DIAGNOSTICS AND DATA

What currents tell us about vibrations

Valuable condition monitoring data, relevant for an entire drive-train can be unlocked using electrical signals in motors.

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Advances in sensing, connectivity, cloud and computing technologies are driving the digitization of industry at an ever-increasing rate. Add state-of-the art analytics algorithms to the mix, and customers are able to extract considerable additional value from their devices, systems and plants. Digitization increases the ability to diagnose and predict the future health of components with greater confidence and accuracy – and optimize maintenance strategies accordingly.

Condition monitoring, or more specifically, predictive maintenance represents one of the most regularly cited applications of advanced data analytics in an industrial context. From a conceptual point of view, condition monitoring is simple: measure and observe parameters that are indicative of the health of a piece of machinery and, when a change is identified in one or more of these parameters, infer what this means for the likely present and future health of the machinery.

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01 A field service and diagnostic engineer connects current and voltage probes to a motor in order to perform a MCSA.

To implement such an application, the engineers developing it must have an advanced understanding of the underlying physics of the system to ensure that the right data is being recorded at the right times. Rotating machinery is a traditional domain for condition monitoring. Sensors such as accelerometers, thermal infrared imaging systems and oil debris sensors are typically used to detect increases in vibrations, temperatures and particle counts, each of which can be indicative of a potential fault in the equipment. Whilst the effectiveness of these methods is beyond doubt, in many cases safety, spatial or financial constraints make it difficult or impossible to gain access to and attach such instruments to the equipment. Fortunately, there are also other sources of data that are well-suited for condition-monitoring. Interestingly, this data is often already being collected but not used.

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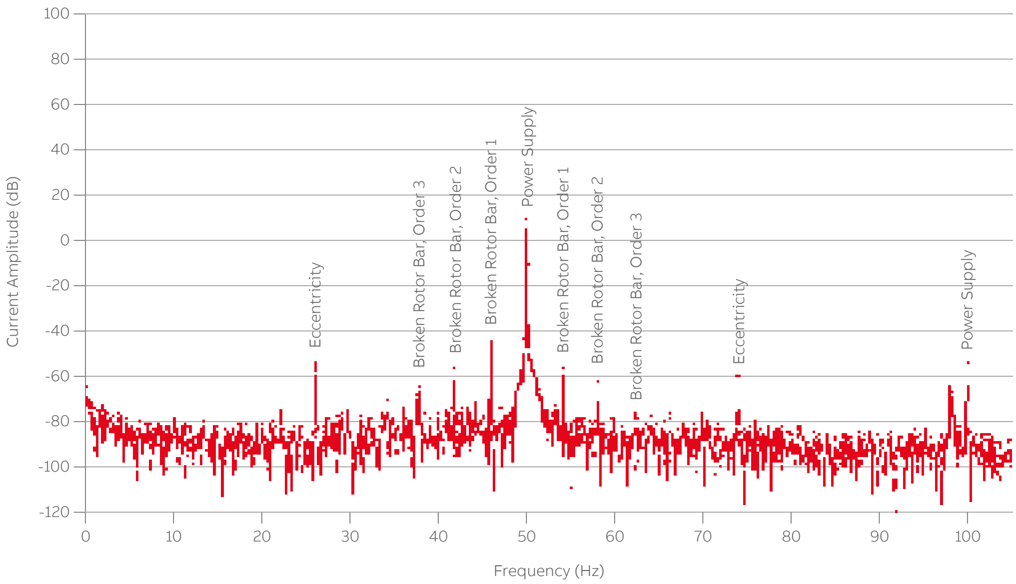

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Induction machines
Their low cost and robust design, coupled with advances in control capabilities have made induction machines so popular that they are now one of the main consumers of total energy generated globally. Such machines can be found in large critical installations, such as the megawatt installations in oil and gas compression stations, as well as in multipurpose general use, where they drive a wide array of applications. In view of the broad distribution of these machines, advances in health-monitoring capabilities have the potential to deliver huge gains in terms of improved up-time, reliability and the associated savings →**1.**

