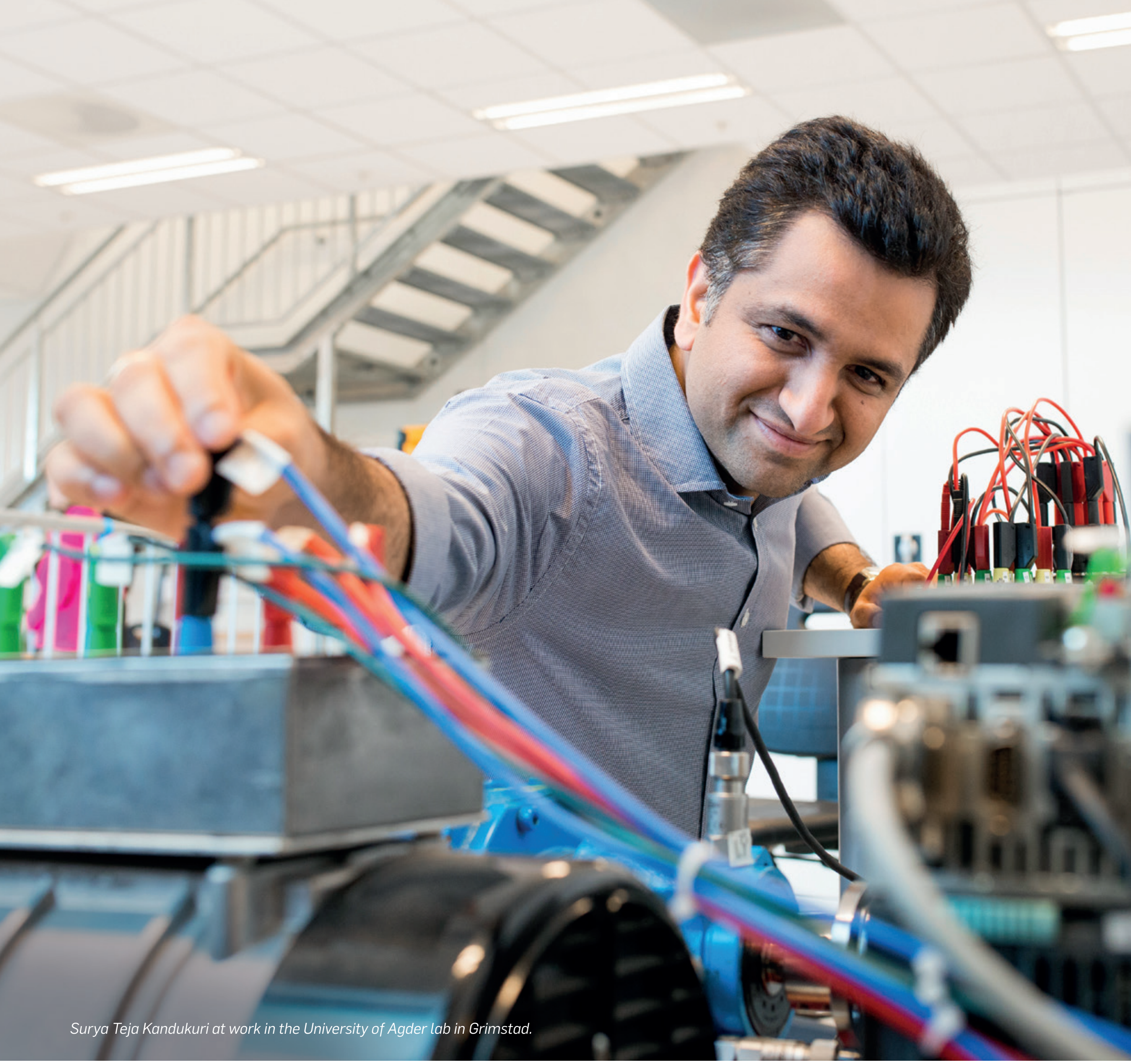
This research is funded by Norwegian Centre for Offshore Wind Energy (NORCOWE) under Grant 193821/S60 from Research Council of Norway (RCN). NORCOWE is a consortium with partners from industry and science, hosted by Christian Michelsen Research.



A two-stage fault detection and classification scheme for wind turbine pitch systems using AI.



Surya Teja Kandukuri at work in the University of Agder lab in Grimstad.

