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GUIDELINE TO ESTABLISH A SUITABLE PREDICTIVE MAINTENANCE MANAGEMENT SYSTEMS FOR ROTATING MACHINES

THE WEARSENS® WS 3000
ONLINE OIL CONDITION MONITORING SYSTEM



APPLICATIONS:

PROCESS PLANTS, AIR SEPARATION PLANTS, REFINERIES, POWER PLANTS (CONVENTIONAL, RENEWABLE, NUCLEAR), CEMENT PLANTS, CHEMICAL, PETROCHEMICAL PLANTS, ETC.

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1. Overview on predictive maintenance management system

Predictive maintenance evaluates the condition of equipment by performing periodic (offline) or continuous (online) equipment condition monitoring. The ultimate goal of the approach is to perform maintenance at a scheduled point in time when the maintenance activity is most cost-effective and before the equipment loses performance within a threshold. This results in a reduction in unplanned downtime costs because of failure where for instance costs can be in the hundreds of thousands per day depending on industry. In energy production in addition to loss of revenue and component costs, fines can be levied for none delivery increasing costs even further. This is in contrast to time- and/or operation count-based maintenance, where a piece of equipment gets maintained whether it needs it or not. Time-based maintenance is labor intensive, ineffective in identifying problems that develop between scheduled inspections, and so is not cost-effective. The fundamental idea is to transform the traditional 'fail and fix' maintenance practice to a 'predict and prevent' approach.

The "predictive" component of predictive maintenance stems from the goal of predicting the future trend of the equipment's condition. This approach uses principles of statistical process control to determine at what point in the future maintenance activities will be appropriate.

Most predictive inspections are performed while equipment is in service, thereby minimizing disruption of normal system operations. Adoption of predictive maintenance can result in substantial cost savings and higher system reliability.

Reliability-centered maintenance emphasizes the use of predictive maintenance techniques in addition to traditional preventive measures. When properly implemented, it provides companies with a tool for achieving lowest asset net present costs for a given level of performance and risk.

One goal is to transfer the predictive maintenance data to a computerized maintenance management system so that the equipment condition data is sent to the right equipment object to trigger maintenance planning, work order execution, and reporting. By doing so the **OPEX and CAPEX saving feature of predictive maintenance solution value is accelerated.**

This document and its attachments provide an insight of how the products of cmc Instruments GmbH help user to achieve their goals in setting up real and beneficiary PREDICTIVE MAINTENANCE MANAGEMENT SYSTEM.

2. WearSens® WS3000 - a new approach to gearbox and bearing failure prevention, online and continuous!

WearSens® is a unique, new system for online oil condition monitoring. Early indication of oil changes leads to optimum loading and/or timely preventative maintenance. The result, huge savings in money, downtime and man hours.

Change in oil is one of the precursors of particle shearing and pitting in the bearing raceway. Early detection can warn of potential damage states, before damage occurs.

WearSens® works from day 1, prior to other technologies limits of detection. Tests have shown that the WearSens® can detect deterioration in oil while standard laboratory analysis still reports oil as good. Vibration and particle monitoring only detect after damage is done.

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Conductivity, permittivity and temperature are measured with high precision. Both conductivity and permittivity are temperature dependent, but the temperature compensation for any pollutants is unknown. WearSens® features a self- adapting temperature compensation algorithm similar to a neural network.

Conductivity is measured in siemens per meter. This sensitive conductivity measurement indicates the formation of compounds from broken oil molecules, the presence of microparticles and the consumption of any additives. The temperature compensated values allow comparison at any time.

Relative permittivity is a measure of the dielectric constant.

Permittivity decreases as additives are used up but will then increase once all additives are consumed. Taken in conjunction with the conductivity values, a clear picture emerges of the changes in the oil.

The web based, decentralized monitoring system is perfect for remote or inaccessible locations. Measurements are transmitted via LAN, WLAN or the serial interface.

Conceived, developed and manufactured in Germany the WearSens® represents a completely new approach to oil condition monitoring in a variety of applications. For the first time, changes in oil can be detected accurately, online and continuously. The result, optimized loading, reduced wear and cost savings.

2.1. Features in a nutshell

i. Optimizes load, reduces wear
ii. Detect change before wear damage
iii. More sensitive than vibration monitoring, more sensitive than lab analysis
iv. Easy to install or retro-fit
v. Web based, decentralized monitoring
vi. Condition Based Maintenance — large cost savings

2.2. Applications

WS 3000 Is applied to all rotating and none rotating machinery such as but not limited to the followings:

i. Wind turbines, gas turbines, reciprocating engines (stationary, mobile or ships), stern tubes, air compressors, refrigerant compressors, ammonia compressors etc.
ii. Oil cooled transformers
iii. All type of gearboxes
iv. Contamination detection
v. Roller bearing wear detection
vi. Oil deterioration monitoring
vii. Oil Condition monitoring solution

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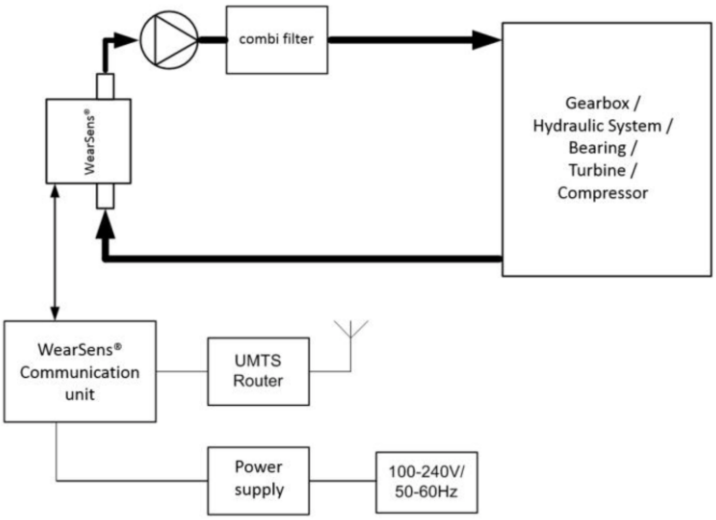


Figure 1: Typical integration scheme of WS 3000.

3. The superb features of the WearSens® WS 3000 sensor system

Differences and advantages of the WearSens® system over conventional optical particle measurement/counting systems

The difference - The crucial difference between the two sensors is that the WearSens® system is used to **prevent damage and limit wear**, however, the particle counter **displays damage done**.

The optical particle counter detects particles from a size of 4 microns. From the number of particles, it provides conclusions about the **state of wear or existing damage**.

The task of the WearSens® sensor system is to **minimize the wear and avoid potential damage.**

Ideally suited for the **early detection of damage**, it detects changes in the oil-machine system by measuring from the outset before any damage occurs (see Figure 1). The smallest amount of wear is detected reliably. The sensor system continuously determines the quality of oil from the dependent parameters of the electrical conductivity and the dielectric constant. With this approach of measuring the change in the oil-machine system, a quasi-continuous assessment of the wear, as well as the contamination and deterioration of the lubricating oil, has been realized. In addition, preventive maintenance measures are indicated. The sensor system increases the operational reliability, increases service life and reduces downtime periods. Oil change intervals are adjusted to actual needs and economic and ecological efficiency improvements are achieved.

WearSens® is an online, continuous system for oil condition monitoring. This permits the reliable detection of incipient damage and the early identification of critical lubrication conditions of bearings and other transmission elements in the gearbox. Wear of the bearing at touching contact surfaces, metal debris, foreign particles, suspended solids and chemically broken oil molecules, which forms acids or soaps all lead to an increase in the electrical conductivity. This increase directly correlates to gear wear and the degree of contamination of the oil due to the initial low conductivity of the oil and relatively high conductivity of the contamination products.

