Abstract: This paper presents a unique technology for early warning of pending failures of industrial equipment. The technology is used to increase productivity and energy efficiency by preventing unexpected downtime and faulty operation of equipment. The technology uses model based fault detection and diagnosis approach using system identification and spectral analysis techniques. Implementation and case studies for iron and steel as well as glass manufacturing industries are presented.

Introduction

Plant Managers are under greater pressure than ever to get the most out of their assets. As this pressure has translated into increasing goals for Asset Effectiveness, condition monitoring has proved a powerful tool in the pursuit of improved availability, production rate, and quality. The primary function of condition monitoring is to provide advance warning of faults, so that breakdowns can be avoided, and maintenance interventions can be carried out less frequently without increased risk. It also allows asset life to be extended, while reducing total cost of ownership by driving down maintenance costs.

Now the focus has shifted towards the need to improve Asset Efficiency, both to hold down energy costs and to minimize carbon footprints. In addition to replacing older equipment with new energy-efficient assets, companies are increasingly looking to monitor and manage the performance of the entire asset base. Condition monitoring systems now have an increasingly critical role to play in this area, in addition to their traditional fault-diagnosis function.
Many users are aware of the connection between deteriorating condition and reduced efficiency. Excessive misalignment, voltage imbalance or mechanical unbalance can have serious impact, as can heating caused by bearing or electrical problems [1,2] as indicated below:

**LOOSE FOUNDATION/COMPONENTS**: Misalignment, physical looseness and imbalance not only adversely affect a motor’s performance and longevity but also its efficiency.

**UNBALANCE/ MISALIGNMENT /COUPLING /BEARING**: Correct shaft alignment ensures the smooth, efficient transmission of power from the motor to the driven equipment.

**BELT/ BLADE / TRANSMISSION ELEMENTS/ DRIVEN EQUIPMENT**: Efficiency is dependent on pulley size, driven torque, under or over belting, and V belt design and construction. Efficiency deteriorates by as much as 5% over time if slippage occurs.

**BEARING**: The presence of bearing defects often results in reduced efficiency, or even severe damage, of the motor.

**STATOR, ROTOR, INTERNAL ELECTRICAL FAULTS**: Heating and increased resistance due to stator, rotor and other electrical faults cause deteriorating conditions and reduced efficiency.

**ELECTRICAL VALUES/EXTERNAL ELECTRICAL FAULT**: Voltage unbalance, over- and under-voltage, low power factor, undersized conductors, leakage to ground, and poor connections-can account for up to 4% of total plant energy consumption.

**TOTAL HARMONIC DISTORTION**: Total Harmonic Distortion causes additional losses on windings and magnetic circuit and increases hysteresis (magnetization) losses in steel and iron cores of transformers, motor and magnetic trip units of circuit breaker.

The ability to proactively manage such problems allows condition monitoring to have a direct impact on operating efficiency. Getting the most out of your assets involves parallel improvements in both efficiency and effectiveness. According to the US Department of Energy [3] “Well-executed operations and maintenance (O&M) programs promote energy efficiency and lifecycle performance, which can save Federal agencies 5% to 20% on annual energy bills without significant capital investments. In addition, successful O&M programs can increase safety while improving comfort and health”.

In order to keep costs down, predictive maintenance implemented through condition monitoring becomes more essential than ever. The approach presented in this paper is specifically designed to bring the benefits of predictive maintenance to as many organizations as possible, including many that may have found traditional approaches too complicated or expensive in the past. Its ability to provide information about energy management allows users to benefit from this functionality without having to make major investments in additional equipment.

**Model Based Fault Detection and Diagnosis**

Although the benefits of predictive maintenance are widely accepted, the proportion of companies taking full advantage of the approach remains relatively small. For many potential users, the complexity and cost of traditional condition monitoring systems remains a significant obstacle. The approach presented here provides a simple, inexpensive, easy to install solution,
and provides flexible links to existing systems. It also avoids putting a heavy setup and analysis burden on busy maintenance staff.