Surya Teja Kandukuri

Surya Teja Kandukuri is presently a doctoral research fellow at University of Agder. His research topic is focused on providing health monitoring solutions to wind turbine pitch and yaw systems. Prior to starting his doctoral research, Surya worked for 7 years in corporate research environment, on condition monitoring, diagnostics and prognostics at GE Global Research and Airbus Defense and Space. Surya holds a master's degree in Systems and Control from Delft University of Technology, in the Netherlands.

DEVELOPING EFFICIENT HEALTH CHECKS ON ELECTRICAL MACHINERY

Condition Monitoring for Electric Drive Components

When electrical machinery catches fever, the consequence can be fatal. Researchers at UiA are exploring new, efficient health checks.

Taking the "patients" temperature with thermal sensors placed on critical machine parts, is how operators have been monitoring machine health. But it has proven to be inadequate, according to Khang Huynh, associate professor at UiA, Department of Technology.

"We are talking about heavy machinery with several layers, i.e a stator. Thermal sensors only measure temperature rise on the surface but will miss out higher temperatures in the inner layers. An evolving machine failure may thus go undetected. This is the ever present nightmare of the operator. To avoid faults, most of electrical machines are working under temperature limits, just based on operation experience or guidelines from manufacturers. This leads to non-optimal operating condition or causes significant energy losses in electrical machines, Huynh says".

The approach of Huynh and his collagues is applying sensorless og 'soft' sensor technology. Sensorless technology monitors signal outputs from the current production output, and use advanced mathematical calculation to predict imminent temperature rise in the machinery.

Alternative approach is using artificial intelligence-based methods, e.g machine learning algorithms, once trained and validated, can fuse and analyse data from a set of different signals of the electrical machinery, and predict future temperature rise.

In Norway, rotating electrical generators produce over 99% of the electrical energy. About 65% of this energy is transformed back to mechanical energy by electrical motors. Lifetime of electrical machines has received an increased attention during the last decades:

Over 30% of faults in conventional electrical machines occur in stator windings, being the thermal stresses directly or indirectly responsible for them. Higher harmonics from the frequency converters cause an additional loss up to 20-30% (resulting in temperature rise) in the electrical machines. As a result, the frequency converters render more failures in electrical machines.

Unlike industrial production, modern electrical machines for electric powertrains (e.g. traction, electric vehicles or pitch/yaw system of wind-turbines) operate dynamically, changing speed and torque according to driver's demands. Moreover, electric drivetrains are intensively exposed to mechanical-, chemical-, dust- and thermal stress in harsh environment and thermal cycling due to the dynamic operation. Consequently, detection and prevention of the faults in the electrical machines in such powertrains are more important and challenging than those in industrial production.

– Within inverter-fed electrical machines, the inverter output voltages as a series of square-pulses change very rapidly within a very short time, resulting in the so-called dV/dt and parasitic effects. These effects produce high-frequency circulating currents in other components in the drivetrain, e.g. bearings or metal-based items. Once these currents pass through a bearing from one ring to another via rolling elements, additional loss or heat is produced on the bearing. Consequently, the faults in bearing and stator winding occur more frequently than before.

Temperature rise, mainly responsible for faults in electric drives, is mostly based on single-point measurements performed by sensors installed in the middle or on the surface of stator windings and switching modules. Those sensors are not able to monitor or predict the maximum temperature since the loss and temperature rise are unevenly distributed in the observed devices due to proximity and skin effects. Installing many sensors at different positions in the winding or frequency converter to monitor the hottest spots is expensive and even infeasible in certain locations. A 'soft' sensor or sensorless approach would be more effective and economic, and would allow avoiding production interruptions due to physical failures of sensors. Our recent activities have focused on numerical analysis, parameter and system identification using nature 'inspired' optimizations, in which the effects of higher harmonics of frequency converters, manufacturer catalogs, and system phenomenon e.g skin depth, cooling, saturation, eddy-currents have been taken into consideration.

Huynh Van Khang conducts research at Teknova's lab in Grimstad.

A simple and reliable thermal model, which was recently developed based on current levels and estimated time constants, can represent major phenomena associated with thermal behavior of small and medium-size electric motors and drives.
For big-size electrical machines, an advanced numerical modelling is required to take the effect of eddy-current, circulating currents, core and manufacturing process into consideration. A co-simulated/coupled thermal and electromagnetic analysis allows predicting temperature rise distribution. Alternatively, a data-driven emulator seems to be a promising approach to predict temperature rises in modern electric drives.

