Predictive Maintenance (PdM) Solutions

Real time monitoring of motors and other equipment using new sensor technologies

STLE Toronto Workshop Nov 27, 2019 – Chris Barnes, P.Eng., MBA, Omron Canada Inc.
Agenda

• Why Predictive Maintenance (PdM)?
• What is Predictive Maintenance (PdM)?
• Sensor Technologies for Live Monitoring
  • Vibration Analysis
  • Current Analysis
  • Insulation Resistance Monitoring
  • Thermography
• Analyzing PdM data with Artificial Intelligence (AI)
• Case Studies and Examples
Why predictive maintenance?

Unplanned downtime can be extremely expensive for our economy.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Cost of downtime (per min.)</th>
<th>Cost of downtime (per hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive – Assembly</td>
<td>$15,000</td>
<td>$900,000</td>
</tr>
<tr>
<td>Automotive – Powertrain</td>
<td>$5,000</td>
<td>$300,000</td>
</tr>
<tr>
<td>Semi-conductor</td>
<td>$4,167</td>
<td>$250,020</td>
</tr>
<tr>
<td>Processed Food Production</td>
<td>$312</td>
<td>$18,720</td>
</tr>
<tr>
<td>Bottled Water Production</td>
<td>$50</td>
<td>$3,000</td>
</tr>
</tbody>
</table>

This does not include the cost to repair or replace the issue!
Why Predictive Maintenance (PdM)?

“Unplanned downtime costs industrial manufacturers an estimated $50 billion annually. Equipment failure is the cause of 42 percent of this unplanned downtime.”

*Wall Street Journal*

US Department of Energy’s Federal Energy Management Program found that PdM provided:

- 30-40% savings vs. reactive maintenance
- 8-12% savings vs. preventative maintenance
- Potential to yield a tenfold increase in ROI
- 25-30% reduction in maintenance costs
- 70-75% decrease in breakdowns
- 35-45% reduction in downtime

Source: Predictive Maintenance Explained, ReliablePlant.com
Why Predictive Maintenance (PdM)?

Deloitte study of several facilities revealed:

- 5-10% cost savings in operations and maintenance, repair and operations (MRO) material spend
- 5-10% reduction in overall maintenance costs; and reduced inventory-carrying costs.

“As far as maintenance costs are concerned, preventive maintenance costs $13 hourly pay per annum while predictive maintenance costs $9 hourly pay per annum, making predictive maintenance a cheaper option” (Ulbert, “The Difference Between Predictive Maintenance and Preventive Maintenance”).

Source: Predictive Maintenance Explained, ReliablePlant.com
Predictive Maintenance Value

What if you could prevent costly production downtime by knowing the status of your assets?

What if a component could be added to your infrastructure to help predict the replacement time of assets?

New sensors are bringing practical Industrial Internet of Things (IIoT) to the component level to improve predictive maintenance routines!
What is Predictive Maintenance (PdM)?

• PdM is maintenance that **monitors** the performance and condition of equipment during normal operation to reduce the likelihood of failures.
• Also known as “Condition-Based Maintenance”
• The goal of PdM is:
  ✓ to predict **when** equipment failure could occur
  ✓ followed by preventing the failure by:
    ❏ Regularly scheduled maintenance and/or
    ❏ Corrective maintenance
• PdM requires Condition Monitoring

Source: Predictive Maintenance Explained, ReliablePlant.com
What is Condition Monitoring?

- The continuous monitoring of machines during process conditions to ensure the optimal use of machines.
- The application of monitoring technologies, sensors, statistical process control or equipment performance for early detection and elimination of equipment defects that could lead to unplanned downtime or unnecessary expenditures.
- Condition Monitoring can be:
  - Periodic = regular testing (e.g. monthly)
  - Online = continuous “live” monitoring of machines or production processes

  This **data enables:**
  - Trending (to see patterns and abnormalities/spikes) and recording
  - Remote monitoring
  - Alarm paging to mobile phones for immediate response to prevent downtime
  - Analysis (including by Artificial Intelligence) to find patterns, solutions, root causes...
  - Early detection to prevent downtime and minimize repair costs

Source: Predictive Maintenance Explained, ReliablePlant.com
What is the **Difference** between **Predictive Maintenance** and **Preventive Maintenance**?

- ✓ inspecting and performing maintenance regardless of whether the equipment needs it
- ✓ maintenance schedule based on usage or time (e.g. kilometers or run hours)
- ✓ determined by using the average life cycle of an asset
- ✓ does not need condition monitoring
- ✓ does not involve as much capital investment in technology and training (short term $ savings)
- ✓ manual data-gathering and analysis

- ✓ performed based on preset and predetermined conditions of specific pieces of equipment, utilizing different technologies.
- ✓ requires investments in people, training and equipment to assess and implement a PdM schedule
- ✓ Increases reliability and reduces downtime
- ✓ uses maintenance labour more efficiently (long term $ savings)

Source: Predictive Maintenance Explained, ReliablePlant.com
What is Reliability Centered Maintenance (RCM)?

Wikipedia: “Reliability-centered maintenance (RCM) is a concept of maintenance planning to ensure that systems continue to do what their users require in their present operating context. Successful implementation of RCM will lead to increase in cost effectiveness, reliability, machine uptime, and a greater understanding of the level of risk that the organization is managing.”

RCM offers five principal options among the risk management strategies:

• Predictive maintenance tasks,
• Preventive Restoration or Preventive Replacement maintenance tasks,
• Detective maintenance tasks,
• Run-to-Failure, and
• One-time changes to the "system" (changes to hardware design, to operations, or to other things).