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A widely recognized approach for identifying faults in motors is MCSA (Motor Current Signature Analysis). Basically, the currents in the motor's connection cables are measured (for example, using current transformers) and then analyzed (for example, using spectral analysis). Induction motors operate on the basis of electromagnetic induction. Interactions between currents and magnetic fields in the stator and rotor generate the torque that drives the rotating equipment. Induction motor faults such as air-gap eccentricity or broken rotor bars change the nature of the rotating magnetic fields, resulting in modulations of the currents. These may be observed in the power supply cables. Analysis can both identify and quantify the severity of faults in the motor. In contrast to the dedicated condition monitoring sensors discussed previously, the power cables of motors are typically easy to access. Furthermore, motor currents and voltages are often already being recorded for other purposes (for example, protection or control). Condition monitoring can thus be implemented on the basis of existing data, without requiring additional sensors →**2.**

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02 Current frequency spectrum measured on an experimental induction motor with various seeded faults.

Frequency components of interest are highlighted, including those that can be used to diagnose specific fault modes.

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03 Oscillations caused by faults in rotating equipment can propagate through to a connected motor.

Beyond the motor
Whilst MCSA is well established for monitoring motor faults, it is less commonly appreciated that faults occurring in components connected to the motor, such as gearboxes, compressors, pumps or fans may also be reflected in these electric signals. The speed and torque of a motor can be estimated on the basis of the voltages and currents measured at the supply terminals. Whereas many control strategies that allow variable-speed drives to accurately regulate the speed and torque of a drive train are commonly referred to as "sensorless", in reality they are based on these parameters. Knowledge of the speed and torque can also provide data on connected components. An oscillation of the motor's mechanical load (due, for example, to a degraded bearing) causes the rotation of the induction machine to vary, which in turn influences the magnetic fields in the motor and the currents and voltages measured at the motor terminals →3.

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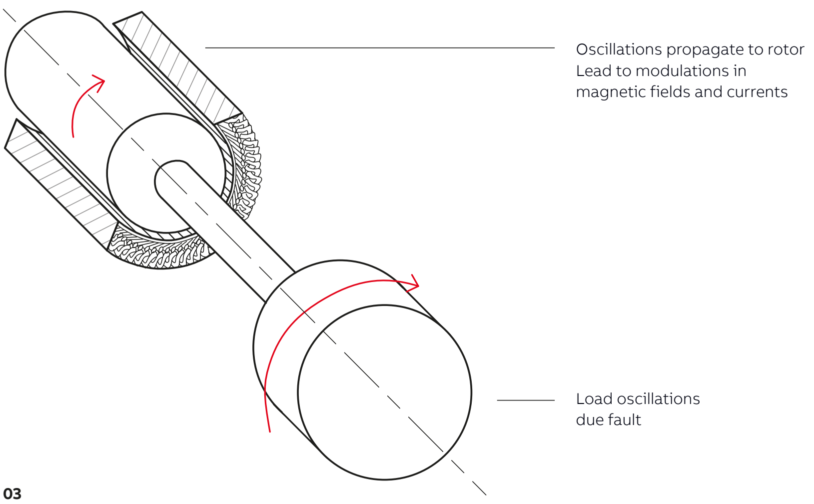
Faults in the induction motor such as air-gap eccentricity or broken rotor bars change the nature of the rotating magnetic fields.

Various technical challenges need to be overcome before MCSA can monitor connected load components. Chief among these is the need to understand the influence of all connected components, as well as a strong understanding of the operation of the motor itself. Cross-disciplinary domain knowledge is required to understand the influence of the electrical subsystems supplying the motor, the mechanical components connected in the drive train and, in many cases, the overall process system which the rotating equipment is contributing to.