Incipient faults normally occur when the system has a change in dynamic operation e.g. load variation, during starting, or shutdown. During the transients, the system qualities are nonstationary or varied in both time and frequency system qualities vary in both frequency and time. Conventional analysis based on stationary qualities and particular sensors has a limited potential to detect a right fault in the transients, and therefore might provide a false indication of the incipient faults in drivetrains. It was shown in our recent work that active and adaptive filters allow observing and extracting weak signatures in the beginning of degradation process of a bearing fault in time domain.
Time-frequency analysis. e.g Short-time Fourier transform (STFT) and Wavelet transform (WT) could analyze nonstationary qualities and explore features of incipient faults during transients while Fast Fourier transform (FFT) is a common tool for the fault detection in steady state.
A combination of advanced filters and signal processing seems to be a right approach to reduce the uncertainty of the fault analysis and computation burden. An alternative approach to detect incipient faults during transients is to use artificial intelligentbased methods, which have been recently developed by other researchers within Dynamics research group.

Deep learning algorithms can improve accuracy of fault detection and classifications. Numerical modelling .e.g finite element analysis can lower challenges in training and validating artificial intelligent based methods.

R&D activities:
About 40% of faults in electrical machines occur in stator windings, being the thermal stresses directly or indirectly responsible for them. Sensors mounted on the surface of stator windings and switching modules are not able to detect maximum temperature rises in electrical machines and frequency converters.

A ‘soft’ sensor or sensorless approach based on production outputs. e.g currents, powers to predict temperature distributions in electric machinery while avoiding production interruptions due to physical failures of sensors. Alternatively, artificial intelligent based methods .e.g data-driven emulator can fuse and analyse data from different signal to predict temperature rises and detect incipient faults in modern electric drives.

Outlook:
A simple and reliable thermal model is important to predict quickly maximum temperature rise in machinery. Incipient faults normally occur when the system has a change in dynamic operation e.g. load variation, during starting, or shutdown. During the transients, the system qualities are nonstationary or varied in both time and frequency system qualities vary in both frequency and time. Advanced signal processing and adaptive filters need to be developed further to detect faults in early stage transient states.

