E-BOOK

The condition monitoring comparison guide

Find out which technologies work best to reduce risk, lower costs, save energy and eliminate unplanned downtime.

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Samotics

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Condition monitoring in industry

From food and water to fuels, paper, medicines and more, countless machines power the industrial processes that nourish our modern lives. These mechanical workhorses are often subjected to harsh conditions, and even in the best case, every machine will eventually fail from simple wear and tear.

A well-rounded condition monitoring toolkit can prevent lost production, expensive repairs and safety risks by detecting upcoming equipment failure at an early stage. By using the right system for each situation, you can uncover critical faults soon after they begin, when repairs are cheaper and faster. What's more, some condition monitoring technologies can provide additional insights that help you achieve safer, more efficient and more sustainable operations over the long term.

Let's dive in for a closer look.

When to use condition monitoring

CONDITION MONITORING is the name for a class of tools that measure one or more physical features—current, lubricant, temperature, vibration, voltage, etc.—to identify changes in a machine's behavior that signal a developing fault. It is the technique that enables predictive maintenance (also known as condition-based maintenance).

Prescriptive maintenance builds on predictive, adding in recommended actions. Proactive and reliability-centered maintenance are umbrella terms that include these condition-based flavors among their component strategies.

There are more names for ways to do maintenance than you can shake a stick at: reactive, corrective, preventive, predictive, prescriptive, proactive, risk-based, time-based, condition-based, reliability-centered, failure finding, run to failure... Some of them are different ways to say the same thing, and some are meta-strategies that bundle several others.

Whatever names you use, every strategy has its place—even run to failure. (Consider a facility's light bulbs, batteries and ceiling tiles.) So we're not here to tell you that strategies based on condition monitoring are the best. They're total overkill for things like light bulbs and ceiling tiles, and not worth the expense for most non-critical equipment. Where they're useful is for critical machines whose failure would be very costly. That cost might be financial, such as lost revenue or parts and labor, or reputational, as with a sewage or chemical spill.

Condition monitoring provides a means to prevent this crippling cost. So that's when you want to use it: when you cannot afford failure.

There are other strategies that help you avoid critical failures. Two tried-and-trusted methods are time-based (preventive) maintenance and machine redundancy, paired with a solid inventory of parts. Condition monitoring has only recently become a contender, with the rise of artificial intelligence and the industrial internet of things. Now that we can gather round-the-clock equipment health data and analyze it in real time, it can be worthwhile to review the need for these two strategies. Modern condition monitoring can sometimes provide better results at a lower cost. You can also use it as an extra layer of protection.

> Condition monitoring is for critical assets whose failure is costly.

Big data and ~~predictive~~ proactive analytics

Before the widespread adoption of computers in the 1980s, condition monitoring required not only manual data collection, but also skilled human experts to analyze and interpret that data. Manual systems still dominate the field; many industries have yet to complete the complex move to digital manufacturing. But the 21st century has provided arguably the best reason to step up those efforts: the marriage between artificial intelligence (AI) and the industrial internet of things (IIoT). We now have the ability to apply automated, expert real-time analysis to vast amounts of continuous data collected by wireless sensors.

That means tried-and-true condition monitoring techniques can now be used to collect asset health datapoints not just once a month or every six weeks, but thousands of times per second, all day every day. On the back end, machine learning software can now process that data in real time to automatically detect developing faults and pinpoint where they're arising: bearings, drive shaft, coupling, impeller, seal, intake, pulley, belt, stator, rotor—the list goes on.

AI-based analysis has significant advantages over human expertise: machine learning systems can rapidly process immense amounts of data (far more than a human can, and far faster), they're constantly refining their knowledge based on new data, and their conclusions are always based on fact, never on intuition. All this means that AI-based condition monitoring systems also get even better at what they do over time. As their "fingerprints of failure" libraries grow, they can ultimately learn to associate these patterns with their underlying cause, enabling proactive and not just predictive action.

Periodic data collection and manual analysis are definitely useful. But in your critical systems, you'll want the level of insight provided by continuous monitoring based on AI and the IIoT. This is the level we focus on in this guide.