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In oils with additives, the consumption of these can be detected via an additional high- precision measurement of permittivity. Continuous evaluation of the chemical aging of the lubricant during operation opens up a new method for preventing premature bearing failures, occurring under vibration-induced mixed friction stress conditions, e.g. in wind energy turbines and other industrial gears, by timely implementation of appropriate corrective measures, such as additive addition or oil change.

This innovative approach goes far beyond the simple early detection of incurred, irreversible damage to the raceway. The components of the sensor measure the complex impedance of the oils. For example, effect of metal wear, broken oil molecules, acids or oleic soaps all increase the electrical conductivity. High quality additive oils will nullify the resulting ions and the acidification of the oil with time constants in the range of minutes but the WearSens® system measures changes in conductivity with time constants in the range of seconds. So WearSens® will detect wear before additives are all consumed.

With the WearSens® system one is capable of examining the friction induced **degradation** of the different 'tribo-layer types' (e.g. additive conditional boundary layers, iron oxide layers).
This creates new opportunities in the development phase of the gears and bearings. By understanding wear mechanisms, optimization of the system can be performed and thus increased operating time.

Existing sensor technologies such as optical particle measurement or vibration sensors can detect particles only after the occurrence of damage.

The WearSens® sensor system allows for continuous condition monitoring from commissioning, significantly increasing the warning time before any damage occurs.

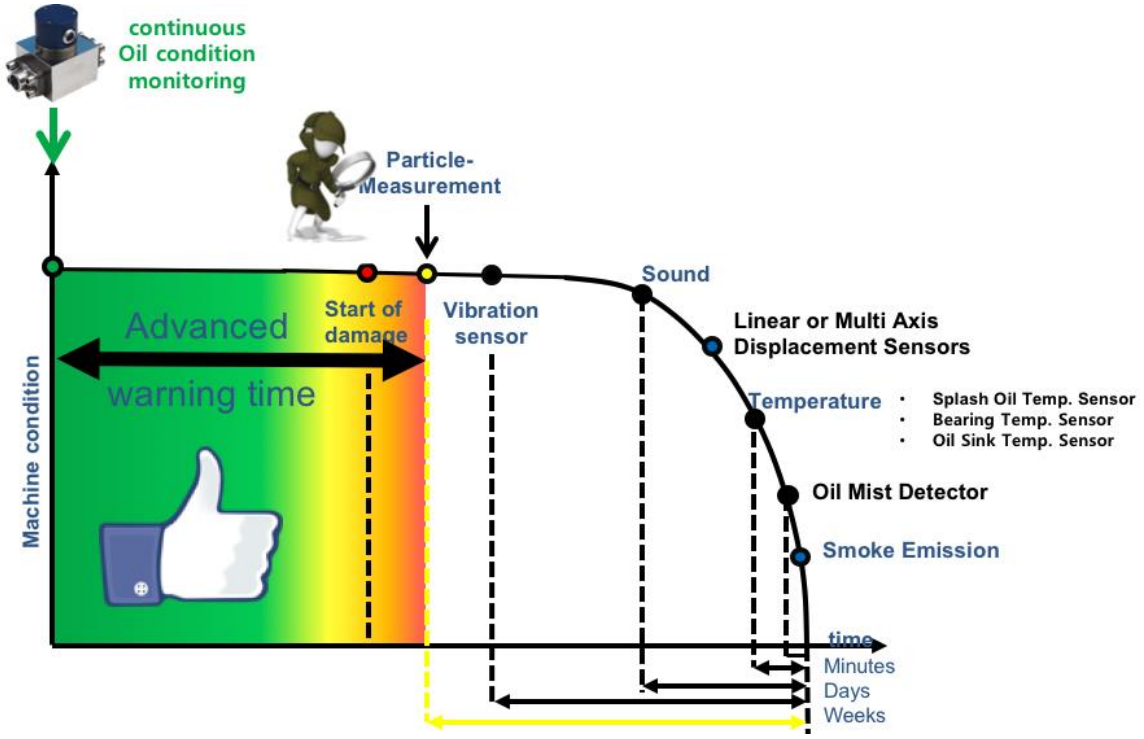


Figure 2: Typical degradation scheme.

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The advantages:

- Prevent damage and limit wear by early implementation of appropriate corrective measures, such as additive addition or oil change,
- Continuous evaluation of component wear, the degradation of the additives and tribo- layers as well as the pollution and aging of the lubricating oil,
- Identification of critical lubrication conditions of bearings and other transmission elements,
- Temperature-compensated measurement system with patented adaptive temperature algorithm,
- In the test and development phase of the gears and bearings on test benches, the sensor supplies essential statements on wear mechanisms. Correlation of test protocols leads to component optimization.

4. Varnish accumulation challenge in air compressors.

New or in use air compressor can become unreliable prematurely if varnish (degraded lubricant which sticks on component surfaces) is allowed to accumulate within that compressor. The WEARSENS® WS 3000 online oil condition monitoring system is able to measure varnish accumulation instantly thanks to its unique feature of measuring the polar elements within liquids. Once varnish accumulation is detected at the rights time (which is provided by WEARSENS® WS 3000) it gives users advance time to react within a PREDICTIVE MAINTENANCE MANAGEMENT SYSTEM scheme and helps ASU's to prevent expensive damages, or expensive downtime of their compressor, thus their entire plant.

Thanks to instant warning and alarm indicators and email messages sent to the operation and maintenance team leaders by the WEARSENS® WS 3000, users have enough time and a full a very valuable and processable information set (i.e. a full information spectrum) to analyze, take measures on the causes and to perform necessary actions to either prevent on time, or to get rid of the varnish accumulated in their compressors. Below you will find five sources of varnish accumulation. Secondly you will find the WEARSENS® WS 3000 oil condition monitoring sensor's measurement and alert features that lead users to handle the matter of varnish accumulation, on time and prior to the machinery disaster.

4.1.Static discharge

Some people replace the filters in their air compressors with models that have a small mesh size in order to remove more contaminants from the lubricant in the compressor. Those replacement filters may generate static electricity as the oil struggles to flow through that fine mesh at high pressure. The static electricity can trigger periodic sparks which can cause the lubricant to degrade under that intense heat. Varnish formation becomes inevitable in such circumstances.

4.2.Fluid incompatibilities

Varnish formation can also accelerate in case you add some additives into the lubricant without ascertaining that those two fluids are compatible. For example, you may wish to use an additive to combat the high levels of moisture within your air compressor. That additive can cause the oil to degrade quickly in case the additive has ingredients which aren't compatible with the oil.

4.3.High operating temperatures

Heat is one of the biggest causes of varnish formation in any piece of equipment, including air compressors. Heat increases the rate at which the lubricant reacts with the oxygen in air. This oxidation results in a rapid break down of the lubricant. High temperatures can result from several factors, such as prolonged use of the air compressor at peak capacity.

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4.4.Reactive gases

The chemical properties of the intake gases processed by the air compressor can also have an effect on how quickly the lubricant will degrade. Reactive gases, such as air that contains sulphates, can accelerate the rate at which the lubricant will age. It is helpful to test the air going into your compressor periodically so that you can identify any reactive constituents which may affect the lifespan of the lubricants which you use.

4.5.Grease contamination

The ingress of grease into the oil in your air compressor can result in varnish formation. Grease increases the viscosity of the oil. Consequently, the oil will be more likely to stick onto components since its flow rate will have been compromised by the heavier contaminant. Grease contamination can result when grease containers are used to top up the oil in the air compressor.
Varnish builds up slowly and its side effects also take time to become evident. Your best approach should therefore entail conducting oil tests as part of your preventive maintenance routine. You may ask air compressor experts for recommendations of the products which you can use to remove varnish from your equipment before the air compressor is adversely affected.

5. Common causes of machine vibrations

Excessive vibrations on rotating equipment like pumps, gearboxes, turbines and compressors are a clear sign that the equipment is not functioning properly. Equipment that is showing excessive vibrations will most likely not achieve the expected lifespan; and can be the source of unscheduled downtime or dangerous situations. Therefore, it is important to find the root cause of vibrations by measuring and analyzing the vibration signals. Common causes of vibrations are discussed below.
Along this document you will find explanations on “How WEARSENS W3000 provides relevant information sets and how it helps users to predict even in an earlier stage the upcoming fault and how to handle and manage such matter”.