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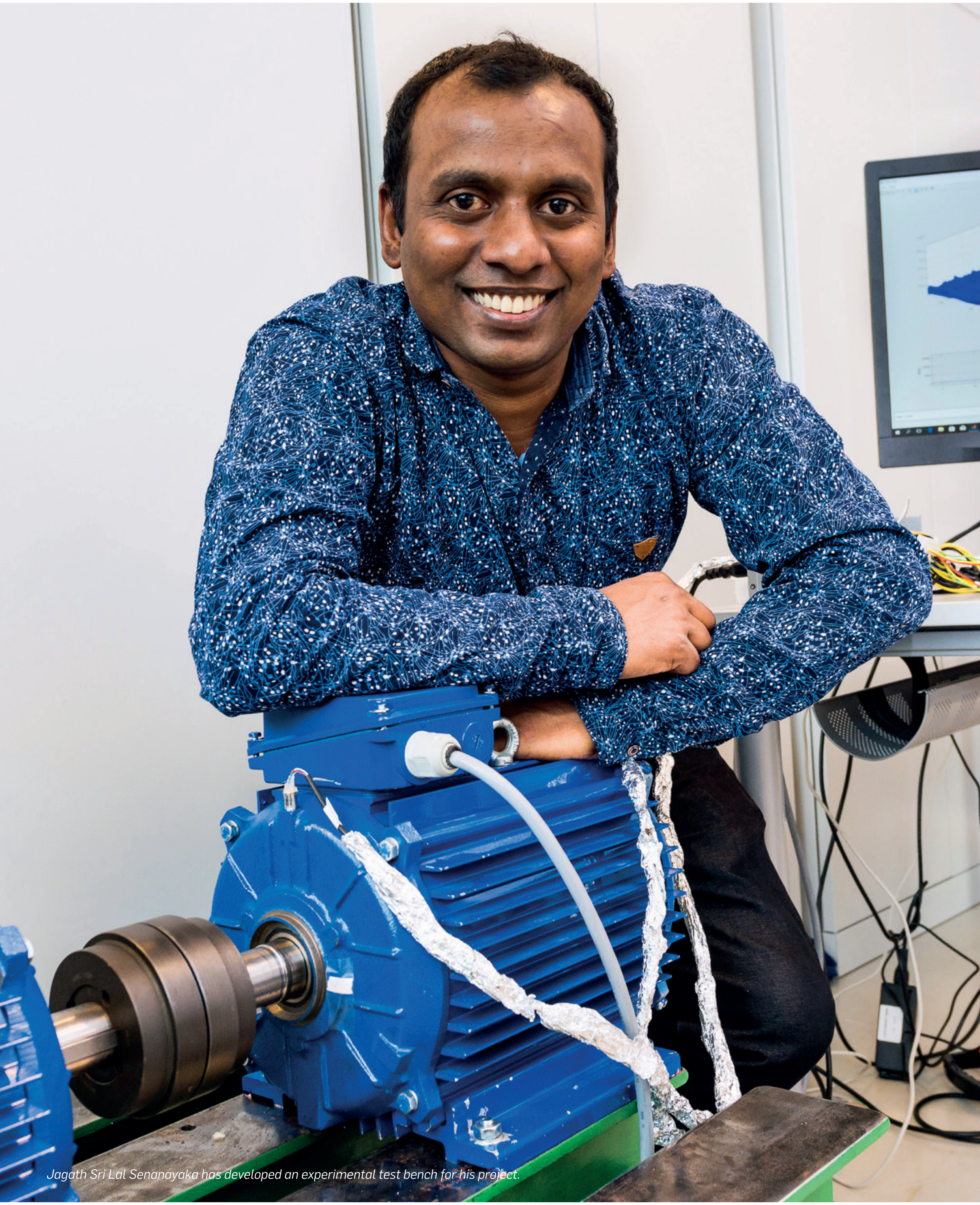
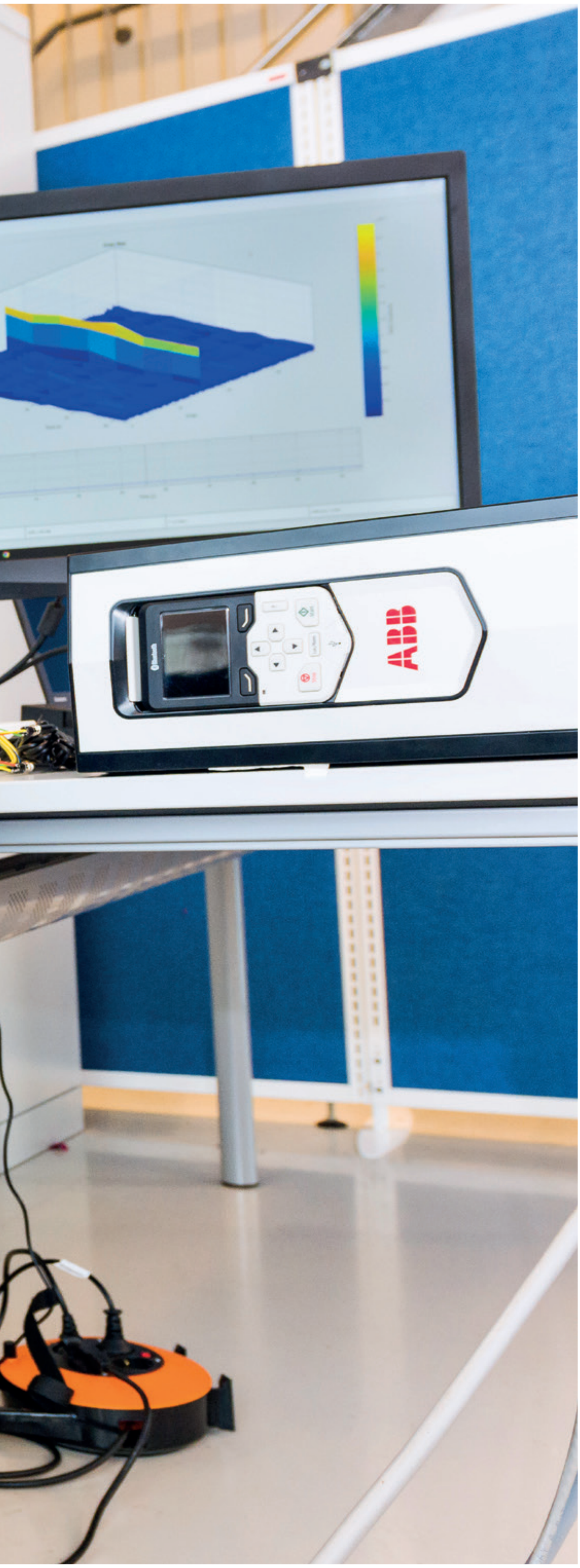
Huynh Van Khang