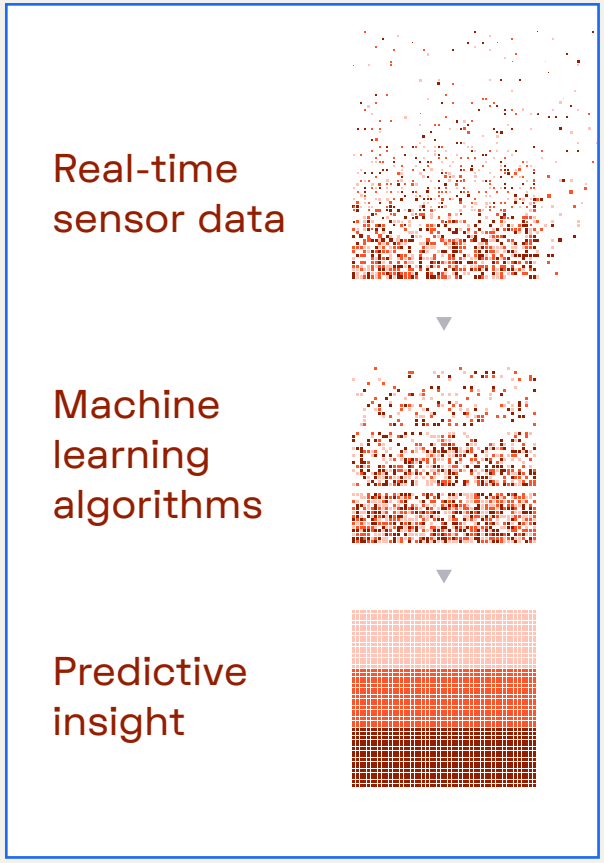

Figure 1. Continuous data + real-time analysis = insight that can drive better decisions and outcomes.

The five major condition monitoring technologies

Condition monitoring requires sophisticated analysis on a reliable source of information-rich data. There are five major technologies, categorized by data source: electrical signals, lubricants, stress waves, temperature and vibrations.

ELECTRICAL SIGNALS

There's a dizzying array of electrical analysis methods out there; sometimes it can feel like you're drowning in acronym soup. But they all fall into two basic categories: electrical signature analysis (ESA), which is performed while the machine is operating normally (or "online"), and motor circuit analysis (MCA), which is performed while the machine is deenergized ("offline"). As is evident from this description, only ESA can provide continuous insight.

ESA is based on the fact that the power drawn by a running motor contains information about the entire drive train. Sensors are placed at a point between the power supply and the machine, rather than on the machine itself. ESA uses several signal processing techniques. For example, motor current signature analysis uses the fast Fourier transform or a wavelet transform to convert the current signal into the frequency domain and search for changes in energy over time. Motor voltage signature analysis does the same for voltage. Power quality analysis checks both signals in the time domain for phase, distortion and balance. Lateral and torsional vibrations can also be extracted from the electrical signal, without the need for additional sensors. (For a closer look at the techniques that make up ESA, check out our ESA explainer.)

The current and voltage sensors used for ESA applications are typically non-invasive clamps that attach around an insulated wire rather than making direct contact with the wire itself. There are several types, based on the electromagnetic effect being exploited. Inductive sensors, for example, make use of the fact that current induces a magnetic field and vice versa, while Hall sensors exploit the fact that a magnetic field induces a voltage across a current-carrying conductor. ESA clamps typically have a wide frequency bandwidth and can be installed anywhere between the power supply and the motor. Another plus: they don't need batteries.

Figure 2 A manual current clamp.

LUBRICANTS

Lubricants are indispensable for the proper working of bearings, gearboxes and hydraulic systems. Here, too, there are several analytical techniques. For example, atomic emission spectroscopy measures the amount of iron, copper, lead and other metals in the lubricant (a sign of wear). Fourier transform infrared spectroscopy measures oxidation and aging. Karl Fischer titration quantifies water penetration. Historically, these techniques have been performed offline on lubricant harvested from the machine, but recent advancements in sensor technology now make it possible to analyze lubricants in place in real time.

> Today almost every physical or chemical property of oil that has traditionally been monitored using lab-based oil analysis can be monitored in real time using a sensor.
>
> —Mark Barnes, Des-Case Corp.

STRESS WAVES

Some faults, such as cracks, leaks and fiber breakage, produce elastic waves (or stress waves) within the material that's cracking, leaking or breaking. This phenomenon is called acoustic emission—not in the everyday meaning of "sound we can hear," but in the scientific sense: acoustics is the branch of physics that deals with pressure waves moving through solids, liquids and gases. (Our everyday "sound" is pressure waves moving through air at frequencies the human ear can hear. We'll stick with the label "stress waves" in this e-book so we don't forget that acoustic pressure waves also move through things like concrete and metal, and at frequencies outside the range of human hearing.)

Acoustic stress waves are a particularly good data source to detect surface and near-surface cracks and pitting, delamination, and corrosion fatigue in concrete, metal and fiberglass. They also capture friction, crushing and leakage. They're great at locating the source of a developing fault (but for that, you'll need multiple sensors). Acoustic emissions analysis relies on signal processing techniques such as the continuous wavelet transform and the Hilbert-Huang transform, as well as the short-time Fourier transform and other Fourier variants.