After being created by the commercial aviation industry, RCM was adopted by the U.S. military (in the 1970s) and by the U.S. commercial nuclear power industry (in the 1980s).
Design, Installation, Potential and Functional Failure (D-I-P-F) Curve:
Asset Lifecycle Curve:

Different defect inspection techniques determine the presence of a defect at different places along the P-F curve.

A failure modes, effects and criticality analysis (FMECA) can help you determine which inspection techniques should be applied, how often and with what degree of redundancy.

Sources: Predictive Maintenance Explained, ReliablePlant.com RCM Blitz® training materials 2006. (D. Plucknette, Reliability Solutions Inc.)
Motors are often a **critical single point of failure** for a facility.
Electric Motor Failure Modes that we want to Detect

**Rotor**
The rotor is the part of the motor that rotates

> Rotor break

**Bearing**
Reduces wear on rotating parts
There are two motor bearings

> Bearing failure
> Bearing scratch
> Inadequate lubrication

**Stator**
Generates the force to turn the rotor

> Stator break
> Insulation aging

**Rotary shaft**
Power transmission to Load side

> Motor burn out

> Electrical leakage

---

> Rotor break

---

> Bearing failure
> Bearing scratch
> Inadequate lubrication

---

> Stator break
> Insulation aging

---

> Motor burn out
> Electrical leakage
Condition Monitoring & Predictive Maintenance Technologies

Rapidly evolving as more sensors become real time = “live data”

- Vibration Analysis
- Current Analysis
- Insulation Resistance Monitoring
- Infrared Thermography
- Acoustic Monitoring
- Ultrasonic Inspection
- Oil Analysis (particle counts, chemistry of additives, contaminants, etc).

Using live data, the industrial internet of things (IIoT) is able to create “advanced prediction models and analytical tools to predict failures and address them proactively. Additionally, over time, new machine-learning technology can increase the accuracy of the predictive algorithms, leading to even better performance”

Source: Predictive Maintenance Explained, ReliablePlant.com, Coleman et al., “Predictive Maintenance and the Smart Factory”
The traditional way...

Periodic manual checking of the condition of a 3 phase motor

**Using Human Senses**
- Hear abnormal noise, feel vibration

**Using Hand Held Tools**
- Vibration tester
- Thermo camera
- Mega-ohm tester
## Examples of Common Manual Motor/Pump Checks

<table>
<thead>
<tr>
<th>Check point</th>
<th>How to check</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal Noise</td>
<td>Human Ear</td>
<td>Empirical knowledge&lt;br&gt;Hands-on experience&lt;br&gt;Arbitrary judgment, varies by machine type and motor speed etc.</td>
</tr>
<tr>
<td></td>
<td>Acoustic tester</td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td>Examination by touch</td>
<td>Depends on machine type and motor speed etc.&lt;br&gt;“Examination by touch” is arbitrary and relies on empirical knowledge and experience</td>
</tr>
<tr>
<td></td>
<td>Vibration tester</td>
<td></td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>Mega-ohm tester</td>
<td>Cannot check while motor is running. (Mega-ohm tester should be set for motor after power on and disconnecting all motor wires)</td>
</tr>
<tr>
<td>Over Current</td>
<td>Ammeter</td>
<td>Motor current level might be changed by motor load, as it’s difficult to define motor failure and workload change&lt;br&gt;It might be too late, when detecting over current by motor failure</td>
</tr>
<tr>
<td></td>
<td>M&amp;M Relay (Current relay)</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>Touch</td>
<td>When the motor temperature is too high, that motor might already be in a terminal condition</td>
</tr>
<tr>
<td></td>
<td>Temperature probe</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermo camera</td>
<td></td>
</tr>
</tbody>
</table>
Motor Failure Modes

Inverter or Electromagnetic contactor

- Phase loss
- Reverse phase

Load side (Ex. Blower fan)

- Imbalance
- Overload

3-phase Induction motor

Current Monitoring Sensor

Vibration & Temperature Sensor

For Bearing failure

* The Current Analysis Sensor can detect both Motor failure and abnormal Load side condition, but it cannot tell you which side (motor or load) might be the problem.
## Motor Failure Modes and Measurement Parameters for Motor Condition Monitoring

<table>
<thead>
<tr>
<th>Motor Failure Mode</th>
<th>Event Probability</th>
<th>Abnormal Noise</th>
<th>Vibration</th>
<th>Insulation Resistance</th>
<th>Over Current</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing Wear</td>
<td>32.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation Aging</td>
<td>20.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overload</td>
<td>15.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase-loss</td>
<td>12.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood</td>
<td>7.1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disconnection</td>
<td>6.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outside Impact</td>
<td>5.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- It's hard to detect motor degradation condition caused by "Phase-loss", "Flood", "Disconnection" and "Outside impact". However, when a Motor is almost in a terminal condition caused by these failure factors, it might have abnormal noise and/or vibration, over current etc.