Huynh Van Khang received the B.Sc. degree in Electrical & Electronic Engineering from Ho Chi Minh City University of Technology, Ho Chi Minh City, Vietnam, the M.Sc. degree in Power Electronics & Motor drives from Pusan National University, Busan, South Korea, and the D.Sc. (Tech.) degree in Electromechanics & Electric Drives from Aalto University, Helsinki, Finland, formerly known as Helsinki University of Technology, in 2002, 2008, and 2012, respectively. From 2012 to 2013, he was a Postdoctoral Researcher with the Tampere University of Technology, Tampere, Finland. Since 2013, he has been an associate professor at the University of Agder, Grimstad, Norway. His research interests include electrical machines, electric drives, power conversion and condition monitoring.



Jagath Sri Lal Senanayaka has developed an experimental test bench for his project.



HOW BIG DATA CAN PROTECT YOUR MACHINE

Condition Monitoring of Electric Powertrains

Big data and advanced algorithms can soon protect your critical electrical machinery and drivetrains more efficiently than conventional manpower.

"Everybody wants safe and reliable operation of their machinery. Analysing vibration and current with sensor technology is an established method of detecting problems. This, however, requires highly specialised maintenance personnel. To many companies the cost and reliability can be a challenge, says Jagath Sri Lal Senanayaka, PhD research fellow at Department of Engineering and Science at UiA".

Jagath thinks implementing the use of big data, machine learning and data fusion can help industry for monitoring their electrical machinery and drivetrains automatically. Machine learning algorithms can be trained to detect failure conditions at early stage and warn the operators of a possible failure. The key is collecting vibrations and current data from thousands of similar machinery running in industries across the world and process these with machine-learning algorithms.

"We need a cloud-based service whereby the manufacturer of the electrical machines collects signal data from the running machines in the plans of their customers. This data would have to be collected online every second day of the week. The manufacturer gets huge amounts of data that can be used in deep machine learning algorithms, and the analysis results can be shared with the customers, Jagath says. This will be an optional cloud-based fault diagnosis service for the customers".