5.1. Alignment problems

When two or more rotating machines are connected, the correct alignment is crucial.
Typical alignment errors are:

1) Parallel misalignment:

The shaft center lines are parallel but are not in line. This can be both horizontal and vertical. Parallel misalignment is also known as offset misalignment.

2) Angular misalignment:

The shafts meet at a point. But are not parallel. This can be both on the horizontal and vertical axis. Angular misalignment is also known as gap misalignment.

3) Combined parallel-angular misalignment:

A combination of both parallel and angular misalignment. Combined parallel-angular misalignment is the most common misalignment.

5.2. Unbalance

When the center of gravity of a rotating object is not exactly in the center line, it causes machine unbalance resulting in vibration. When a machine is unbalanced, it can cause damage to the machine itself, the foundation, pipes, etc. There are three types of unbalance: static unbalance, coupled unbalance and dynamic unbalance.

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1) Static unbalance

Static unbalance is when the center of gravity axis (inertia axis) is not in line with the center of rotation (shaft center line), and the heavy spot and the center of gravity are in the same plane. Static unbalance can be the result of a parallel displacement of the principal mass axis relative to the shaft center line, and can be caused by non-symmetric mass distribution or deformation. In theory, static unbalance can be detected by placing the object with a point of rotation on each end. When there is static unbalance and friction is zero, gravity will turn the heavy side downwards.

2) Coupled unbalance

Coupled unbalance appears when a rotating object has two or more unbalanced masses in different planes, that equal each other out in rest position. The principal mass axis is no longer in parallel to the center of gravity, but crosses the center of gravity axis. When the system starts to rotate, these masses will be influenced by centrifugal forces, resulting in vibration.

5.3. Resonance

Every machine has one or more resonance frequencies (natural frequency). When a rotation frequency coincides with the resonance frequency of the machine, resonance occurs. Resonance can have major impact.

5.4. Loose parts

Loose bearings, loose bolts and corrosion can cause the machine to vibrate excessively. Due to the mechanical forces in the machine, loose parts can rapidly cause damage.
Dynamic unbalance is the most common type of unbalance and the result of static and coupled unbalance. The principal mass axis is displaced and not parallel to the shaft center line.

5.5. Bearing damage

In rotating machinery, we come across two main types of bearings: roller bearings and sleeve bearings.
A roller bearing can be damaged in several ways, each with its own vibration fingerprint:

- Damage to the inner ring
- Damage to the outer ring
- Damage to the cage
- Damage to rolling elements (e.g. cylinders, cones and needles)

Each part of a roller bearing has its own frequency. By calculating these frequencies, it is possible to use vibration analysis to determine whether the vibrations are a result of bearing damage.
In contrast to roller bearings, sleeve bearings do not use a rolling element, but use a fluid (oil) film to reduce friction. Vibrations can be caused by inaccuracies in the fluid film; if a stable oil film cannot be formed, it can break, resulting in an oil whip or oil whirl. Additionally, this type of bearing is more sensitive to external influences on the position of the shaft, because its position in the bearing is not fixed.

5.6. Damaged or worn out gears

Gearbox vibrations are often caused by damaged or worn out gear teeth. When gear tooth engagement involves a damaged tooth, the force cannot be transferred as with the other gear tooth engagements. If a gear tooth is broken, less force can be transferred at this point of the cycle. Vibrations occur as a result.

WEARSENS® WS 3000 is able to measure and inform users on time about the emerging pre-vibration events (originated by any cause) already on the front end of the problem, thanks to its unique metering method and alert systems.

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6. Shortfall of conventional oil analysis methods in catching varnish accumulation on time

Conventional oil analysis methods (such as Relative RPVOT (ASTM D2272), or TAN Increase (ASTM D-664), or ISO Cleanliness Code 4406) aren't well suited for varnish prediction, thus new and alternative methods like the WEARSENS® WS 3000 is required to identify changes in the oil at an early stage.
Since the mid 90's the industry has been working to better predict varnish turbine hydraulics. RPVOT, TAN, Particle Counts testing methods were utilized, but user were still experiencing varnish and sludge formation triggering shutdowns, and even prevention of starting up the turbine.

Such file addresses case studies of some of the obstacles emerged in the oil circuits, measured by our WEARSENS® WS 3000 sensor system, backed and proven by laboratory analysis of the clients and actions taken by our thereto.

Please have a look at Page 10 – 13 (of the file named "Predictive Operation & Maintenance Management System Guideline for WEARSENS3000") which gets deeper into the sludge and varnish formation matter. Primarily polar-oxidation products come out of the solution and agglomerate, they accumulate on the metal surface to from varnish & sludge. Please remember! WEARSENS® WS 3000 measures polar elements and so on and so forth.

Please understand us that we won't disclose some of our know-how at this point of time, whereas some other know-how is protected by agreements with our other clients. Whereas further, after contract signing with your esteem company, our full know-how will become to your disposal. We are counting on your understanding in this regard.

7. Oil analysis - the basics

Lube oil is the life-blood of machinery. Much like doctors assess our health though blood analysis, critical plant equipment must be monitored in much the same manner. Chronic lubricant or equipment symptoms show up as indicators in oil analysis samples and, if left uncorrected, can lead to equipment degradation and lost productivity. Therefore, the goal of a proactive oil analysis program is to trend gradual changes in fluid properties, contaminants and wear debris so that corrective action can be initiated in a controlled, planned manner.

7.1. Oil analysis benefits include:

- Optimum Equipment Life
- Extended Oil Life
- Reduced Downtime
- Improved Safety
- Environmental Awareness

7.2. Oil analysis assists maintenance personnel in two primary ways:

1) First - Determining the physical condition and contamination of the oil. Lubricant serviceability can be impacted by either reached a point requiring a drain and refill, unless purification is an option. When talking about contaminants, the objective is to detect the presence of foreign components and to ask "What are they? Where did they come from (built-in, generated, ingressed, introduced)? How can I prevent further entry or generation?" Contaminants act as a catalyst for wear. This generated wear debris further acts as a catalyst for wear accelerates and downgraded serviceability results.

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2) Second - Monitoring wear metals for abnormal machinery distress conditions. Wear debris analysis relates specifically to the health of equipment. As you know the main function of a lubricant is to separate two surfaces, in relative motion to each other, from making contact. However, it is generally impractical to maintain a lubricant film that will keep those same surfaces totally separated from each other. Thus, metal-to-metal contact can occur, even in today's high-tech equipment. In addition, keep in mind that boundary lubrication will always be present during start-up. At that critical point in the machines, operation some normal and/or abnormal wear metals will be generated, with the amount depending on equipment design and whether or not it has proper lubrication.

7.3. Testing

In general, the following tests are used (depending on application) to determine changes in physical properties of the oil, oil contamination and equipment wear debris:

- Viscosity by ASTM D 445: indicates changes in fluid's resistance to flow. Viscosity results can indicate either physical changes or contamination by other fluids.
- Oxidation by FTIR (Fourier Transform Infrared Spectrometer): identifies harmful by-products of thermal degradation. Lubricants oxidation represents a physical change.
- Nitration by FTIR: identifies harmful by-products of fuel combustion. Nitration is a physical lubricant change, much like oxidation.
- Glycol by FTIR/ASTM D 2982: identifies the presence of engine coolants.
- Soot by FTIR: identifies the by-products of unburned fuel. This is also contamination.
- Water by FTIR/Hot Plate/Karl Fisher ASTM D1744: identifies the presence of water, a common and potentially harmful fluid contaminant that can accelerate physical lubricant change and rapidly degrade metal surfaces.
- Total Acid Number (TAN) by ASTM D 664: measures/identifies acid by products of oxidation and contamination. TAN is physical change.
- Total Base Number (TBN) by ASTM 4739: identifies acid neutralizing capacity. This is a physical lubricant change.
- Fuel Dilution by Gas Chromatography: identifies the presence of fuel, another contaminant.
- Elemental Analysis by ICP (Inductively Coupled Plasma Spectroscopy): identifies both additive and wear debris metals.
- Total Base Number (TBN) by ASTM 4739: identifies acid neutralizing capacity. This is a physical lubricant change.
- ISO Particle Count: identifies the size and amount of solid contaminants.