Acoustic emission sensors are typically piezoelectric transducers. These use a crystal or ceramic (that's the "piezo" part) to convert the tiny surface displacement caused by the stress wave—we're talking nanometers here—into an electric charge. There are also piezoresistive sensors, which measure how the applied stress changes the crystal's or ceramic's electrical resistance (the ability to repel the flow of charge). And there are capacitive sensors, which measure a change in electrical capacitance (the ability to store charge). All these are available in many different versions, depending on the desired frequency range and other parameters. Sensors in the ultrasonic range can effectively measure low-energy sources of stress amid higher-energy structural vibrations and noise. There are also sensors based on fiber optics, which can handle higher temperatures and are unaffected by electromagnetic interference.

TEMPERATURE

Temperature sensors range from simple thermocouples that measure the temperature at one location to infrared cameras that can capture the heat map for a whole area.

Thermocouples use the Seebeck effect: if two wires made of different metals are joined at one end, a change in temperature will produce a voltage across the other, unjoined, ends of the wires. Thermocouples come in different combinations of metals, each with its own temperature range. They also come in sheathed and unsheathed versions, depending on whether they'll be exposed to corrosion, oxidation and other hazards.

Thermal cameras use Planck's law: any object with a temperature above absolute zero emits infrared radiation, and the amount increases with temperature. (Infrared radiation is the same phenomenon as ordinary light—just at wavelengths outside our visible range. Radio waves and x-rays are other sections of this same electromagnetic spectrum.) Thermal cameras come in handheld and mounted types; for real-time insight, you'll need them permanently installed. Accuracy can be affected by the camera's focus and by how reflective the surfaces being filmed are, as well as air currents and the ambient temperature. Thermal cameras also need a source of power, either wired or from batteries.

The captured infared signal is directly converted into a color map inside the camera. Each color in the image represents a different temperature. To identify fault-related changes over time, thermal analysis uses the techniques of computer vision, a field of machine learning focused on interpreting images. Here, too, wavelets and Fourier transforms are important.

Figure 3. A handheld thermal imaging camera.

VIBRATIONS

In condition monitoring, vibrations are the regular oscillating movements that we mean in our everyday use of the word "vibration." As with acoustic stress wave sensors, vibration sensors are commonly piezoelectric transducers, and there are also resistive and capacitive versions. Some of these measure displacement, like acoustic sensors, while others measure velocity or acceleration. Piezoelectric accelerometers are the most common choice. Sensors based on MEMS (micro-electronic mechanical systems) technology are smaller, cheaper, and can integrate analysis right into the device, but are more sensitive to noise.

To capture linear (back and forth) vibrations in all three directions, you'll either need three sensors (one for each direction), or a triaxial sensor that can measure all three directions. To capture rotational vibrations, you'll also need to install an angular sensor called an encoder. (Install two if you want to capture torsional vibrations.) The sensor's frequency range is also important to consider.

Like the other techniques, vibration analysis performs its signal processing in both the time and frequency domains using the FFT and other algorithms.

Matching each use case to the right data sources

Each data source carries different information, which means there's no "best" choice across the board. In ideal conditions, you would use them all for maximum insight. In practice, the constraints of cost and accessibility will usually force you to choose. Here are three pointers to help you find the best fit for each critical machine.

KNOW YOUR FAILURE MODES

Each industrial process is prone to specific kinds of equipment failure. For example, a centrifugal pump may experience cavitation, where bubbles form in the liquid being pumped; when these bubbles collapse, the resulting shock waves can damage the impeller. Common conveyor system problems include a misaligned belt or a failure in the drive coupling, pulley or gears.

Each of these failure modes has a unique fingerprint in terms of vibration, noise, heat, oil changes and so forth. Some of these fingerprints are so pronounced that a sensor can pick them up as soon as they start to develop; others don't reach a measurable level until system failure is imminent. (Think smoke.) How useful each category will be depends on what failures you're likely to encounter. (A FMECA analysis is a great tool for this—see the reference at the end.) Knowing your failure modes will also help you choose the right frequency ranges for vibration and stress wave sensors, if you use them.