- These 2 measurement parameters often change when a motor is in a terminal condition.
Predictive Maintenance Sensor Types by Motor Failure Modes

- **Failure Mode**
  - Insulation Degradation
  - Bearing Failure
  - Rotary Shaft Condition (Imbalance/Misalignment/Rotor&Stator break)
  - Load Side Condition (Cavitation for Pump/Overload)

- **Installation**
  - Rotary Shaft & Load side condition may damage Motor bearing

- **Motor Running**
  - Dried Grease

- **Motor Degradation**
  - Bearing Wear
  - Vibration Acceleration Sensor
  - Current Analysis Degradation Sensor

- **Motor Failure**
  - Bearing Failure
  - Vibration Velocity Sensor
  - Electric Current Sensor
  - Temperature Sensor

- **Load Side Aging**
  - Load Side Aging
  - Current Analysis Degradation Sensor

- **Outside of Motor Failure**
  - Inside Motor
  - Failure

- **Inside Motor Failure**
  - Current Analysis Degradation Sensor

- **Current Analysis Degradation**
  - Inside Motor Failure

- **Run Side Aging**
  - Running Start

- **Worker can’t sense**
  - Noise, vibration

- **Worker can sense**
  - Noise, vibration
Predictive Maintenance Sensor Types by Motor Failure Modes

- **Insulation Degradation**
  - Installation
  - Motor Running
  - Motor Degradation
  - Motor Failure
  - Insulation Degradation
  - Insulation Breakdown
  - Insulation Resistance Sensor

- **Bearing Failure**
  - Bearing Wear
  - Bearing Failure
  - Vibration Acceleration Sensor
  - Vibration Velocity Sensor
  - Current Analysis Degradation

- **Rotary Shaft Condition**
  - Imbalance
  - Misalignment
  - Rotor & Stator break
  - Current Analysis Degradation Sensor

- **Load Side Condition**
  - Cavitation for Pump/Overload
  - Electric Current Sensor
  - Temperature Sensor
  - Vibration Velocity Sensor

- **Motor System Setting**
  - Running Start
  - Motor Aging

- **Motor Running Start**
  - Running Start
  - Load Side Aging
  - Electric Current Sensor

- **Motor Aging**
  - Current Analysis Degradation Sensor

- **Motor Degradation**
  - Dried Grease
  - Vibration Acceleration Sensor
  - Vibration Velocity Sensor

- **Motor Failure**
  - Bearing Failure
  - Vibration Acceleration Sensor
  - Vibration Velocity Sensor

- **Inside Motor Failure**

- **Outside of Motor Failure**

- **Motor System Setting**

- **Current Analysis Degradation Sensor**

- **Vibration Acceleration Sensor**

- **Vibration Velocity Sensor**

- **Electric Current Sensor**

- **Temperature Sensor**

- **Vibration Velocity Sensor**
# PdM Vibration Sensors for Motor Bearings

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Installation</th>
<th>Motor Running</th>
<th>Motor Degradation</th>
<th>Motor Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing Failure</td>
<td>Dried Grease</td>
<td>Bearing Wear</td>
<td>Bearing Failure</td>
<td></td>
</tr>
</tbody>
</table>

## Motor Vibration Image

- **Amplitude of Vibration**
- **Vibration Wavelength**

## Vibration Wavelength

- **High Frequency** (Over 20 or 30kHz)
- **Middle Frequency** (around 1 to 20kHz)
- **Low Frequency** (Below 1kHz)

## Type of Vibration Sensor and Range

- **Acceleration Sensor**
  - 10kHz
- **Velocity Sensor**
Why do we need 2 vibration sensors (**Acceleration & Velocity**)?

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Installation</th>
<th>Motor Running</th>
<th>Motor Degradation</th>
<th>Motor Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing Failure</td>
<td></td>
<td>Dried Grease</td>
<td>Bearing Wear</td>
<td>Bearing Failure</td>
</tr>
<tr>
<td>Motor Vibration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Wavelength and Amplitude of Vibration are too small to detect**
- **“Acceleration Sensor”**
  - “Acceleration” is like an intensity of velocity change for vibration.
  - (from 1kHz to 10kHz range it is too fast for the velocity sensor to detect).
- **“Velocity Sensor”** can detect vibration speed. (below 1kHz range the velocity change is too small for the acceleration sensor to detect the vibration).
Installation of an On-line Motor Vibration Sensor Head

✓ Drill a hole (M6 x 8mm tap) for the sensor perpendicular to the rotary shaft

✓ If you don’t want to drill a hole on the motor, the sensor head (with the magnetic adaptor attached) should be glued / siliconed in place. Detection of motor temperature and high frequency vibration will be impeded, impairing early stage bearing failure.

3 sensors in one
- Acceleration sensor
- Velocity sensor
- Temperature sensor
### Predictive Maintenance Sensor Types by Motor Failure Modes

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Installation</th>
<th>Motor Running</th>
<th>Motor Degradation</th>
<th>Motor Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation Degradation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearing Failure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary Shaft Condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load Side Condition</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

- **Bearing Failure**: Rotary Shaft & Load side condition may damage Motor bearing
- **Insulation Degradation**: Current Analysis Degradation Sensor, Electric Current Sensor, Temperature Sensor
- **Load Side Condition**: Electric Current Sensor, Temperature Sensor
- **Rotary Shaft Condition**: Electric Current Sensor, Temperature Sensor

**Inside or Motor Failure**
- **Insulation Degradation**: Insulation Resistance Sensor, Electric Current Sensor
- **Bearing Failure**: Vibration Acceleration Sensor, Vibration Velocity Sensor
- **Rotary Shaft Condition**: Vibration Acceleration Sensor, Vibration Velocity Sensor
- **Load Side Condition**: Vibration Acceleration Sensor, Vibration Velocity Sensor