7.4. Where to start

It is easy to see the importance of a proactive oil analysis program, but knowing where to start can often be overwhelming. Don't let the vast array of analysis hardware and test results keep you from getting started. Here's a simple seven-step process to get you off and running:

Step 1: Identify "Mission Critical" Equipment

It is not necessary to perform oil analysis to every lubricated system in your plant. Identify critical applications that would seriously jeopardize production if they were to shut down.

Step 2: Register Your Equipment

It is important to have your equipment properly registered to the lab. This supports routine trending and plays a key role in early detection of lubricant or equipment problems. There's no need for you to decide which tests are appropriate for a particular application because the lab has already established test slates for specific applications.

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Step 3: Establish Best Practices
Establish a consistence of how-to taking oil samples from your equipment and train your maintenance personnel to use this practice. Correct sampling practices are critical to the value received from the analysis data. This extremely important step rarely gets the attention it needs.
Step 4: Sample
Retrieve samples in accordance with your best practice and send them to the lab as soon as possible. Samples that are set aside may deteriorate and give non-representative results.
Step 5: Analyze
A thorough analysis, keyed on trends, helps determine your systems conditions. General laboratories may have a pretty good idea of what they are measuring, but often know little about specific formulations and don't always understand whether or not the differences they see are significant.
Step 6: Interpret
Reviewing the results and determining what, if any, action is required can make or break a successful program. Oil companies have an extensive database of test results that provides guidance to corrective actions.
Step 7: Take Corrective Action and Document, Document, Document!!!
As always, documentation is key to knowing where you've been and where your're going. Document corrective actions resulting from oil analysis. Historical oil analysis and corrective action documentation is difficult for an OEM to dispute when you call for warranty work.

7.5. Why sampling programs fail

When sampling programs fail, the reason is usually one of five major factors:

- **Lack of Understanding:** Knowing what to expect from your analysis program helps determine the rights units to sample and the best sampling frequencies. Before starting a sampling program, you'll find it useful to define why you need a sample program and how the test data relates to the productivity of your equipment.
- **Lack of Interpretation Knowledge:** It is important to know the equipment well enough to quickly relate the analysis results to the noted performance of the equipment being tested.
- **Lack of Commitment:** There must be a mutual commitment from all involved, from the highest levels of management down to the person taking the sample. For the program to succeed all parties must be willing to devote time and training to the program.
- **Poor Sampling Procedures and Practices:** Improper sampling procedures cause erroneous results.
- **Irregular Sampling Frequencies:** Monitoring fluid condition and system performance by trending is far superior to hit-or-miss sampling methods. Lubrication scheduling and oil analysis software can assist in the implementation and tracking of routine sampling.

Although it reflects the 20th century of measurement technique oil analysis is a useful, predictive and proactive tool that can help prevent equipment breakdowns, determine the root cause of failure an aid in locating operational and contamination problems.

7.6. The weakness in purely relying on oil analysis

Oil analysis is taken in intervals which are either determined by the machinery manufacturer or the lubrication oil provider. Typical intervals are 1-12 months for rotating machines and 12-24 months for none rotating machines.
The oil sampling method is helpful in determining a slowly emerging and evolving fault but can't overcome the following challenge. Assuming a T1, T2, T3 time interval for offline oil samples.

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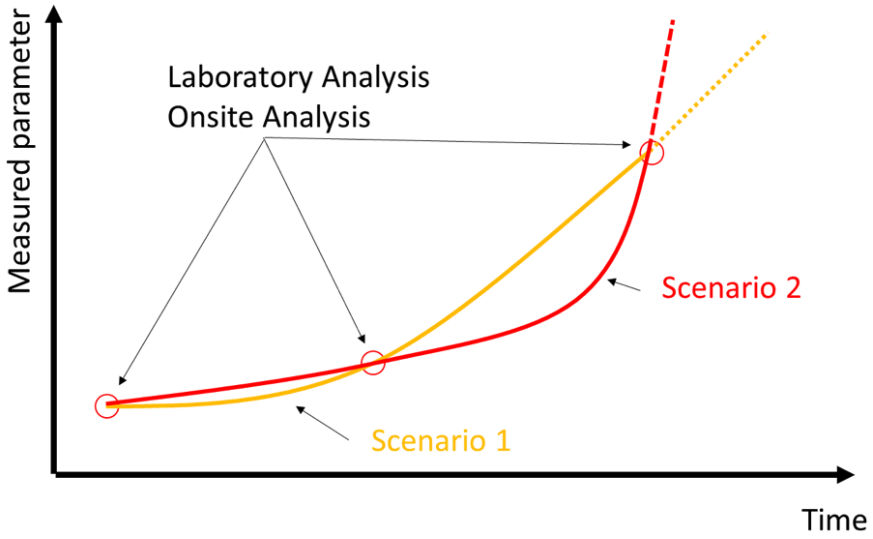


Figure 3: Periodic offline laboratory analysis.

i) The statistical method of recording events has the huge potential of misleading the prediction of an upcoming next event, in case if the additives (or inhibitors) do neutralize the event happened.
ii) Whereas the unique capacity of WEARSENS® WS 3000 (and OILQSENS® OQ3000) is to capture the event at the moment of time when it happens. It also monitors the post event era where the additives (or inhibitors) start hiding the event, against the cost of additive depletion.
iii) The none hideable part is then also reflected in the next oil samples analysis. But this is not enough to insure, a full spectrum and measure of wear and tear emerging inside the machine. A responsive operation and maintenance team cannot “sweep dust under the carpet”.

WEARSENS® WS 3000 insures, that the machine operator has always a full insight on the conditions of the machine 7/24.

8. Oil degradation and additive depletion

Oil degradation is a general term used to describe the destructive mechanisms that cause physical and chemical changes to rotating machinery (compressor, gearbox, turbine, stern tube, reciprocating engine etc.) fluids while in service. Oil degradation results in a deterioration in fluid performance and a dramatic reduction in fluid service life. If ignored, oil degradation will progress and can lead to failures of critical rotary machinery components. Understanding the mechanisms of oil degradation and their impact on fluid properties and performance, enables rotary machinery users to proactively maintain fluid health, maximize fluid life, and avoid costly oil changes and major repairs.

Oxidation is primary oil degradation mechanism and is the chemical reaction that naturally occurs between the oil and oxygen from the air. Rotary machinery fluid is extremely vulnerable to oxidation since the rotary machinery’s design provides an extreme, oxygen-rich environment. Oxidation is an auto-catalytic series of chemical reactions that continuously produces acids, depletes additives, and ultimately will form harmful varnish and sludge in many rotary machinery fluids. Oxidation rates and acid production continuously accelerates as operating temperatures increase (doubles for every 180F increase), as acid levels (TAN) increase, as additive levels (antioxidants) decrease, and as fine metal catalysts accumulate in the fluid. Oxidation also impacts rotary machinery internals by promoting corrosive wear, pitting and rust to unprotected metal surfaces.

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Additive Depletion is another harmful process that reduces the performance, protection, and service life of rotary machinery fluids. Lubricant formulators rely heavily on performance enhancing additives to control fluid service life, inhibit oxidation, and protect rotary machinery internals from corrosion. While in service, additive levels continuously deplete which reduces the oil's ability to resist oxidation and limits oil service life. Like oxidation, additive depletion is accelerated by catalysts like acids, water and fine metals. Monitoring fluid additive levels and replenishing the fluid's additive package when necessary, helps maintain fluid chemistry and performance, and can dramatically extend fluid service life.