In order to illustrate this, a previously developed suite of algorithms was considered, designed for monitoring the health of gearboxes on the basis of electrical signals recorded from a connected induction motor [1]. A mathematical model of a gearbox connected to an induction motor via a flexible coupling was developed. A space phasor model of an induction machine, which often forms the basis of sensorless control strategies, was combined with a low-degree-of-freedom, lumped parameter model of a gearbox. In order to properly understand the signatures that might be observed under healthy operation of the gearbox, various nonlinearities, including backlash and



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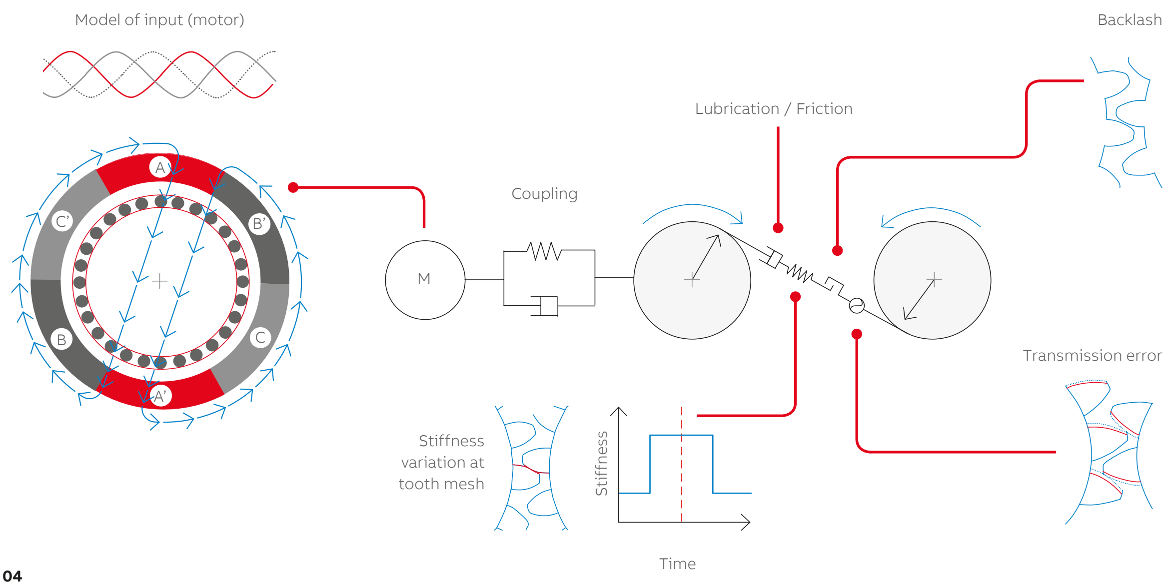
tooth stiffness variations, were incorporated into the model. Gear tooth faults were simulated via a no-load static transmission error function. Such a low-degree-of-freedom modelling approach strikes a balance between modelling detail and complexity, allowing the influence of few key parameters on the response of the system to be understood for a wide range of operating conditions and device configurations →**4**.

By combining all three phases using space vector approaches such as the Extended Park Transform, the signals can effectively be demodulated.

Insights obtained from this digital model were combined with further domain knowledge to develop signal-processing algorithms that identify fault signatures. Synchronous signal averaging is used regularly in vibration analysis to detect tooth faults in gearboxes. The approach involves recording vibration signals synchronously with the angular position of the gear shaft. By averaging the vibration signal from rotation to rotation, noise components are suppressed and components relating to the gear mechanics reinforced. This approach allows subtle fault signatures to be extracted from noisy signals. ABB investigated whether a similar approach could be applied when looking at measured motor currents instead of vibrations. When examining a single phase in isolation, motor currents are dominated by the power supply frequency. However, by combining all three phases using space vector approaches such as the Extended Park Transform, the signals can effectively be demodulated, leaving only components caused by imperfections and faults in the motor and load. Specially designed experiments validated the



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04 A low-degree-of-freedom model of an induction motor and gearbox with tooth faults.

developed approach, showing that faults in gear teeth could indeed be detected by analyzing the electric currents supplying a connected induction motor. This information may be used to identify