**Outside of Motor Failure**
- **Insulation Degradation**: Insulation Resistance Sensor, Electric Current Sensor
- **Bearing Failure**: Vibration Acceleration Sensor, Vibration Velocity Sensor
- **Rotary Shaft Condition**: Vibration Acceleration Sensor, Vibration Velocity Sensor
- **Load Side Condition**: Vibration Acceleration Sensor, Vibration Velocity Sensor
3 Phase Induction Motor Monitoring Sensors

Visualize a motor’s maintenance requirements

- Degradation level
- Normal rotational axis
- Abnormal rotational axis
- Increased distortion

- Threshold level “Failure critical”
- Threshold level “Failure warning”

- Setup and installation
- Operation
- Degradation progress
- Failure

Time
Basic Principle of **Current Analysis Sensors**

3-phase induction motor (3-wire)

- **current**
- **not connected to the motor**

**N**

**earth**

(1) **Healthy Motor current waveform**
- "PURE" sine current waveform
- Smooth rotation

(2) **Unhealthy Motor current waveform**
- "DISTORTION" with sine current waveform
- Abnormal vibration

Healthy Motor current waveform

Unhealthy Motor current waveform

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INTEGRATED | INTELLIGENT | INTERACTIVE
Predictive Maintenance with **Current Analysis Sensors**

Can detect abnormal motor loads

If the motor and load are abnormal, noise appears in the current waveform as shown below. A value that expresses this state numerically is the degree of degradation that can be monitored with the Comprehensive current diagnosis type.

1. Motor and load are normal. The current is a smooth "sine wave".
2. An abnormality is occurring. "Noise" may come up in the current.

<table>
<thead>
<tr>
<th>Abnormality affecting degradation level</th>
<th>Major factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Misalignment</td>
<td>Coupling abnormal, centering shortage, etc.</td>
</tr>
<tr>
<td>Load imbalance</td>
<td>Unbalance of rotating objects such as fans</td>
</tr>
<tr>
<td>Motor insulation error</td>
<td>Insulation deterioration inside the motor</td>
</tr>
<tr>
<td>Rotor abnormality</td>
<td>Breakage inside the motor</td>
</tr>
<tr>
<td>Cavitation</td>
<td>Vacuum bubbles in water stream</td>
</tr>
<tr>
<td>Overload</td>
<td>Excessive rotational load</td>
</tr>
</tbody>
</table>
Degradation Level = measurement of change in the current waveform

“PURE” sine current waveform (Healthy Motor)

“DISTORTION” with sine current waveform (Unhealthy Motor)

Current Analysis can measure (digitally quantify) the current waveform gap between “PURE” and “DISTORTION” = “Degradation Level”
“Degradation Level” is from waveform shape
“Ampere” is amplitude

“Degradation Level”
Calculated by an algorithm comparing “PURE sine current waveform” and “K6CM measuring sine current waveform”

“Current Ampere”
Measure current wave amplitude
Example: Water Pump failure by “Cavitation”

“Degradation Level” increased from “13” to “41” due to “Cavitation” (like a load side failure), however current wave amplitude is not changed. (almost same “Current Ampere”)

![Graph showing normal and cavitation conditions](image)
Set-up: Choose Current Transformer (CT) and install

- Choose Current Transformer (CT) and install

2 types of input voltage
- 100-240VAC
- 24VAC/DC

You can clamp CT for any 1 wire of motor cable

* Clamp type CT
  Permissible attachment/removal frequency: up to 100 times
How to calculate “Motor Ampere” to choose CT size

Motor Ampere (A) = \[
\frac{\sqrt{3} \times \text{Motor Voltage (V)} \times \text{Power Factor (0.9)} \times \text{Efficiency (0.8)} \times \text{Motor Power (kW)} \times 1,000}{1,000}
\]

<table>
<thead>
<tr>
<th>CT Model</th>
<th>CT Tolerance</th>
<th>Recommendation Motor (AC200V)</th>
<th>Recommendation Motor (AC400V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K6CM-CICB005 5A</td>
<td>from 1.00A to 5.25A</td>
<td>0.75kW</td>
<td>from 1.5kW to 2.2kW</td>
</tr>
<tr>
<td>K6CM-CICB025 25A</td>
<td>from 5.00A to 26.25A</td>
<td>from 1.5kW to 5.5kW</td>
<td>from 3.7kW to 11kW</td>
</tr>
<tr>
<td>K6CM-CICB100 100A</td>
<td>from 20A to 105A</td>
<td>from 7.5kW to 22kW</td>
<td>from 15kW to 45kW</td>
</tr>
<tr>
<td>K6CM-CICB200 200A</td>
<td>from 40A to 210A</td>
<td>from 30kW to 45kW</td>
<td>from 55kW to 90kW</td>
</tr>
<tr>
<td>K6CM-CICB400 400A</td>
<td>from 80A to 420A</td>
<td>from 55kW to 90kW</td>
<td>from 110kW to 200kW</td>
</tr>
<tr>
<td>K6CM-CICB600 600A</td>
<td>from 120A to 630A</td>
<td>from 110kW to 150kW</td>
<td>from 250kW to 300kW</td>
</tr>
</tbody>
</table>

Motor current might be almost half of calculated ampere without motor load. Hence “CT” should be detected from 50% through 100% of calculated motor ampere.
### Reference: CT selection table for AC200V motor