Contamination of air rotary machinery fluids by foreign substances (solids, liquids or gases) can significantly accelerate fluid degradation and create a host of additional problems to air rotary machineries. Rotary machinery have a "forced-contamination" design that continuously ingests atmospheric contaminants and forces them into the oil. Many of the airborne contaminants found in industrial environments (combustion exhausts, cooling tower chemicals, welding fumes, process vapors) are strong oxidizers that will accelerate fluid oxidation and acid production. Internally generated contaminants, like the acidic byproducts of oxidation, and fine metals (rust and wear particles), also add fuel to the auto-catalytic degradation cycle.

WEARSENS® WS 3000 is able to measure and inform users on time about the emerging oil degradation (oxidation, additive depletion, contamination) events already on the front end of the problem, thanks to its unique metering method and alert systems.

Attached to this document you will find another file named "Predictive Operation & Maintenance Management System Guideline for WEARSENS 3000", which contains case-studies with measurements and backed by laboratory analysis. Many other matters are addressed within our other bulletins and tailor-made presentations suiting your individual needs.

9. Importance of measuring diesel and gas engine oil online

This example is based on ME type engines.

Concept of ME Engines

The ME engine concept consists of a hydraulic-mechanical system for activation of the fuel injection and the exhaust valves. The actuators are electronically controlled by a number of control units, forming the complete engine control system.

The fuel pressure booster consists of a simple plunger powered, by a hydraulic piston activated, by oil pressure. The oil pressure is controlled by an electronically controlled proportional valve.

The exhaust valve is opened hydraulically by means of a two-stage exhaust valve actuator activated by the control oil from an electronically controlled proportional valve. The exhaust valves are closed by the 'air spring'.

In the hydraulic system, normal lube oil is used as the medium. It is filtered and pressurized by a hydraulic power supply unit, mounted on the engine or placed in the engine room

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Critical Oil Circuits in ME Engines Which Require Oil Condition Monitoring

1. Lubricating and Cooling Oil System
2. Hydraulic Fuel Injection System
3. Cylinder Lubrication (i.e. Piston Rod Stuffing Box Drain Oil)
   3.1. Scavenge Oil (Drain Oil)
4. Fuel Supply
   4.1. Prior to the main fuel storage tank,
      4.1.1.Furnace Oil (FO)
      4.1.2.Marine Diesel Oil (MDO)
      4.1.3.High Spell Diesel (HSD)
   4.2. Prior to the engine fuel inlet
      4.2.1.Furnace Oil (FO)
      4.2.2.Marine Diesel Oil (MDO)
      4.2.3.High Spell Diesel (HSD)
5. Servo oil system for VBS type CP propeller
6. Hydraulic Power Unit for CP propeller
7. Hydraulic Control Unit

Tailored Oil Condition Monitoring Design for ME Marine Engines

In normal applications the “engine system oil” is used for Lubricating and Cooling Oil System and the Hydraulic Fuel Injection System are collected in a common sump tank, from where low pressure pumps are **feeding bearings, chains etc. and providing piston cooling**. The hydraulic system medium is system oil further boosted to the required high pressure, but medium is the same.

The **stuffing box drain oil** is a mix of system oil (most) and scavenge drain oil (least).

The **scavenge drain** oil is also a mix of system oil (quite little) and scavenge drain oil (most, consist of **exhausted cylinder oil** and combustion residue).

Fuels can be Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), High Spell Diesel (HSD) of which there are many variations, diesel and gas oil.

Where to Install the WS3000 on engines?

If we install WS3000 at each oil circuit’s return line, we will monitor the wear and tear and additive depletion there. If we find a way to make each crank section’s oil touch the WS3000 sensor plates, we will monitor the conditions of each section of the Slider-Crank Mechanisms.

In marine applications we measure Furnace Oil (FO), Marine Diesel Oil (MDO), High Spell Diesel (HSD), Low Sulphur Heavy Stock (LSHF), Automotive Gas Oil (AGO), Premium Motor Spirit(PMS), Lubricating Oil (LUBEOIL), Low Pour Oil (LPFO), High Pour Oil (HPFO), Grease.

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Lubricating Oil

The circulating oil (lubricating and cooling oil) must be of the rust and oxidation inhibited type of oil of SAE 30 viscosity grade.
Engine makers recommends the use of system oils with the following main properties:

- SAE 30 viscosity grade
- BN level 5 - 10
- adequately corrosion and oxidation inhibited
- adequate detergency and dispersions.

The adequate dispersion and detergent properties are in order to keep the crankcase and piston cooling spaces clean of deposits. Alkaline circulating oils are generally superior in this respect.

The major international system oil brands listed herein have been tested in service with acceptable results.

Company	Circulating oil SAE 30, BN 5 - 10
Aegean	Alfasys 305
Castrol	CDX 30
Chevron	Veritas 800 Marine 30
ExxonMobil	Mobilgard 300
Gulf Oil Marine	GulfSea Superbear 3006
Indian Oil Corp.	Servo Marine 0530
JX Nippon Oil & Energy	Marine S30
Lukoil	Navigo 6 SO
Shell	Melina S 30
Sinopec	System Oil 3005
Total	Atlanta Marine D3005

Table 1: Typical oils.

Cylinder Oil

The Cylinder oil is essential for a two-stroke engine. Today, cylinder oils are made with a complex chemistry and the individual feed rate must therefore be assessed for each oil brand, viscosity class and BN level. A cylinder oil is mixed to achieve the necessary level of detergency and dispersancy to keep the piston rings and piston crown clean, and the necessary base number (BN) to neutralize the acids formed during combustion.

The cylinder oil not only serves to lubricate the moving parts but is also designed to control the degree of corrosion on the liner surface. In order to simplify the lubrication process on board the ships, as well as the logistics of supply, the oil companies have developed cylinder lube oils that can lubricate the cylinders regardless of the Sulphur content in the fuel:

Such oils have BN levels that are lower than the traditional BN 70 cylinder lube oils

Engine makers recommends use of cylinder lube oils that are characterized primarily by its BN number and SAE viscosity and to use a feed rate according to the BN in the cylinder oil and Sulphur content of the fuel.

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A drain oil analysis is also a strong tool for judging the engine wear condition. Drain oil samples taken in active ACC (Adaptable Cylinder oil Control) operation will show if the oil feed rate can be optimized while keeping the BN between 10-25 mgKOH/kg and the iron (Fe) content below 200-300 mg/kg in the drain oil.

The Integrating of WS3000 with and ME Engine Management Services (EMS) System (example):

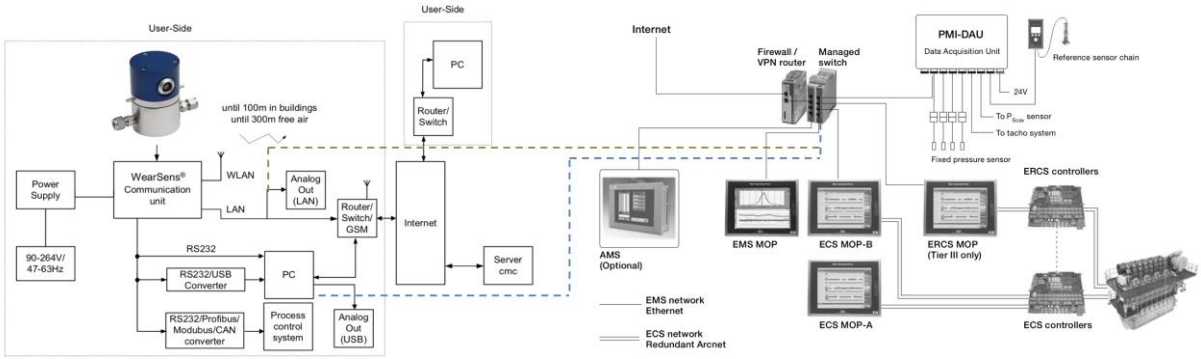


Figure 4: Schematics of the implementation into an existing PLC environment.