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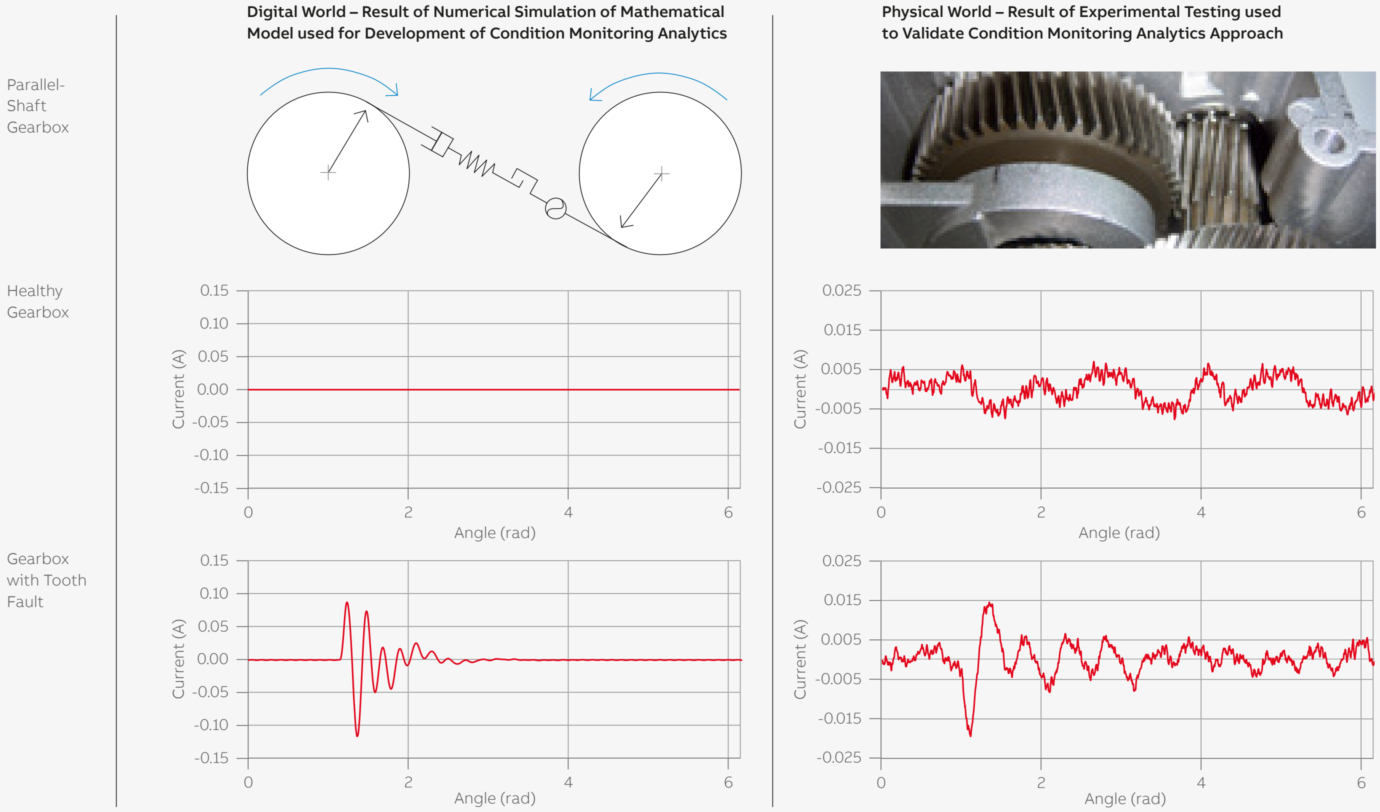
Equipment does not operate in isolation, but as systems of interacting components.

metrics that quantify the level of the fault. Such information can be trended over time to identify degradation →**5.**

Approaching complexity
Similar processes can be applied to develop methods for monitoring faults in other components, also using motor currents. Planetary (epicyclic) gearboxes are typically found in power-dense, critical applications such as wind turbines, gas turbines, helicopters or mining equipment. Despite having a more complex design than the standard parallel shaft gearbox considered previously, it was found that similar approaches for monitoring tooth profile faults could be applied [2] →**6.** The method has also been successfully applied to diagnosing motor faults in complicated cases such as wood chipping applications, where the measured signals are highly non-stationary. The approach has also proven itself in other load applications such as compressors, pumps and fans.