<table>
<thead>
<tr>
<th>Motor Power &amp; Motor Current</th>
<th>CT Model &amp; CT Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75kW (2.0~3.0A)</td>
<td>K6CM-CICB005 1~5A</td>
</tr>
<tr>
<td>2.2kW (5.8~8.8A)</td>
<td>K6CM-CICB025 5~25A</td>
</tr>
<tr>
<td>3.7kW (9.8~14.8A)</td>
<td>K6CM-CICB100 20~100A</td>
</tr>
<tr>
<td>5.5kW (14.6~22.1A)</td>
<td>K6CM-CICB200 40~200A</td>
</tr>
<tr>
<td>7.5kW (20~30A)</td>
<td>K6CM-CICB400 80~400A</td>
</tr>
<tr>
<td>11kW (29~44A)</td>
<td>K6CM-CICB600 120~600A</td>
</tr>
<tr>
<td>15kW (40~60A)</td>
<td></td>
</tr>
<tr>
<td>18.5kW (49~74A)</td>
<td></td>
</tr>
<tr>
<td>22kW (58~88A)</td>
<td></td>
</tr>
<tr>
<td>30kW (79~120A)</td>
<td></td>
</tr>
<tr>
<td>37kW (98~148A)</td>
<td></td>
</tr>
<tr>
<td>45kW (119~180A)</td>
<td></td>
</tr>
<tr>
<td>55kW (145~220A)</td>
<td></td>
</tr>
<tr>
<td>75kW (199~301A)</td>
<td></td>
</tr>
<tr>
<td>90kW (238~361A)</td>
<td></td>
</tr>
<tr>
<td>110kW (291~441A)</td>
<td></td>
</tr>
<tr>
<td>132kW (349~529A)</td>
<td></td>
</tr>
</tbody>
</table>
Reference: CT selection table for AC400V motor

Motor Power & Motor Current

CT Model & CT Tolerance

K6CM-CICB005 1~5A
1.5kW (2.0~3.0A)

K6CM-CICB025 5~25A
2.2kW (2.9~4.4A)
3.7kW (4.9~7.4A)

K6CM-CICB100 20~100A
5.5kW (7.3~11A)
7.5kW (10~15A)
11kW (15~22A)

K6CM-CICB200 40~200A
15kW (20~30A)
18.5kW (25~37A)
22kW (29~44A)
30kW (40~60A)
37kW (49~74A)

K6CM-CICB400 80~400A
45kW (60~90A)
55kW (73~110A)
75kW (99~150A)
90kW (110~180A)

K6CM-CICB600 120~600A
110kW (146~221A)
132kW (175~265A)
150kW (198~300A)
200kW (265~401A)
250kW (331~501A)
300kW (397~601A)
Problems are detected by the “Degradation Level” when the "Motor" and/or the "Load" have these failure factors:

<table>
<thead>
<tr>
<th>“Degradation Level” influence factor</th>
<th>Failure factor examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing failure</td>
<td>Abnormal Bearing</td>
</tr>
<tr>
<td>Rotor break</td>
<td>Motor inside broken</td>
</tr>
<tr>
<td>Misalignment</td>
<td>Motor coupling failure (misalignment/maladjustment)</td>
</tr>
<tr>
<td>Load Imbalance</td>
<td>Load Imbalance like a Fan motor</td>
</tr>
<tr>
<td>Motor Insulation failure</td>
<td>Motor Insulation aging</td>
</tr>
<tr>
<td>Cavitation</td>
<td>Water flow vacuum bubble (for water pump)</td>
</tr>
<tr>
<td>Overload</td>
<td>Excess rotational load</td>
</tr>
</tbody>
</table>

The value might go over 100 depending on the Motor or Load failure condition.

Current Analysis “Degradation Level” without Invertor

* “Degradation Level” might still be a high number for a healthy motor, depending on the motor. Trend and baseline, and adjust the “Threshold” for each motor system with Invertor.
Predictive Maintenance Sensor Types by Motor Failure Modes

- **Installation**
  - Insulation Degradation
  - Bearing Failure
  - Rotary Shaft Condition
    - (Imbalance/Misalignment/Rotor & Stator break)
  - Load Side Condition
    - (Cavitation for Pump/Overload)

- **Motor Running**
  - Dried Grease
  - Motor System Setting
  - Running Start
  - Load Side Aging

- **Motor Degradation**
  - Bearing Wear
  - Motor Aging
  - Running Start
  - Load Side Aging

- **Motor Failure**
  - Insulation Degradation
  - Insulation Breakdown
  - Bearing Failure
  - Vibration Acceleration Sensor
  - Vibration Velocity Sensor
  - Current Analysis Degradation
  - Electric Current Sensor
  - Temperature Sensor

Rotary Shaft & Load side condition may damage Motor bearing.

Load Side Aging

Current Analysis Degradation Sensor

Electric Current Sensor

Vibration Velocity Sensor
The insulation resistance is the resistance in ohms of wires, cables and electrical equipment. It is important to guard against electric shocks and avoid equipment damage from accidental discharges.

You can clamp ZCT for all 3 wires of motor cable. Up to 7.5kW motor.

2 types of input voltage:
- 100-240VAC
- 24VAC/DC

Insulation Resistance Sensors (actually measuring current leakage)
3 phase connections for installation of Insulation Resistance Sensors

Insulation resistance sensors can be installed in Delta or Star connection configurations:

3 phase 3 wires S-grounding
(with/without Inverter)

3 phase 4 wires N-grounding
(without Inverter)
Infrared Thermography - Thermal Monitoring Sensors for PdM

Importance of the temperature monitoring

Device failures have various causes; most of which lead to insulator breakage due to overheating, resulting in an abnormal stop.