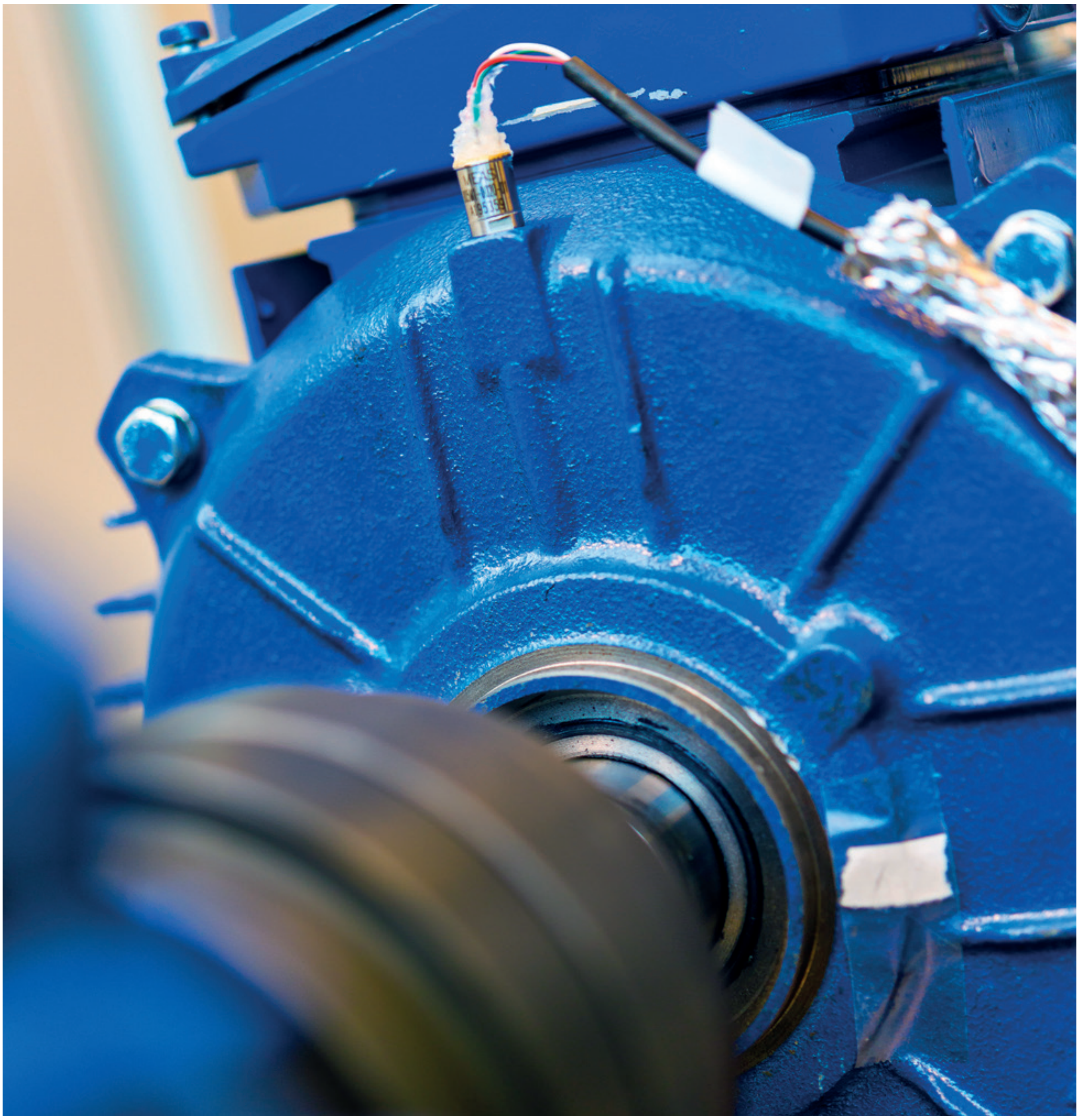
According to Jagath , the system will be able to detect and classify faults and provide a prognosis of how long will he machine continue until it fails.

It is important to guarantee the safe and reliable operations of critical industrial machines such as electric generators, turbines, pumps, conveyors, compressors, fans. To ensure the safe and reliable operations, Modern industrial maintenance strategies comprise with condition monitoring methods. Based on measured machine conditions, predictive maintenance schedules are arranged and prognosis techniques are used to find out the remaining life of the machine or component.

Vibration signal and current signal analysis together with advanced signal processing techniques have been widely used in modern condition monitoring applications. These techniques highly rely on domain expert knowledge and the methods are expensive as it requires separate department with a skilled staff.

Machine learning algorithms have shown success in many different application areas such as computer vision, e-commerce, data security, natural language processing, medical diagnosis etc. Machine learning algorithms are grounded on data-driven approach where the algorithms can be trained for specific tasks such as classification, detection and pattern recognitions. There is high industrial demand for intelligent fault diagnosis and prognosis algorithms in critical machine applications where the focus is to reduce the maintenance cost by applying on-line condition monitoring techniques and decrease the human staff. Therefore, the state-of-the-art condition monitoring techniques combine the condition monitoring domain knowledge together with the machine learning algorithms.

Even though there are many machine learning algorithms and fancy promises from these Data-driven approaches, proper selection of algorithms is a challenging task. Condition monitoring domain experience, signal processing and machine learning algorithms expertise are critical for



selecting appropriate algorithm for the intended applications. Furthermore, together with machine learning algorithms, Data fusion approach can provide more reliable and accurate fault diagnosis capabilities than diagnosis using separate sensors alone. Therefore, my PhD research project focus on developing an online condition monitoring and fault diagnosis system based on machine learning and data fusion approach.