This article has already highlighted that approaches for monitoring load components using electrical motor signals potentially allow the monitoring of systems that cannot be instrumented with more traditional condition monitoring hardware. There are, however, various other reasons why motor currents should be part of a condition monitoring system:

- The premise that underpins this method is that equipment does not operate in isolation, but as systems of interacting components. Considering components in isolation can lead to false and missed alarms as dependencies on operating conditions and propagations of dynamics between components are neglected. Comprehensive, holistic monitoring approaches to system monitoring are preferable.
- Sensors are often complementary – one type of sensor or feature extraction approach will react better to certain faults than others (and vice-versa). Hence fusing data from multiple sources can improve the reliability and robustness of diagnosis.
- Sensors can fail: The motor current can be used as a fallback strategy when other condition monitoring sensors cease to be available.
- Sometimes motor currents are recorded for purposes other than condition monitoring (e.g. for control purposes in variable speed drives). It has been demonstrated that drive signals can be used for condition monitoring purposes [3-4].


Digital World – Result of Numerical Simulation of Mathematical Model used for Development of Condition Monitoring Analytics
Physical World – Result of Experimental Testing used to Validate Condition Monitoring Analytics Approach
Parallel-Shaft Gearbox
Healthy Gearbox
Gearbox with Tooth Fault
Current (A)
Angle (rad)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
0.025
0.015
0.005
-0.005
-0.015
-0.025
0
2
4
6