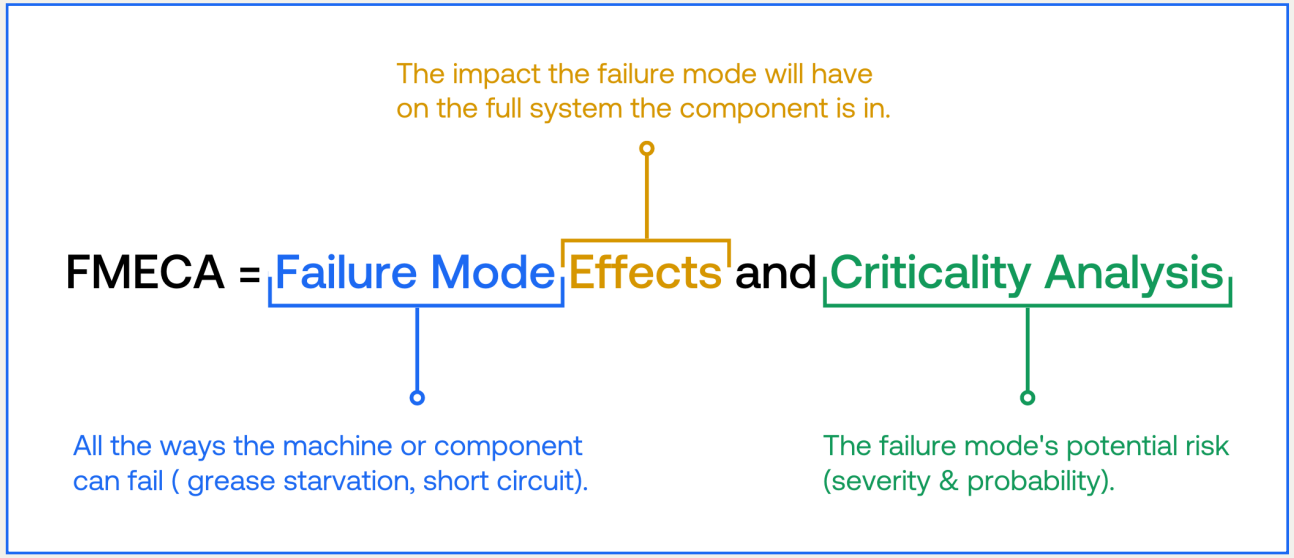

Figure 4. FMECA helps you qualify and quantify the impact and likelihood of machine failure.

A P-F CURVE CAN HELP YOU MAKE A FIRST CHOICE

On a P-F curve, P stands for potential failure; F stands for functional failure. The P-F interval is the time between when we notice that a machine is starting to deteriorate (point P) and when the machine actually fails (point F). There's a third point, A, which is when the machine first begins to degrade.

(There's a fourth section we could add to this graph on the far left. This is where you choose the right equipment for the job: for example, a coupling that's rated for the correct power, torque, starting load and so on. But that's outside the realm of condition monitoring.)

The closer P is to A for a given condition monitoring system, the better. The sooner you detect a developing fault, the less damage the machine will suffer, the less energy it will waste, and the less it will cost to service it.

A full P-F curve results from a detailed analysis that depends on the specifics of the failure mode, the machine and the environment, but you can use a quick-and-dirty version as a visual aid to help you start making choices. In this version, we divide the curve into three sections—proactive, early enough, and on the late side—and put each technology into one of those sections, based on how soon it will pick up on a developing failure mode and how well it can identify the root cause of the problem.