- Overload
- Over current
- Vibration and shock
- Loosening of screw
- Ambiance temperature
- Damage
- Moisture absorption and corrosion
- Surge

Overheating
- Temperature

Thermal degradation
- Temperature

Insulation breakdown

Abnormal stop

Tracking
- Temperature

Insulation deterioration

Most of the abnormal modes show symptoms in the temperature deviation.
Thermal Monitoring Sensors

Remotely monitor and analyze thermal condition of equipment

- Prevent panel fires from overheating components
- Offer a product with thermal imaging technology
- Reduce manual inspections
- 24/7 thermal condition monitoring of critical components
- Measure specific point temperatures in panel vs. ambient temperature
- Reduced manual inspections
- Enable Predictive Maintenance
- Live DATA for trending/alarming/AI
- Reduce downtime
Critical heat generation areas in panels to monitor

- Invertor Overload
- Damage to line filter
- Transformer heat generation
- Loose Connections
- High voltage contactors
- Solid State Relays
- Insulation breakdown

Variable Frequency Drives
### Common methods of measuring panel temperature

<table>
<thead>
<tr>
<th>Method</th>
<th>Pro</th>
<th>Con</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodic manual inspections using temperature gun or thermal imager</td>
<td>Simple to perform. Cost effective</td>
<td>No continuous monitoring, method only monitors temperature at time of inspection. Limited maintenance staff available for inspection. Few data points No live trending, alarming</td>
<td>Hiring a contractor to inspect panel = $2500+ annually</td>
</tr>
<tr>
<td>Smoke detector</td>
<td>Cost effective, simple to install</td>
<td>Unable to predict thermal events. Damage has already been done once smoke has been detected</td>
<td>$50-$100 + labor</td>
</tr>
<tr>
<td>Thermo-couple</td>
<td>Cost effective, can use to monitor panel temperature continuously</td>
<td>Can only measure ambient vs. specific component temperature. Requires additional programming and setup time.</td>
<td>$110-$400 + labor</td>
</tr>
</tbody>
</table>
Live On-Line Thermal Monitoring Sensors for PdM

- Infrared (IR) Thermal imaging camera
- Detects temperatures from 32°-392°F (0-200°C)
- Built-in abnormal detection algorithms
  - Predict overheating based on rate of rise in temperature
- 90 degree viewing angle
- Digital display with 3 alarm level
- Magnetic back for easy panel mounting
- RS-485 connection
- Ethernet IP/Modbus Connectivity
- Push-in Plus Terminals for wiring
- 31 cameras/sensors per controller
- Free PC monitoring software included

K6PM-THS3232
IR Sensor

K6PM-THMD-EIP
Controller
Infrared (IR) Thermal Monitoring Sensor + Display

**Condition bar**
- Normal
- Caution
- Warning

**Input voltage** (24VDC)
- Trigger input

**Measured temperature** (°C/°F)

**CH No.** (1~31)

**Sensor communication**

**EtherNet/IP**

**MODBUS TCP**

**Display selection switch**

**Alarm output × 3**

**SEG No.** (1~16)

**OMRON** INTEGRATED | INTELLIGENT | INTERACTIVE
Infrared (IR) Thermal Sensors

- Distance to measurement object:
  - 100mm
  - 200mm
  - 400mm

- Cell size:
  - 400mm/32cell = 12.5mm/cell
  - 200mm/32cell = 6.25mm/cell

- Built-in ambient temperature sensor

- Vertical Mount

- Horizontal Mount

- Aftermarket mount

- RS485

- 31 sensors
Patented Abnormality Detection Algorithms for Thermography

**Differential Temperature**
Allows accurate thermal monitoring in environments that have frequent changes in ambient temperature. Uses IR, ambient temp sensor and thermal sensor to calculate warning level.

**Temperature Prediction**
Monitors temperature trends and can predict a warning level before it reaches the threshold. Notifies the user by sending an early alarm.
Patented Thermography Abnormality Detection Algorithms

- **Automatic Threshold Setting**

  A built in feature that automatically calculates the caution and warning levels based on a maximum ambient temperature. Helps reduce setup time.

  This feature will set the caution threshold when approaching 10%, and a warning threshold when approaching 50%.
Examples of Thermal Sensors installed in Panels for Live Monitoring
Examples of Thermal Sensors installed in Panels for Live Monitoring
Applications for On-line Thermography Sensors

High voltage motor applications + High voltage switchgear panels

Refiners, large extruders, mills, crushers, air separation plants, blast-furnace blowers, gas compressor stations and gas liquefaction, generator plants.
Live Data can be Collected, Monitored, Trended, Shared (Industrial Internet of Things – IIoT) Analyzed (including by Artificial Intelligence), Used for Alarm Paging, Reporting (pharma, data centres)
PdM Sensor Monitoring Example

“Conveyor M-2” motor has failed!

“Water Pump” is operating in “Normal” condition

Local alarm display at motor draws attention and identifies which one to avoid errors!

Maintenance is needed for “Stamping-2” Motor

“Motor No.9” may be in normal condition but a communication error has occurred
Alarm Event History Example for 3 PdM Sensor Types

- Vibration Sensor
  - Velocity
  - Acceleration
  - Motor Temperature
  - Delta T vs. ambient

- Insulation Resistance Sensor

- Current Analysis Sensor

Sensor Types:
- Conveyor M-1
- Lift A
- Lift B
- Conveyor M-2
- Water Pump
- Air Blow
- Stamping-1
- Stamping-2
- Motor No.9
- Motor No.10

Sensor Parameters:
- Velocity
- Acceleration
- Motor Temp.
- Temp. Gap
- Ins. Resistance
- Degradation
- Current

Timeline:
- 1 hour
- 1 day
- 1 month
- 3 months
- 6 months
- 1 year
- 2 years
- 5 years
- 10 years
- 20 years
Example: Data Trending Graph for Vibration (Velocity + Acceleration)
What is an “Edge” device?