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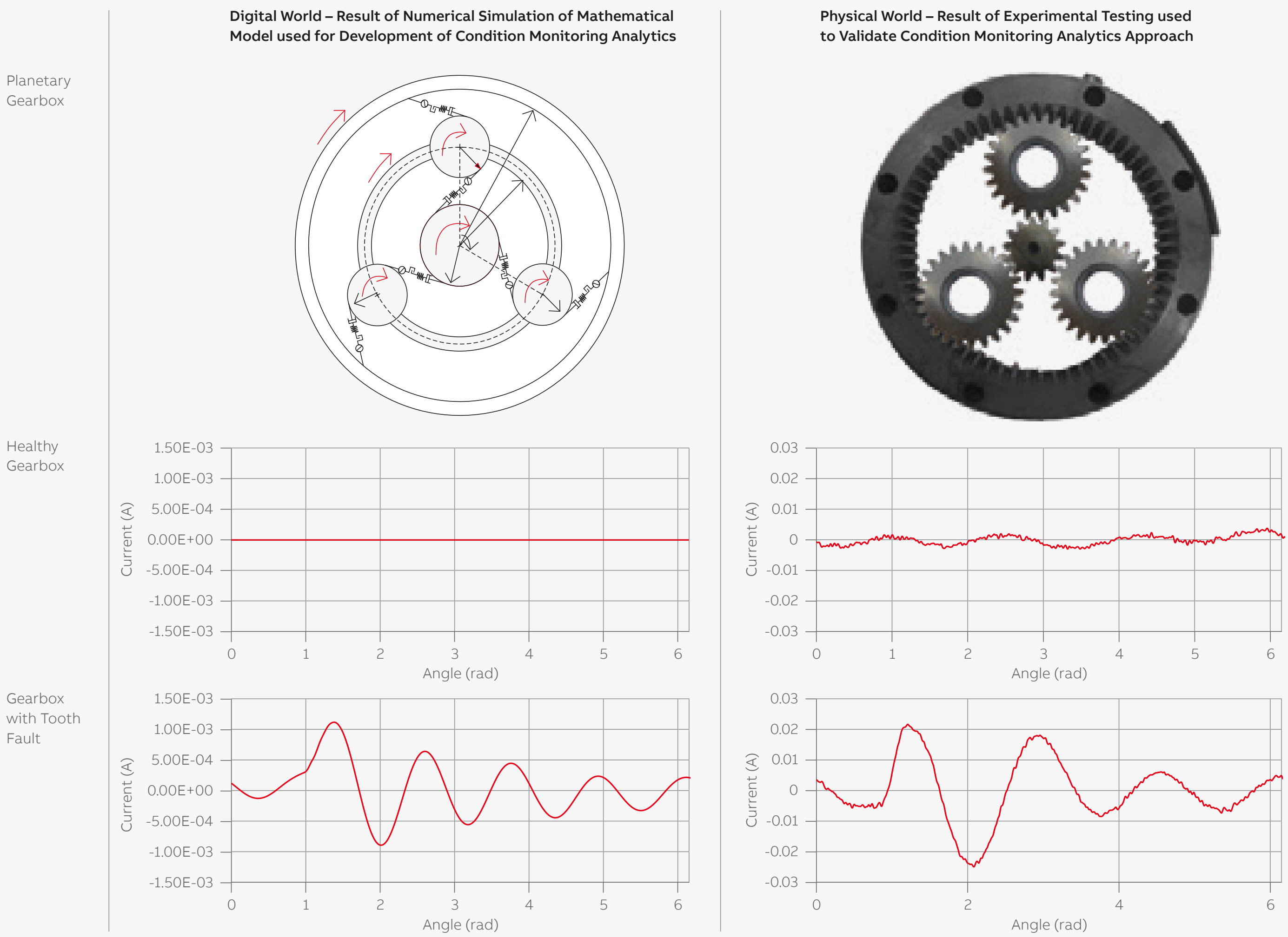
Digital World – Result of Numerical Simulation of Mathematical Model used for Development of Condition Monitoring Analytics
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Planetary Gearbox
Healthy Gearbox
Gearbox with Tooth Fault
Current (A)
Angle (rad)
1.50E-03
1.00E-03
5.00E-04
0.00E+00
-5.00E-04
-1.00E-03
-1.50E-03
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
0
1
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05 Comparisons between numerical simulation and experimental results validate that gear tooth faults can be observed in induction motor currents.

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06 Gear tooth faults can be observed in induction motor currents even in the more complicated case of a planetary gearbox.

The digital revolution is enabling the further development of condition monitoring analytics methods for optimizing customer maintenance operations. In order to accurately monitor the health of a component it is necessary to record the right data at the right times at the right data volumes at the right locations. Often value can be extracted from different, non-obvious data sources. In this article, for example, it was shown that motor currents can be used either in place of, or in combination with, other sensors in order to monitor rotating equipment. The understanding built during such a development can guide decisions regarding the design of a complete condition analytics system, ranging from the choice of sensors and sampling rates, through to which machine learning algorithm is most applicable and what calculations should be performed at the edge and what should be calculated in the cloud. Development of next-level condition monitoring analytics solutions requires multidisciplinary domain expertise in order to understand customer systems and processes in a holistic manner. With its mastery of the control room obtained over many years of industrial automation experience, ABB is well-placed to continue to develop and deliver further holistic condition monitoring analytics solutions in the future. ●

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References

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[2] J.R. Ottewill, A. Ruszczyk and D. Broda, 2017. Monitoring tooth profile faults in epicyclic gearboxes using synchronously averaged motor currents: Mathematical modeling and experimental validation, Mechanical Systems and Signal Processing, Volume 84, Part A, 1 February 2017, pp. 78-99.

[3] Michal Orkisz, Maciej Wnek, Pieder Joerg, “Hidden treasure – Drive data are a treasure trove of hidden information that can help industries solve problems before they even happen”, ABB Review 1/2010 (2010)

[4] Trond Haugen, Edgar Jellum, Michal Orkisz, “Doing more with less – The drive for greater productivity”, ABB Review 1/2009, pp. 49-53 (2009)