Machine learning algorithms are the central part of this proposed system. There are several chooses for selecting a proper algorithm for the application. We can either use traditional machine learning algorithms such as support vector machine, decision tree, artificial neural networks with few hidden layers or contemporary deep artificial neural networks with several hundred hidden layers. This algorithm can be trained using supervised or unsupervised passion, and after the training process, it can be employed for real-time condition monitoring tasks.

R&D activities:
Various machine learning and data fusion algorithms have been developed and tested using publicly available rotational machine fault related data sets. Based on the analysis results, serval research papers were published. Furthermore, an experimental test bench is developed for this study which consisted of an electric power-train and an adjustable load. Seeded Bearing faults, gearbox faults and electric motor faults can be tested using this experimental setup. The electric discharge machining method will be used to make controlled mechanical damages in bearings and gears.

Outlook:
Different types of faults such as bearing faults, gear faults and electrical winding faults will be tested using this test setup. Vibration and motor currents will be recorded and based on this information, several signal processing, machine learning and data fusion techniques will be tested, and best method for this application will be identified. Furthermore, robust against different loads, speeds, operational environment, noise and disturbances will be tested.

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Jagath Sri Lal Senanayaka

Jagath Sri Lal Senanayaka Received the B.Sc. degree in Electrical and Information Engineering from University of Ruhuna, Sri Lanka in 2007 and a MBA degree in Technology management from university of Moratuwa, Sri Lanka in 2012. He gained a M.Sc. degree in Renewable energy from university of Agder, Norway in 2014. He worked as a research assistance in university of Agder from 2014-2015 where his research focus was control strategies of small wind turbines which are optimised for low wind speed conditions. currently, he is a PhD research fellow at University of Agder. His contemporary research interests are focused on Condition monitoring of industrial electric powertrains using Machine learning and data fusion techniques

SFI offshore mechatronics

SFI Offshore Mechatronics is based on the Agder cooperation within the field of Mechatronics, initiated by University of Agder with partners from the local industry of oil- and gas equipment production. This cooperation has been active for several years, and has its origin in the establishment of Master and PhD education to produce needed candidates for the regional and national labour market. Since then, the cooperation has developed to include R&D projects and mobility between industry companies and the university.

The main goal of SFI Offshore Mechatronics is to develop new concepts for autonomous systems where the construction, engineering and design, invite autonomy to minimize the number of manual processes, as well as to reduce risk and cost related to offshore drilling operations. The research shall result in enabling technologies, equipment, processes and solutions for autonomy and monitoring of heavy machinery, and for handling and analysing large data flows under demanding conditions. The research is carried out in six work packages: WP1 Drives, WP2 Motion Compensation, WP3 Robotics and Autonomy, WP4 Modelling and Simulation, WP5 Monitoring Techniques and WP6 Data Analytics, IT Integration and Big Data.

SFI
OFFSHORE
MECHATRONICS

Other relevant projects

LOGLTP

The aim of the project is to develop a scientific method for converting logged operational data from equipment into useful information for maintenance and design purposes.

The current project is directed towards the offshore industry, using case studies together with the project partners, MacGregor, Cameron, and Certex. However, the methods and algorithms developed will apply to other kinds of machinery as well, wherever solid constructions and moving components are involved.