Within the Machine or Production Line, without any separate Windows® PC or remote server (Cloud) or Internet

<table>
<thead>
<tr>
<th>Computing</th>
<th>Collect</th>
<th>Analyze</th>
<th>Utilize</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Data Collection → Processing</td>
<td>Storing → Modeling</td>
<td>Real-time Monitor → Control FB ✔ -</td>
</tr>
<tr>
<td>Cloud</td>
<td>✔ -</td>
<td>✔ +</td>
<td>Long-term Monitor → Visualize ✔ +</td>
</tr>
<tr>
<td>Fog</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Edge</td>
<td>✔ +</td>
<td>✔ -</td>
<td>Real-time Monitor → Control FB ✔ +</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Long-term Monitor → Visualize ✔ -</td>
</tr>
</tbody>
</table>
What does an “Edge” Artificial Intelligence “AI” Controller do?

Detects outliers (failures, defectives) by learning from historical data in the machine

1) Issue definition

Based on failure impact and feasibility study of AI Controller utilization, define issue

2) Cause identification

Based on Cause and Effect Diagrams, identify cause of machine defect

3) Prepare sensors

Based on the cause, add necessary sensors to machine

AI Controller fully covers the data collection, analysis, and utilization.
Omron also offers startup support for the entire process.

4) Collect

Collect the raw sensor and machine data

Eliminate noise, create and collect the features of normal/abnormal state

5) Analyze

Store the characteristics data

Create model data after causal analysis

6) Utilize

Status monitoring and control function block based on model data

Human

Machine
AI Machine Learning for Anomaly Detection

Anomaly Detection

Learn without being explicitly programmed
### AI Application Components

Pre-made Controller Programming Function Blocks (FB) for...

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Failure Type</th>
<th>Machine event (failure causes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Cylinder</td>
<td>Operation stop</td>
<td>Rubber Gasket broken (Rod/Piston)</td>
</tr>
<tr>
<td></td>
<td>Over speed</td>
<td>Speed Controller broken</td>
</tr>
<tr>
<td></td>
<td>Over vibration</td>
<td>Air Cushion broken</td>
</tr>
<tr>
<td></td>
<td>Operation stop</td>
<td>Contamination</td>
</tr>
<tr>
<td>Ball Screw</td>
<td>Operation stop</td>
<td>Guide broken</td>
</tr>
<tr>
<td></td>
<td>Operation stop</td>
<td>Ball Bearings falling out</td>
</tr>
<tr>
<td></td>
<td>Operation stop</td>
<td>Contamination</td>
</tr>
<tr>
<td>Conveyor Belt or Pulley</td>
<td>Vibration and low accuracy</td>
<td>Contamination</td>
</tr>
<tr>
<td></td>
<td>Operation stop</td>
<td>Belt loosen</td>
</tr>
<tr>
<td></td>
<td>Operation stop</td>
<td>Belt broken</td>
</tr>
<tr>
<td></td>
<td>Operation stop</td>
<td>Pulley broken</td>
</tr>
</tbody>
</table>
Value of an “edge” AI Controller

Helps improve OEE at the machine level by increasing uptime

<table>
<thead>
<tr>
<th>Uptime</th>
<th>Downtime</th>
<th>Loss types</th>
<th>Improved by AI Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating time</td>
<td></td>
<td>1: Equipment failure</td>
<td>1: ✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2: Changeover</td>
<td>2:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3: Part replacement</td>
<td>3: ✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4: Waiting for material</td>
<td>4:</td>
</tr>
<tr>
<td>Net operating</td>
<td>Performance Loss</td>
<td>5: Minor stoppage/idle</td>
<td>5: ✓</td>
</tr>
<tr>
<td>time</td>
<td></td>
<td>6: Deceleration/slowing</td>
<td>6:</td>
</tr>
<tr>
<td>Value operating</td>
<td>Defect Loss</td>
<td>7: Defect/modification</td>
<td>7: ✓</td>
</tr>
<tr>
<td>time</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

OEE
Overall Equipment Effectiveness

= Availability

x Performance

x Quality

OEE
Overall Equipment Effectiveness

= Availability

x Performance

x Quality
Preventing Sudden Stops, Downtime, and Production Defects

**Customer**
- **Application**
  - Textile/Chemical industry
  - Liquid pump
  - Monitor “Bubble” (Cavitation /Air lock) in Pump system
  - Cavitation damages impeller & pump and “defective product” has bits of metal from impeller

**Food & Beverage industry**
- **Application**
  - Homogenizer
  - Rubber Gasket (consumable parts) condition monitoring
  - Failure of rubber gasket produces “defective product”

**Customer**
- **Demand**
  - K6CM-CIM Monitor “Bubble” (Cavitation /Air lock) in Pump system

**Homogenizer**
- Damaged impeller by cavitation
- Pump

**K6CM-CIM**
- Damage
- Rubber Gasket (consumable parts)
Detecting “Air Lock” and “Cavitation” in Water Pumps

**Situation**
A “Bubble” gets into the Pump system. “Air Lock” means “Air Bubble” in the Pump, and “Cavitation” occurs when there is a “Vacuum Bubble” in the Pump system. “Bubbles” in the Pump system decrease water pressure and damage the Pump Piston or Screw.