The ‘model-based fault detection’ approach used is not only innovative, but unique in its field. The advanced algorithms used in this technology were originally developed under a NASA contract [4, 5, 6, 7] and are the subject of careful patent protection. Developing this mathematical process into a practical tool required a considerable development effort, which included tests on several million electric motors to ensure the accuracy and repeatability of the diagnostics.

The approach [8, 9] develops mathematical models of the equipment being monitored. It uses measurements of voltage and current signals only, allowing it to be installed in the motor control cabinet without long cable runs. Once installed, it automatically initiates a self-learning phase during which it builds up a reference mathematical model. This model includes information about all electrical and mechanical characteristics of the motor and its driven system. This requires no input from the operator at all, and covers all operating states experienced during training, such a different speeds and loads.

When the reference model is complete, the approach switches to a monitoring mode in which a new model of the system is created every ninety seconds. This new model is then compared statistically with the reference model, and potential faults are identified and characterized. Both the observed changes in the parameters as well as the spectral analysis of the difference between model estimate of the output and the actual output are used simultaneously to detect and diagnose faults.

The approach is then able to assess the severity of the problem and produce a series of local indications to suggest what action should be taken. Diagnostic information is also sent to a connected computer where detailed information is presented to the maintenance group – including the specific fault, the recommended action, and an estimate of time to failure. Electrical and mechanical problems are diagnosed, including common faults like insulation breakdown, damaged rotor bars, imbalance, and bearing defects.

This approach monitors and compares 22 different model parameters, which represent a wide range of electrical, mechanical, and operational faults. In addition to recognizing problems with the electrical supply, internal electrical problems like insulation breakdown are monitored. Mechanical faults identified by the system include foundation and coupling looseness, imbalance and misalignment, and bearing deterioration. Operational problems leading to changes in load or electrical characteristics are also recognized. The model-based approach has proved very sensitive to early-stage faults, but is not vulnerable to false alerts.

In addition to its diagnostic capabilities, it also provides the user with a wide range of electrical parameters. These include active and reactive power, allowing the system to be used for energy consumption assessments. Parameters like total harmonic distortion, supply harmonic content, and voltage imbalance also provide a valuable power quality analysis capability.
The above mentioned model based approach is used to develop products for instant condition assessment of equipment, Asset Management Toolbox (AMT), and for continuous monitoring of equipment, AnomAlert. The case studies resulting from the use of these systems in Metallurgical industry are presented in the following sections.

**Instant Condition Assessment**

AMT Toolkit is a portable motor driven equipment test system which automatically generates a condition assessment report indicating existing faults (both electrical and mechanical), time to failure information, recommended corrective actions, and effects of faults on energy efficiency. This unique instrument is capable of monitoring three phase AC motors and generators (as well as driven equipment) of all sizes and power levels to provide clear, unambiguous indications when the performance of a motor driven equipment begins to degrade. The toolkit uses three current sensors and three voltage sensors, making the system straightforward to install, and use without in-depth training of personnel. The test duration is approximately one hour allowing 5-7 tests to be performed in a day. Report is issued immediately at the end of the test.

The first case includes equipment tested at a chrome compounds manufacturing facility. Five equipment were monitored with AMT toolkit system in the plant. Condition of the monitored equipment list is given below:

- Number of equipment that are working as expected: 0
- Number of equipment that need maintenance in 3 months: 2
- Number of equipment that need maintenance in 6 months: 3

Monitored equipment, suggestions for the required maintenance, and maximum amount of energy saving by fixing the faults is given on the table below:

<table>
<thead>
<tr>
<th>EQUIPMENT NAME</th>
<th>CONDITION/EXPLANATION</th>
<th>TIME</th>
<th>MAXIMUM AMOUNT OF ENERGY SAVING BY FIXING THE FAULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mill Motor</td>
<td>Maintenance should be planned for isolation problem</td>
<td>In 6 months</td>
<td>$16,100</td>
</tr>
<tr>
<td>Rotary Kiln Main Drive 2</td>
<td>Maintenance should be planned for mechanical looseness and reduction gear problems</td>
<td>In 6 months</td>
<td>$1,900</td>
</tr>
<tr>
<td>Rotary Kiln Main Drive 1</td>
<td>Maintenance should be planned for mechanical looseness and reduction gear problems</td>
<td>In 6 months</td>
<td>$2,800</td>
</tr>
<tr>
<td>Rotary Kiln Fan 1</td>
<td>Maintenance should be planned for unbalance, misalignment, rotor eccentricity, and stator faults</td>
<td>In 3 months</td>
<td>$1,600</td>
</tr>
</tbody>
</table>
Rotary Kiln Fan 2