More information on this topic is available in the files named as CMC_WS3000_MAN-ME_2 Stroke Application.pdf.

10.Online monitoring features of WS 3000

The integration into a suitable communication structure and the realization of an online monitoring system offers an interesting practice-oriented utilization of the oil sensor system. This is briefly discussed below.

Preferred areas of application of the sensor system are energy production and automated technical plants that are operated locally, like e.g. wind turbines, generators, hydraulic systems or gearboxes. Plant employers are interested in continuous automated in vivo examination of the oil quality rather than interrupting the operation for regular sampling. Online oil status monitoring significantly improves the economic and ecological efficiency by increasing operating safety, reducing downtimes or adjusting oil change intervals to actual requirements. Once the oil condition monitoring sensors are installed on the plants, the measuring data can be displayed and evaluated elsewhere. A flexible decentralized monitoring system also enables the analysis of measuring signals and monitoring of the plants by external providers. A user-orientated service ensuring the quantitative evaluation of changes in the oil-machine system, including the recommendation of resulting preventive maintenance measures, relieves plant operators, increases reliability and saves costs.

In a web-based decentralized online oil condition monitoring system, the sensor signals are preferably transferred through the Internet to a database server and recorded on an HTML page as user interface.

Following authentication, a simple web browser permits access via the wired or wireless LAN. In case of alarm signals, an immediate automated generation of warning messages, for instance by e-mail is possible from any computer with Internet connection.

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10.1. Automated remote monitoring and alert features of WS 3000

The basic architecture of our online oil condition monitoring system is described in the figure below.

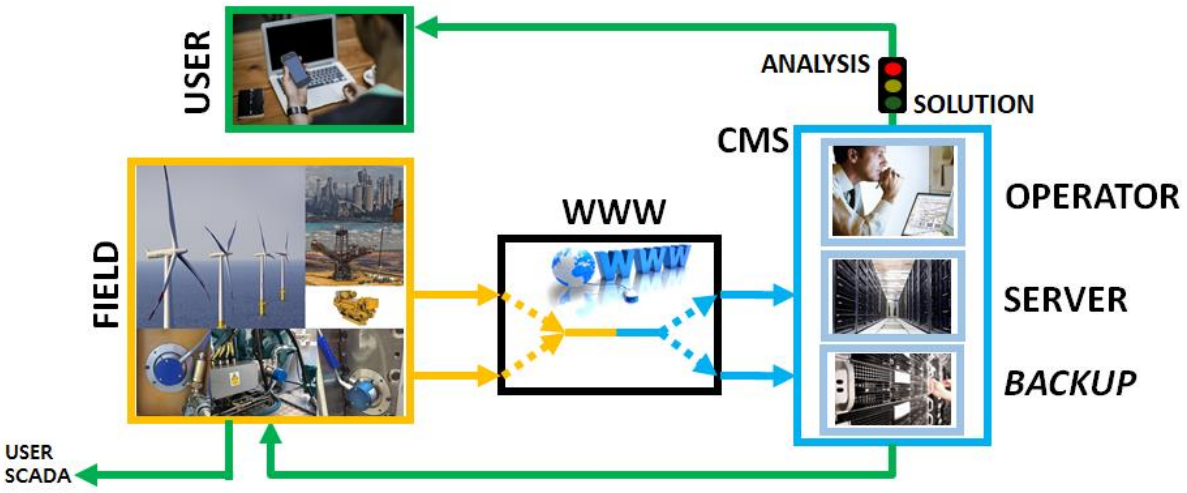


Figure 5: Signal Chain of the WearSens® WS 3000 online sensor system.

The data is recorded in the field: in regions with a good infrastructure, or in remote areas, like offshore wind parks for example. The data can be transmitted locally to the existing PLC hardware or via an internet access (provided by the client) or a GSM Module (SIM card to be provided by the client) to the server of cmc Instruments, localized in Frankfurt (Eschborn). Every time new data is transmitted this data is compared against defined threshold values. The typical time interval is about 45 seconds, i.e. more than 2000 data sets per day consisting of conductivity, relative permittivity, the corresponding compensated values and temperature, the WearSens® Index WS_i is computed on the cmc server.

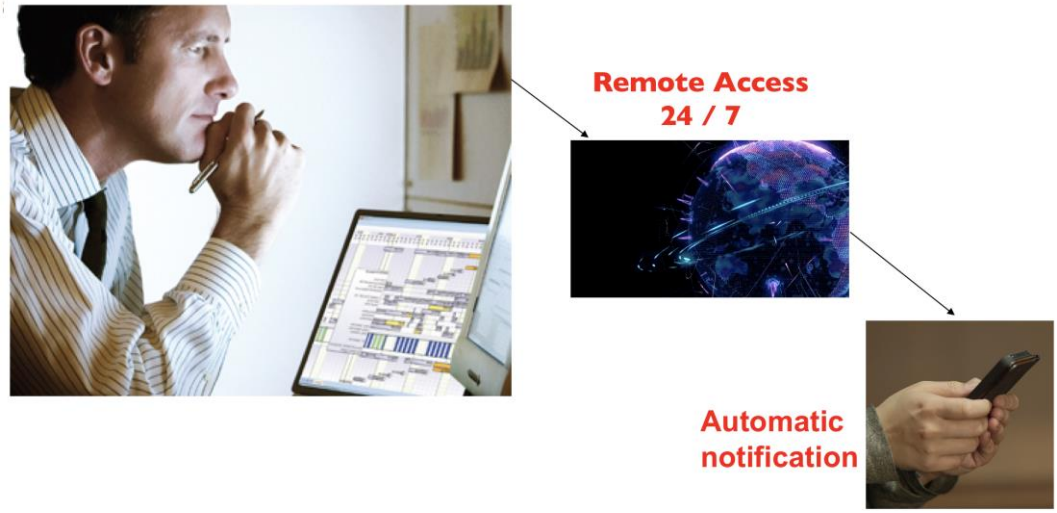


Figure 6: Online Visualization and online data access 24/7/365.

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10.2. Two dimensional WearSens® Index WS_i map

The stress of the lubricant and the monitored asset itself is based on the actual environmental condition, load fluctuations and machine settings, resulting in instantaneous changes of the conductivity and relative permittivity and their gradients. Frequent critical operation conditions lead to faster degradation of the oil additive complex. The hypothesis is that the consumption of the additives is directly correlated with the reduction of the relative permittivity of the oil. The gradient, i.e. the time derivative, of the conductivity or the dielectric constant progression respectively represents a measure of the additive degradation and consumption. Critical operation conditions result in an increased charge carrier generation and will change the conductivity and its gradient significantly.

The initial threshold values for the WearSens® index WS_i in eq. 1 $\kappa_{i40}, \varepsilon_{ir40}, \Delta\varepsilon_{ir40}, \Delta\kappa_{i40}, T_i$ are identified after the installation at the monitored gearbox itself.

The idea of using two dimensional graphs with colour coded WearSens® index WS_i information is to get a quick overview on the single operation conditions of monitored asset of the same type, for example, all wind turbines in a wind park for one year. To do this, the daily average of the WearSens® Index

$$WS_i = \mathrm{f}(\kappa_{40}, \kappa_{i40}) + \mathrm{f}(\varepsilon_{r40}, \varepsilon_{ir40}) + \mathrm{f}\left(\frac{\Delta\varepsilon_{r40}}{\Delta t}, \Delta\varepsilon_{ir40}\right) + \mathrm{f}\left(\frac{\Delta\kappa_{40}}{\Delta t}, \Delta\kappa_{i40}\right) + \mathrm{f}(T, T_i) \qquad Eq.\ 1$$

is calculated and normalized for each day *x* of the month *y*:

$$WS_i\ MAP\ (x,y) = \overline{WS_i}\ (x,y) \qquad Eq.\ 2$$

This daily average value WS_i map (x,y) is computed from more than 2000 WS_i values per day. The graphs in figure 6 below show the WS_i map of two offshore wind turbines (a) WT 1 and b) WT 2).