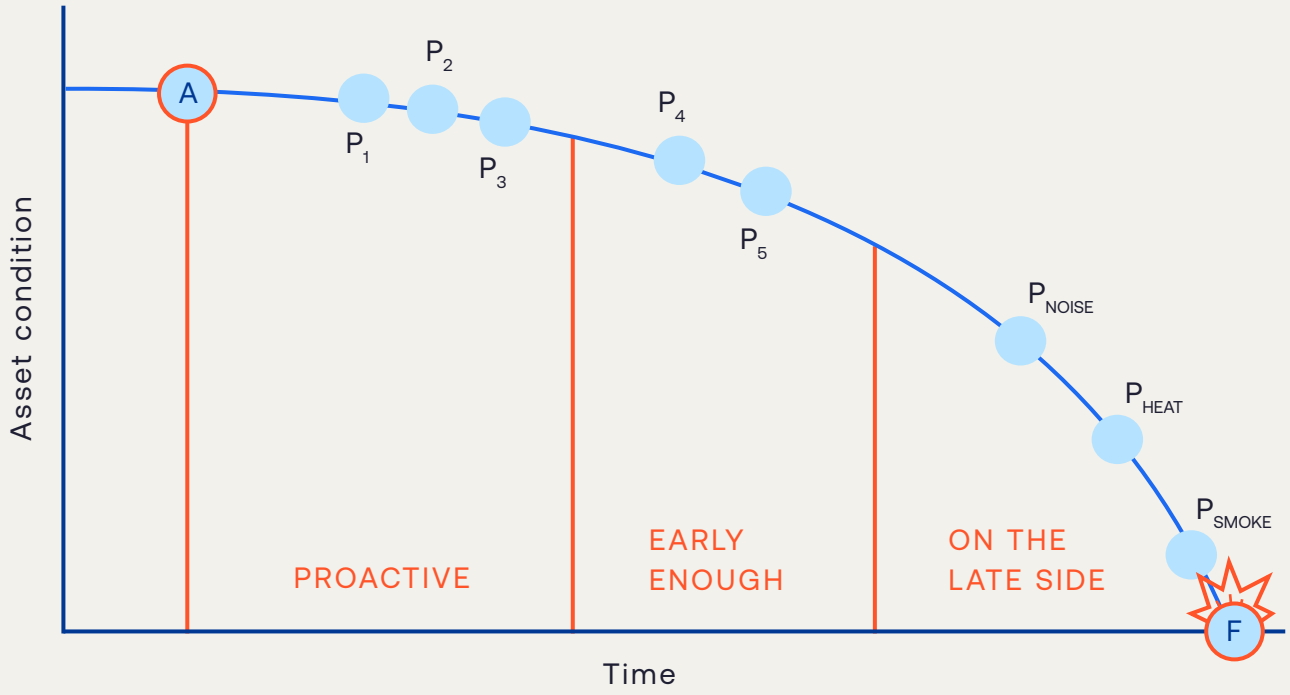

Figure 5. Sample P-F curve for a specific failure in a specific production system. The locations of the various signals on the curve will be different for each machine, production environment and failure mode.

CONSIDER THE MACHINE'S LOCATION

Last but not least, factor in the environment where the machine operates. It may limit the types of sensors you'll be able to use.

All condition monitoring sensors are delicate pieces of equipment, and in general they must be shielded from environmental extremes: very high or low temperatures, high humidity, strong magnetic fields, shocks, corrosive substances, dirt and grit, and so on. It can be tough to mount sensors directly on hard-to-reach equipment such as submersible pumps or motors encased in larger machines. ATEX zones and other restricted locations may also pose a problem. Check whether your machines have built-in sensors you can exploit. You can also find external sensors rated to withstand moisture, heat and other hazards—at an understandably higher cost. Be sure to compare apples to apples when you're ranking different systems.

Figure 6. A submersible pump in a chemical bath.

Example 1: Bearing failure

Bearing failure can be the visible fallout of widely different causes, from shaft misalignment to water contamination to a poorly grounded electrical system. A damaged bearing can also be a non-obvious symptom of a more subtle problem. If a bearing keeps wearing out faster than it should, look to other components for the cause.

Properly sized and placed vibration sensors will be very early to catch most types of bearing damage. Seven decades of analysis have built a storehouse of standards and known patterns that make this data source the clear king for early detection and root cause tracking.

Acoustic sensors are a better choice for low-speed rolling element bearings, where standard vibration sensors have trouble.

Lubrication issues are a top cause of bearing failure, which makes lubricant sensors another great choice. This data source is also the only one that can directly identify contamination by fluids or foreign matter.

Temperature sensors can identify overheating bearings, which can signal both under- and overgreasing, but also mechanical problems such as inadequate internal clearance and worn housings. Generally speaking, a rise in temperature is the result of damage that's already happened, not an early indicator of the problem that will cause it.

Electrical sensors capture damage-related changes just as well as vibration sensors do, but only for bearings in the motor. The further down the drive train a bearing is, the less information it transmits via the current and voltage signals, meaning electrical methods won't spot developing damage until late in the game. For motor bearings, they are a top choice for VFD-induced bearing currents. Low-speed operation is also no problem.

Figure 7. A tapered roller bearing.

Always-on lubricant sensors can pick up the root cause right away, before the water has had time to cause corrosion or degrade the lubricant. (It's up to you to fix the reason why water is able to get inside, and not just replace the existing bearing.) Thermal sensors can pick up on overheating once the lubricant's viscosity has been affected. The other three techniques will pick up on the problem once structural damage begins—not as early as lubricant sensors, but early enough to schedule planned maintenance before failure occurs.