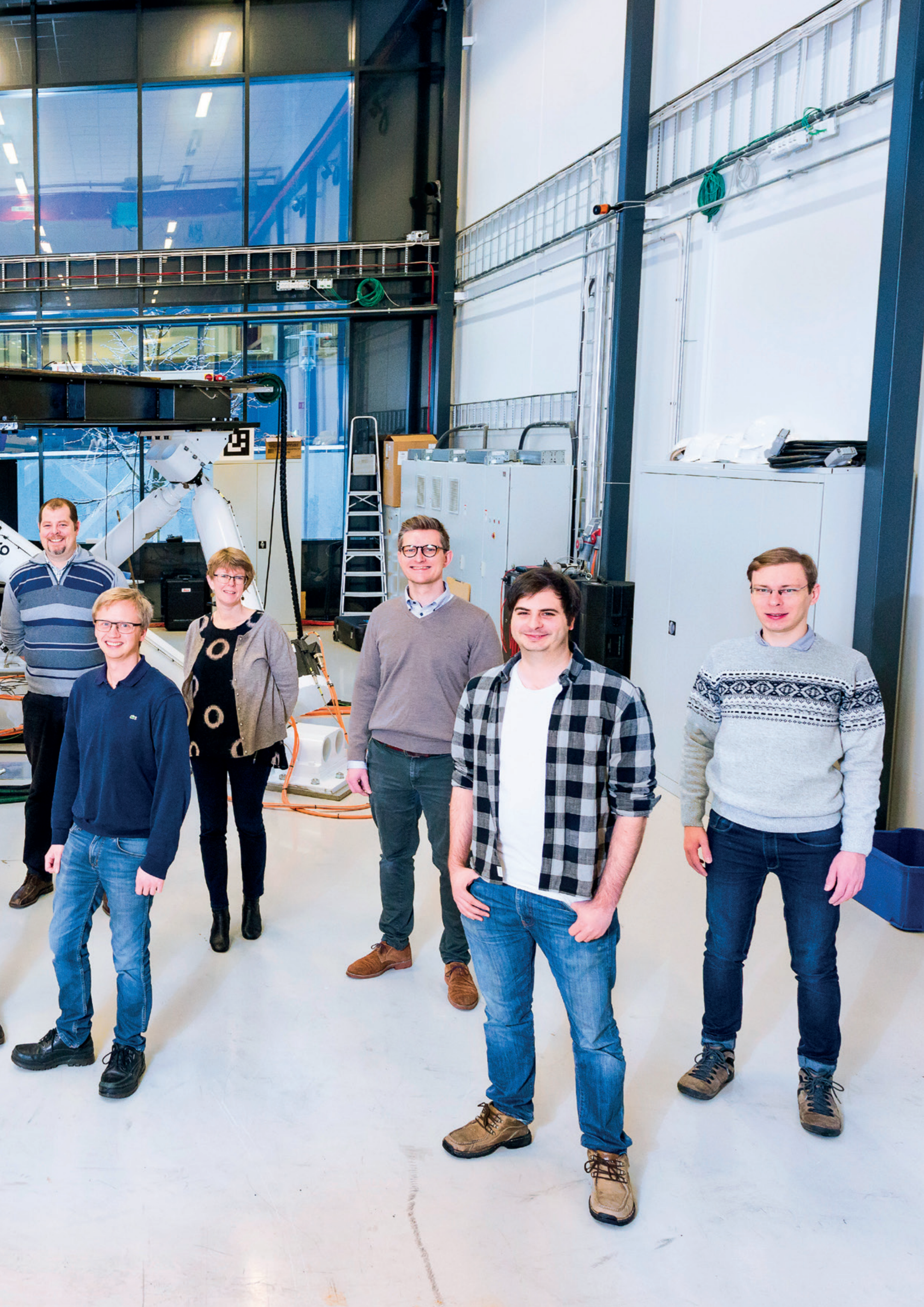
To do this, we will convert the computationally expensive general methods for fatigue calculation into more specific, simplified models. These surrogate models can then run in real-time with operational data as input, resulting in real-time availability of remaining useful life. With knowledge of how the equipment is actually used, maintenance intervals may be adjusted, and design of future products can be done with much better insight into the actual requirements and needs of the customer.

Pole Project

“Remote sensing has been successfully used for surface monitoring of electricity power lines, poles, transformers and other equipment so that defects are discovered and power supply interruptions are reduced. Nevertheless, remote sensing technologies and techniques are still facing the complex task to effectively screening the inside of the infrastructure and detect hidden defects, for example, rot inside utility poles and over and underground, thus, hardly any non-visible damage and defects can be recognized without to destructively reveal them.

This competency building initiative is devoted to establishing a benchmark concept and methodologies for airborne remote sensing of subsurface defects in large and complex infrastructures, specifically, of wooden utility poles within the electricity transmission and distribution network.
The ambition of this project is to lay the foundation to enable that all poles are in service to their true remaining useful lifetime and preventing unpredicted failure.

Left back: Prof. Kjell G. Robbersmyr, Martin Hemmer, Andreas Klausen, Dr. Thomas J.J. Meyer, Prof. Geir Grasmo, Bernt Inge Øhrn, Dr. Ellen Nordgård-Hansen, Dr. Morten Kollerup Bak and Zbigniew Mikulski.
Front left: Shaun Falconer, Dr. Tor Inge Waag, Svein-Inge Ringstad, Dr. Rune Schlanbusch and Benyamin Akdemir.



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