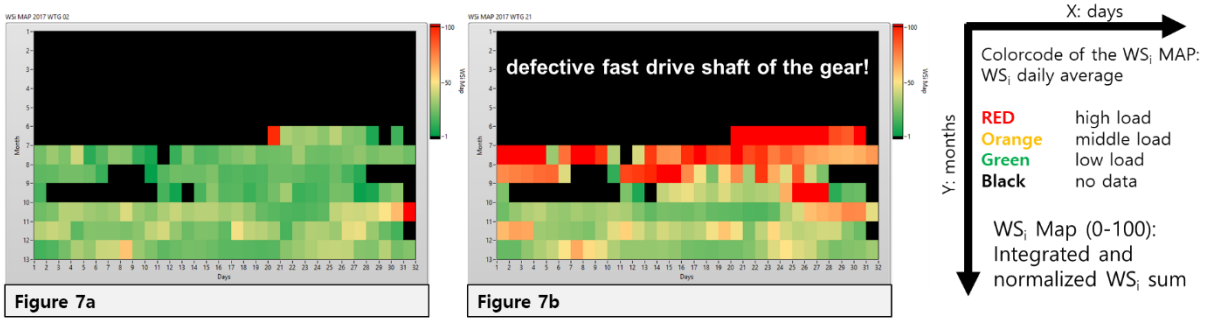


Figure 7: WS_i map for two offshore wind turbines: a) WT 1 with a good overall condition, b) WT 2 with a forming damage and high / overload conditions from June to July.

These two WS_i maps can be compared directly because the two wind turbines face quite the identical wind profile and they have the same operational lifetime and oil exchange interval. The wind turbine WT 1 in figure 7a) shows a normal behavior at middle to high load conditions, whereas WT 2 in fig. 7b displays an increased WS_i map signal output, which stands for high and overload condition. Due to the fact, that this is not a single day event and progresses over time for more than three months this correlates with a forming damage, which has been confirmed by an endoscopic analysis of the gear fast drive shaft. After the wind turbine has been repaired in August, the WS_i map values have been back on normal conditions and nearly match the values of wind turbine WT1.

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10.3. Online consultation and periodical reporting for the WearSens® WS 3000

The online diagnostics system measures components of the specific complex impedance of oils. The indication of forming stage of damage and wear is measured as an integral factor of, e.g., the degree of pollution, oil aging and acidification, water content and the decomposition state of additives, which is correlated to the changes in the electrical conductivity and relative permittivity. By the adaptive temperature compensation of the measured values, it is possible to identify even small variation in the actual charge carrier generation and additive consumption. For an efficient machine utilization and targeted damage prevention, the WearSens® online condition monitoring system offers the prospect to carry out timely preventative maintenance on demand rather than in rigid inspection intervals. The benefits of an extended oil change interval are reduced costs, preservation of the environment and resource protection. The customer can decide to receive a direct feedback from the cmc server in the case of a threshold violation by email. A more detailed report can be compiled individually on these events. Furthermore, half year to year-based reports

11. What to do if WS 3000 launches an alert: a practical guidance towards predictive maintenance of rotating machines

During the oil operation time the oil composition will continuously change depending on the dominating effect: additive consumption, contamination or aging processes. The figure below illustrates the effect on the different branches on the electrical conductivity and relative permittivity at a constant oil temperature. The parameter space of the fresh oil (shown as a purple disc) is moving on the different branches over time. Whereas additive consumption, oil aging and contamination are on the mid to long term time scale, the critical lubrication conditions – occurring only in operation – are in the seconds to minute regime; when the critical event is over the parameters are going back to the actual initial oil condition.

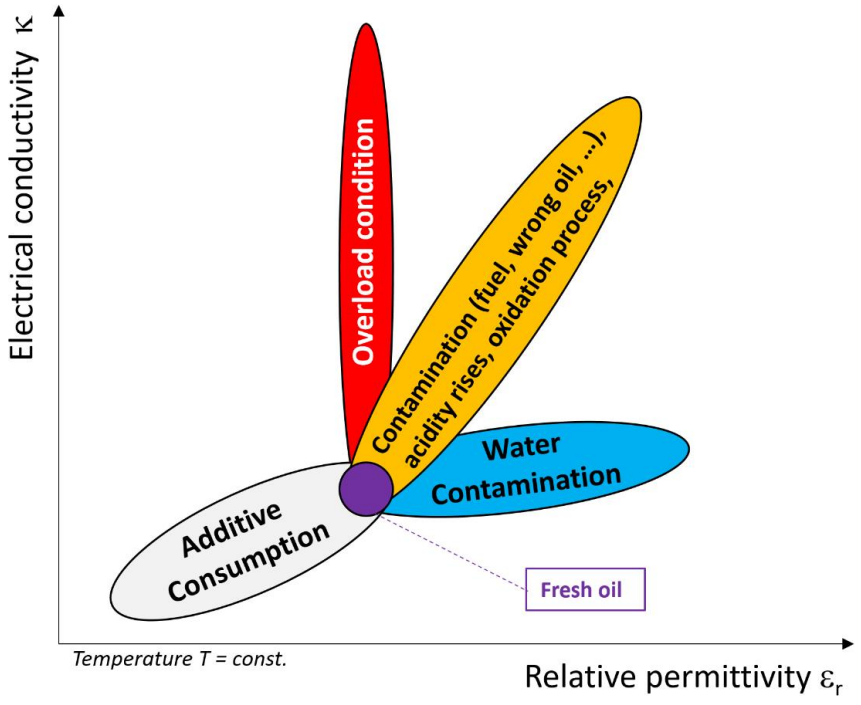


Figure 8: Parameter space for different effects: electrical conductivity and relative permittivity.

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Additive Consumption:

The additive consumption in lubrication oil has a higher impact on both parameters compared to insulation oils; this mainly depends on the additive composition of the particular oil and its higher contribution to the initial conductivity and permittivity level.

Contamination, acidification, oil aging:

The contamination of engine oils with the wrong / incompatible oil type, impurities, fuel will result in a permanent increase of both parameters. An increased acidity level will also rise □r and □. The oil oxidation / oil aging is increasing the electrical conductivity.

Water contamination (after additives can't handle the amount of incoming water)

First of all, incoming water (ε_r = 80) will react with the corresponding additives, which take care of emulsification of water, so the conglomeration of water droplets is minimized and a blank metal surface without lubrication film / tribological layer protection is prevented. ε_r is decreasing a bit. After the additives for water emulsification are depleted, ε_r will start to increase again, due to the higher value ε_r of water, compared to oil (ε_r between 2 to 3).

Overload condition (conductivity peak, only on a short time scale)

The base conductivity level will rise for a short time during the load/overload event due to the increased charge carrier generation of the system oil-machine.

12. The most advanced online oil degradation - *(varnish, additive depletion etc.)* and wear & tear determination method and technology - WearSens® WS 3000 online oil condition monitoring system

Knowing the above-mentioned major reasons of emerging errors in rotary machinery, we can say that WEARSENS® WS 3000 is able to measure all those events already on the front end of the problem.

WEARSENS® WS 3000 sensor system is intended for the use in instant and online measuring liquid fuels and lubricants used in compressors, reciprocating engines, gas turbines, stern tubes, gearboxes (these are commonly used in the ASU's, refineries, petrochemical-, chemical-, steel mills, wind turbines, cement mills, paper mills, ships and many other industries) to monitor operating fluids and their operating conditions (e.g. wear, tear, overload, contamination).

Short-term signal changes in the event of overloads or contamination, as well as slow oil degradation (varnish formation or similar) or additive ageing phenomena can be identified via the WEARSENS® WS 3000 continuous online monitoring with measurement interval of < 1 minute.