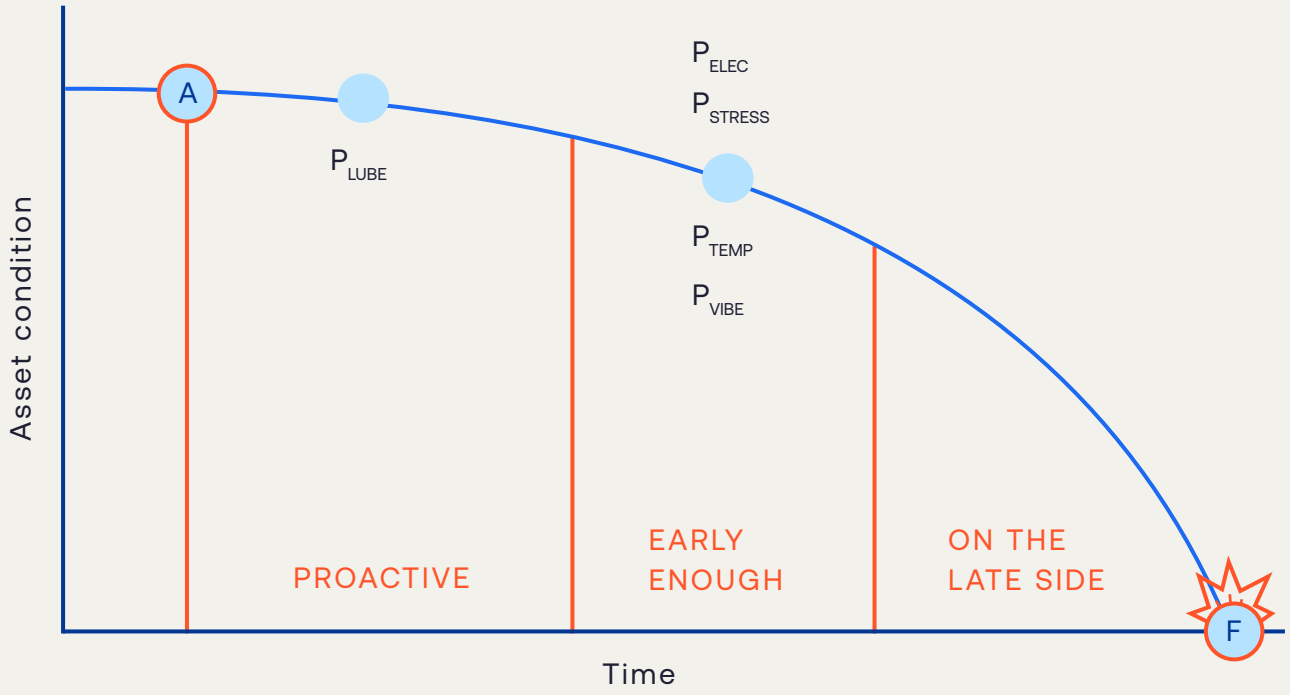

Figure 8. Quick-and-dirty P-F curve for a bearing contaminated by water, showing best-in-class potential performance for each condition monitoring data source. Specific vendors' systems may perform worse than shown here.

Example 2: Stator winding short circuit

A true short circuit will stop the motor at once, so the key to preventing this failure mode is detecting changes in the insulation that shields the windings. Because there are multiple reasons why insulation might degrade, tracking indirect causes can help, too—but only if you act right away.

Heavy vibration can loosen the stator coils and cause them to abrade against the metal housing; vibration sensors placed on the motor will alert you to this root cause. But act fast; once the coils are loose, fixing the excess vibration won't stop further damage.

Because they operate at high frequencies, acoustic sensors won't pick up on the vibrations that loosen stator coils. They may, however, pick up on "coil whine" (electromagnetically induced noise) after the insulation has started breaking down. Ultrasonic sensors are good choices to detect partial and corona discharge.

Overheating from poor ventilation or running the motor above its rated load can cause thermal damage to the insulation; temperature sensors will alert you to this root cause.

In motors connected through a variable frequency drive (VFD), the pulse width modulation required to simulate the desired AC signal can cause currents through the insulation, which will degrade it over time. Electrical sensors can alert you to this root cause. They're also the only data source that can directly track other electrical causes, such as voltage surges and voltage imbalance, as well as the electromagnetic changes caused by degrading insulation itself. And, of course, electrical sensors can test for partial discharge, which is widely considered the most reliable early warning indicator of insulation degradation.

Lubricant is the poorest data source. While lubricant can leak into the stator windings and cause damage, you wouldn't generally install a lubricant sensor here (since there shouldn't be any lube to measure).

Figure 9. This stator has seen better days.

Electrical sensors, vibration sensors whose frequency range includes 120 Hz, and stress wave sensors in the 600-800 Hz frequency range can pick up on short-term voltage unbalance right away. (It's up to you to fix the problem before it has time to degrade the insulation.) Temperature sensors can pick up on overheating from prolonged unbalance, but not if the unbalance comes and goes. Ultrasonic stress wave sensors will pick up on insulation voids (a sign of damage that's already occurred). Lubricant sensors won't pick up on anything at all.