**Example of Air Lock**
(1) Air Bubble inside
(2) Compressed Air Bubble
(3) Impact due to swelling Air Bubble
Detecting Pump “Air Lock” with Current Analysis Sensors

**Bottle Washing Machine**
3 phase AC200V /11kW motor with Inverter
Water pressure 10MPa Pump system

**Test result**
Normal mode : K6CM-CIM “Degradation Level” 20.4 (average)
   “Current Level” 36.7A (average)
Water Pressure : 10MPa

Air Lock mode : K6CM-CIM “Degradation Level” 74.7 (average)
   “Current Level” 22.3A (average)
Water Pressure : 4MPa
* Pump system has abnormal noise and vibration
Comparison of Motor Current Waveforms

**Normal Mode**
K6CM-CIM “Degradation Level” 20.4 (average)
“Current Level” 36.7A (average)

**Air Lock Mode**
K6CM-CIM “Degradation Level” 74.7 (average)
“Current Level” 22.3A (average)

* Exact Degradation Level value differs by application. This is one example.*
Homogenizers and Whirring Machines are commonly used in the Food & Beverage industry and the Pharmaceutical industry.

Many OEMs produce these machines, whose main purpose is mixing and/or homogenizing material for food and medicine.

When Homogenizers and Whirring machines stop due to motor and/or consumable parts failures, production plants have to scrap material and product and it takes a few hours of downtime to replace the motor.
Current Analysis Sensor on a Homogenizer

- **Homogenization Unit**
- **Pulley**
- **Vee belt**
- **Material Liquid IN**
- **Material Liquid OUT**
- **Motor**
- **K6CM-CICB Sensor**
- **Controller**
- **Piston Pump**
  - **Slide**
  - **Metal Piston**
  - **Rubber Gasket (consumable parts)**
  - **Metal Cylinder**
Homogenizer – Early Detection of Degradation with a PdM Sensor

Current Analysis Sensors can detect the gasket condition inside the Homogenizer

*Exact Degradation Level depends on application. This is one example.*
Predictive Maintenance Case Studies – IR Temperature Sensors

Panasonic (Facility management div.)
- Distribution board on production line equipment in service 24/7 for 30+ years
- Wiring overloaded and wire temperature exceeded 60°C
- 100 similar boards, but difficult to repair due to 24 hour operation
- Solution = temperature monitoring

Taiyo Nissan Engineering (Production Technology Div.)
- Power board on panel of OEM equipment
- Abnormal power system overload
- Quick and easy retrofit to predictive maintenance by using magnetic thermography sensors
- Provides IoT implementation for OEM's equipment
Predictive Maintenance Case Studies – IR Temperature Sensors

**LION** (Facility management div.)
- Electrical fire on 30+ year old control panel
- Loose contactor terminal wires
- Abnormal terminal screw loosening due to low frequency vibration
- Need to protect panels against a repeat

**Electrical Security Association**
- High voltage panels
- Streamline building maintenance by using IoT PdM sensors for insulation and temperature monitoring
- Abnormal temperature abnormality in general
Predictive Maintenance Case Studies – IR Temperature Sensors

**Nissan**

- Monitoring temperature of hydraulic valve
- Clogging due to abnormal deterioration
- Live thermography sensors replaced reading manually with a hand held device
- Now able to trend and graph data

**Bridgestone**

- Control board for a critical conveyor that collects from 8 conveyors from 250 vulcanizers and transports them to the next process
- Frequent sudden temperature-induced stoppage occurs and causes a production bottleneck.
- Preventative maintenance inspections are too late to catch the issue due to the lack of humanpower / maintenance workers.
Predictive Maintenance Sensor Application Examples

Detecting water pump cavitation
- Buildings
- Water and wastewater treatment
- Food and beverage

Remote pump monitoring
- Water and wastewater treatment
- Food and beverage

Motor monitoring in Food Processing
- Scraped surface heat exchangers (crystallization process)
- Baking ovens

Detecting fan issues on HVAC equipment
- Buildings, hospitals, manufacturing plants
Reference: Set-up for 3 Motor Condition Monitoring Sensors

AC200-480V 3-phase induction motor

Vibration/Temp. Sensor head

Pre Amplifier

Data Storage

Setting & Simple monitoring Software

EtherNet/IP

AC100-240V or DC24V

ZCT

Insulation resistance (Electrical leakage)

Current Analysis

Alarm output (x3)

In control panel

PLC
<table>
<thead>
<tr>
<th></th>
<th>+</th>
<th>Skills</th>
<th>+</th>
<th>Incentives</th>
<th>+</th>
<th>Resources</th>
<th>+</th>
<th>Action Plan</th>
<th>=</th>
<th>Confusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vision</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Anxiety</td>
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<tr>
<td>Vision</td>
<td>+</td>
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<td>Resistance</td>
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<td>Vision</td>
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<td>Skills</td>
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<td></td>
<td>+</td>
<td>Frustration</td>
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<tr>
<td>Vision</td>
<td>+</td>
<td>Skills</td>
<td>+</td>
<td>Incentives</td>
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<td></td>
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<td></td>
<td>+</td>
<td>False Starts</td>
</tr>
<tr>
<td>Vision</td>
<td>+</td>
<td>Skills</td>
<td>+</td>
<td>Incentives</td>
<td>+</td>
<td>Resources</td>
<td></td>
<td></td>
<td>+</td>
<td>Change</td>
</tr>
</tbody>
</table>

Source: David Naylor adapted from Knoster, Villa & Thousand’s A framework for thinking about systems change.
Thank You!

Questions?