Cmc Instruments GmbH has a wide range of experience in the different areas of large industrial gear units, hydraulic systems and contamination-, loads detection in nearly type of oils thereto, and of all type of rotating machines.

The WEARSENS® WS 3000 sensor system can measure oil conditions inflow (lubrication circuits), as well as inside the stationary medium (oil tank, oil cooled transformer). Depending on the application, one or the other installation may be suitable. Best fit application details are determined during a site inspection, jointly with our customers.

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cmc Instruments GmbH offers its customers almost any industrial standard interface to the communication unit of the sensor system like but not limited to, RS232, LAN (TCP IP), Modbus (TCP or serial), Profibus, CAN, Profinet etc.

If requested, the sensor's data transmission can be routed via the Internet to the cmc Instruments server for hosting, reporting, consulting purpose. So that our customers have an all-round data

12.1. WearSens® WS 3000 operation principles

The WEARSENS® WS 3000 sensor measures the electrical conductivity, relative permittivity and the temperature of the fluid.

The sensor consists of three plates which are arranged parallel to each other. These form a capacitor. The fluid flows between the capacitor plates and forms the dielectric between the plates.
Thus, it is possible that the capacity of this capacitor can be measured. On the basis of capacity, the relative permittivity is defined.

Furthermore, the resistance between the plates can be measured. For instance, metal abrasion, broken oil molecules, acids or oil soap all bring about an increase in electric conductivity, which, on account of the low conductivity value of oil as compared to all these contamination products, directly correlates to the degree of pollution. Since oil is an excellent insulator, it has conductivities between 1 to 90,000pS/m. Opposite is the conductivity of pure water which is a few µS/m and metals, which are some MS/m. This means with water is more conductive than oil by a factor of 300 to 105 or metals than oil by a factor of 1016.

The temperature is measured to allow comparison of permittivity and conductivity values at different temperatures. The electrical parameters of relative permittivity and conductivity are temperature dependent. A self-learning, adaptive temperature compensation algorithm allows accurate comparison of data taken at different temperature.

13. cmc Instruments's presentation: 'Predictive Operation & Maintenance Management System Guideline for WEARSENS® WS 3000'

Predictive maintenance techniques are designed to help determine the condition of in-service equipment in order to estimate when maintenance should be performed. This approach promises **cost savings over routine or time-based preventive maintenance**, because tasks are performed only when warranted. Thus, it is regarded as **condition-based maintenance** carried out as suggested by estimations of the degradation state of an item.

The main promise of predictive maintenance is to **allow convenient scheduling of corrective maintenance, and to prevent unexpected equipment failures. The key is "the right information in the right time"**. By knowing which equipment needs maintenance, maintenance work can be better planned (spare parts, people, etc.) and what would have been "unplanned stops" are transformed to shorter and fewer "planned stops", thus increasing plant availability. Other potential advantages include increased equipment lifetime, increased plant safety, fewer accidents with negative impact on environment, and optimized spare parts handling.

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Predictive maintenance differs from preventive maintenance because it relies on the actual condition of equipment, rather than average or expected life statistics**, to predict when maintenance will be required.**

Some of the main components that are necessary for implementing predictive maintenance are data collection and preprocessing, early fault detection, fault detection, time to failure prediction, maintenance scheduling and resource optimization. Predictive maintenance has also been considered to be one of the driving forces for improving productivity and one of the ways to achieve "just-in-time" in manufacturing.

cmc Instruments Gmbh's products such as WEARSENS® WS 3000 continuous online oil condition monitoring system and OILQSENS® OQ 3000 continuous online monitoring system provide the necessary measured information set to our Customers to develop their advanced methods and technologies for their **tailored predictive maintenance management system**. **The developed approaches have been successfully validated in over 500 projects**, conducted with research and industry partners for enabling products and systems, to achieve and sustain zero breakdown so far. Our vision is to estimate the current health of a plant equipment and predict the next fault event for improved productivity and asset utilization.

Cmc Instruments has an extensive database of test results and has developed recommended control limits based on years of testing. I any case, it's important to remember that an alert sample does not necessarily mean imminent failure. Seek consultation on alert samples and re-sample to confirm present data before taking massive corrective action.

Attached to this document you will find another file named "Predictive Operation & Maintenance Management System Guideline for WEARSENS3000", which contains case-studies with measurements and backed by laboratory analysis. Many other matters are addressed within our other bulletins and tailor-made presentations suiting your individual needs.

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14. Matrix Symptom – Probable Cause – Solution

POS	SYMPTOMS	PROBABLE CAUSE	SOLUTION
1	$WS_{i\text{-}COP}$ shows several peaks above the warning limit.	Wear or tear in the machine during operation at increased machine stress level.	1) Check conductivity and permittivity trending. 2) Start close tracking of the machine. Perform a cross-correlation of other sensor information if available.
2	$WS_{i\text{-}COP}$ shows several peaks above the alarm limit.	Wear or tear in the machine during operation at increased machine stress level.	1) Check conductivity and permittivity trending. 2) Reduce machine load to 70%. Increase load step by step 5% every 15 minutes until full load. Check out the impact of the reloading sequence on the conductivity and permittivity values. 3)Take oil sample and perform detailed oil analysis. 4) Start close tracking of the machine. Perform a cross-correlation of other sensor information if available.
3	$WS_{i\text{-}OCI}$ exceeds warning limit.	Oil degradation, additive consumption	1) Check conductivity and permittivity trending. 2) Compare the temperature dependency of the conductivity and permittivity with historical data. 3) Take oil sample and perform detailed oil analysis.
4	$WS_{i\text{-}OCI}$ exceeds alarm limit.	Oil degradation, progressive additive consumption	1) Check conductivity and permittivity trending. 2) Compare the temperature dependency of the conductivity and permittivity with historical data. 3) Take oil sample and perform detailed oil analysis. 4) Change the oil.
5	Abnormal increase in conductivity.	Contamination, oxidation, acidity increase	1) Check conductivity and permittivity trending. 2) Compare the temperature dependency of the conductivity and permittivity with historical data. 3) Take oil sample and perform detailed oil analysis.
6	Abnormal decrease in conductivity.	Contamination, additive consumption	1) Check conductivity and permittivity trending. 2) Compare the temperature dependency of the conductivity and permittivity with historical data. 3) Take oil sample and perform detailed oil analysis.
7	Abnormal increase in permittivity.	Contamination, oxidation, acidity increase	1) Check conductivity and permittivity trending. 2) Compare the temperature dependency of the conductivity and permittivity with historical data. 3) Take oil sample and perform detailed oil analysis.
8	Abnormal decrease in permittivity.	Contamination, additive consumption	1) Check conductivity and permittivity trending. 2) Compare the temperature dependency of the conductivity and permittivity with historical data. 3) Take oil sample and perform detailed oil analysis.
9	Joint increase of conductivity and permittivity	Contamination, oxidation, acidity increase	1) Check conductivity and permittivity trending. 2) Compare the temperature dependency of the conductivity and permittivity with historical data. 3) Take oil sample and perform detailed oil analysis.
10	Joint decrease of conductivity and permittivity	Additive consumption	1) Check conductivity and permittivity trending. 2) Compare the temperature dependency of the conductivity and permittivity with historical data. 3) Take oil sample and perform detailed oil analysis.

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15. Attachments

ANNEX-I # Predictive Operation & Maintenance Management System Guideline for WEARSENS® WS 3000

ANNEX-II # CMC_WS3000_Flyer_Industry_2019

ANNEX-III # Datasheet WearSens® WS 3000 - a new approach to gearbox and bearing failure prevention, online and continuous!

ANNEX-IV # Online TBN_TAN Determination by WS3000

ANNEX-V # CMC_WS3000_MAN-ME_2 Stroke Application

16. Publications

The publication list and other informative publications can be downloaded here:
https://cmc-instruments.de/download.php