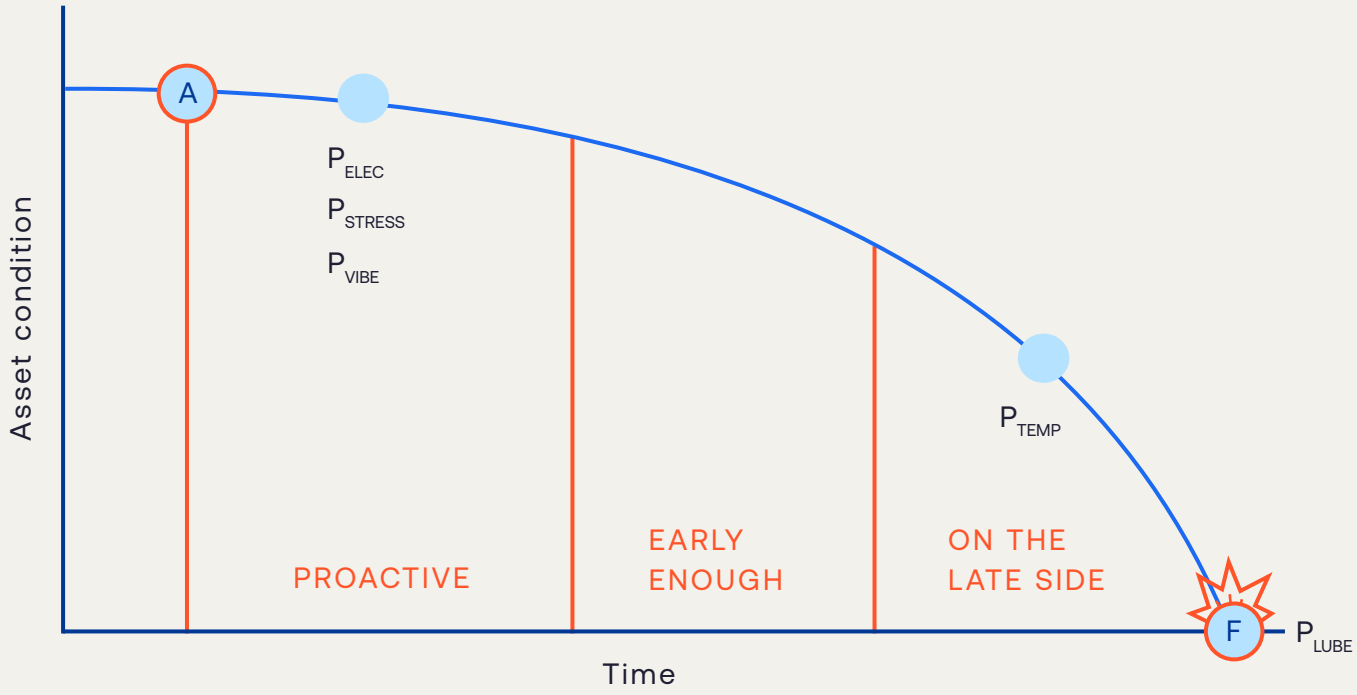

Figure 10. Quick-and-dirty P-F curve for transient voltage unbalance, showing best-in-class potential performance for each condition monitoring data source. Specific vendors' systems may perform worse than shown here.

Example 3: Cavitating pump

Though cavitation is not itself a failure that will stop a pump from working, over time it will lead to erosion damage, seal and bearing wear, and possibly sudden impeller breakage. Prolonged cavitation shortens a pump's lifespan and wastes energy.

Common causes of cavitation include clogged filters and pipe blockage. Cavitation is also a danger when a pump runs too far to the right or left of its performance curve.

Vibration, stress wave and electrical sensors are the top choices to detect cavitation while it's occurring. All three data sources can pick up on the collapsing air bubbles that signal this phenomenon.

Through the affinity laws, electrical data can also be used to track a pump's real-time pressure and flow, to additionally identify real-time operation where cavitation is likely.

Temperature sensors are a poor choice. Though some research has shown that infrared cameras can detect the minimal thermal changes that occur during cavitation, the camera must have a direct line of sight to to the fluid, which is impractical in an industrial production pump.

As for lubricant, this data source can only detect the effects of long-term cavitation on lubricated elements, which by definition is too late to prevent damage.

Figure 11. Holes in impeller blades caused by long-term cavitation.

Electrical, vibration and stress wave sensors can directly detect the shock created by the collapsing bubbles. With a large enough library of real-world data, the system's AI can pinpoint a clogged filter as the cause. Internal MEMS pressure-temperature sensors could theoretically measure heat patterns consistent with cavitation, but the pressure changes are a better indicator; external temperature sensors may detect overheating once there's damage. Lubricant sensors installed in the pump's seal housing will pick up on changes in the oil's conductivity once the seal is damaged.

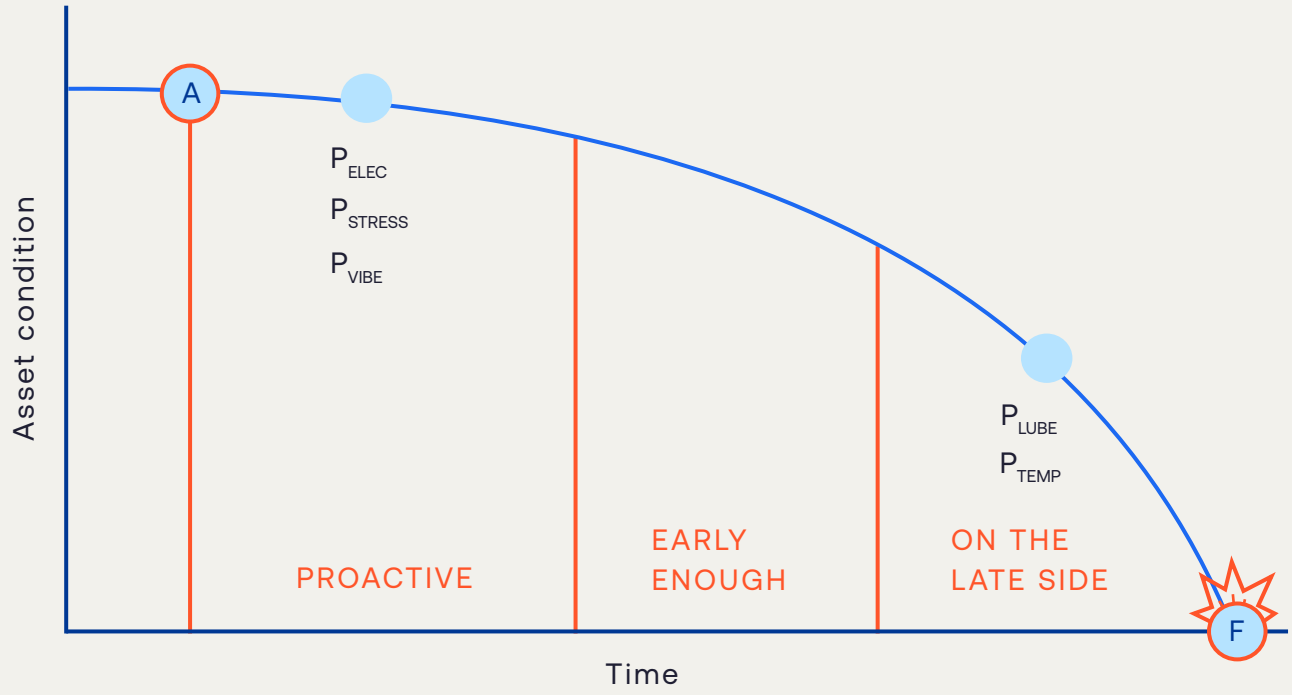

Figure 12. Quick-and-dirty P-F curve for pump cavitation, showing best-in-class potential performance for each condition monitoring data source. Specific vendors' systems may perform worse than shown here.

At a glance

Now it's your turn! Before we go, here's a quick recap of some major pros and cons of each data source, for easy reference.

LEGEND

ELEC - electrical signals
LUBE - lubricant
TEMP -temperature
STRESS - acoustic pressure waves
VIBE - vibration

Localized - downside: multiple sensors must be placed to capture data for the entire drive train (motor, transmission, load). Upside: high information content for every component, no matter where in the drive train.

Non-localized - upside: one set of sensors can capture data for the motor, transmission and load. Downside: the further away from the motor a component is, the less information is available in the signal.

	ELEC	LUBE	TEMP	STRESS	VIBE
Sensor placement	Non-localized	Localized	Localized	Localized	Localized
Pros	ATEX zones, submerged, harsh conditions Energy & performance insights Directly captures load & speed	Bearing & gearbox contamination Bearing currents	Overheating Leaks	Bearing damage Cracks, leaks, breaks, pitting, delamniation, corrosion fatigue	Bearing damage has ISO standards, best practices, vast literature
Cons	AC machines only	Lube is a late indicator for most things	Ambient heat, air currents, reflective surfaces (for IR cameras)	Only actively developing faults; existing not detected	Very slowly rotating machines, low energy applications

Conclusion

There you have it: a brief comparison of the strong and weak points of the major condition monitoring data sources. We hope this guide helps you start choosing the best techniques for your critical machines, and we wish you the best of luck in putting together the perfect condition monitoring toolkit for your systems and applications.

If electrical signature analysis is among your selection, we'd be happy to tell you more about our solution, SAM4. Please contact us to book a no-obligation demo at your convenience.

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