Maintenance should be planned for unbalance, misalignment, rotor eccentricity, and stator faults in 3 months $6,800

Operating equipment with electrical and mechanical faults causes decrease in energy efficiency and production loss due to unexpected downtime. It is estimated that this plant can save tens of thousands of dollars preventing unexpected downtime and eliminate indirect costs due to downtime. There is a potential saving of $29,200 in the plant if the existing faults detected by AMT Toolkit are corrected.

Rotary Kiln Fan 2 motor should be replaced with efficient motor. Return on investment is calculated as 1.1 years for this motor.

In general, equipment efficiency is not constant and it can vary depending on operation conditions. Online condition monitoring helps increasing persistency in equipment efficiency by monitoring equipment status and correcting the faults at early stage. The cost of such project is $19,000 and return on investment is less than 5 months.

A typical condition assessment report instantly and automatically generated by the AMT toolkit is given below for the mill motor. In this report the first page contains a simplified version of the spectral plot describing the condition of the equipment as a bar graph. This graph also compares the condition of the equipment with respect to the average condition of all the equipment monitored by AnomAlert. In this report the condition of the mill motor, existing faults and their effect on energy efficiency are presented. The next page of the report provides information about the electrical parameters of the motor and gives warning if the parameters are outside of the expected range. Finally a power spectral density plot of the mill motor is presented for advanced users.
**CONDITION ASSESSMENT REPORT**

**Equipment Name**: 15-28 Mill Motor  
**Nominal Voltage**: 6000 V  
**Equipment Type**: Other  
**Nominal Current**: 56 A  
**DB Start & End Date**: 2012-11-21 10:10:12 -  
**Motor Speed**: 750 rpm  
**Frequency**: 50 Hz

![Bar Chart]

- **High**: Equipment comparison with MCM monitored equipment
- **Caution**:  
- **Normal**:  
  - Loose Foundation/Components  
  - Imbalance/Misalignment  
  - Transmission Elements  
  - Bearing  
  - Rotor  
  - Stator  
  - Other

- **Watch existing faults** These faults should be checked for verification and corrective action should be taken at the next scheduled maintenance but no later than six (6) months.

**Electrical Fault Indications**
- **Stator.** Check stator for short circuit, winding slackness, isolation faults, and partial discharge. **EEE**: Heating and increased resistance due to stator, rotor and other electrical faults cause deteriorating conditions and reduced efficiency.
<table>
<thead>
<tr>
<th>Status</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK</td>
<td>Power Factor</td>
<td>0.97</td>
</tr>
<tr>
<td>OK</td>
<td>Active Power [kW]</td>
<td>448</td>
</tr>
<tr>
<td>OK</td>
<td>Reactive Power [kVar]</td>
<td>121</td>
</tr>
<tr>
<td>OK</td>
<td>Vrms [V]</td>
<td>6022</td>
</tr>
<tr>
<td>OK</td>
<td>Irms [A]</td>
<td>43</td>
</tr>
<tr>
<td>OK</td>
<td>V Imbalance [%]</td>
<td>0.40</td>
</tr>
<tr>
<td>Watch</td>
<td>1 Imbalance [%]</td>
<td>3.3</td>
</tr>
<tr>
<td>OK</td>
<td>Frequency [Hz]</td>
<td>50</td>
</tr>
<tr>
<td>OK</td>
<td>THD [%]</td>
<td>2.4</td>
</tr>
<tr>
<td>OK</td>
<td>3th Harmonic [%]</td>
<td>0.90</td>
</tr>
<tr>
<td>OK</td>
<td>5th Harmonic [%]</td>
<td>2.0</td>
</tr>
<tr>
<td>OK</td>
<td>7th Harmonic [%]</td>
<td>0.21</td>
</tr>
<tr>
<td>OK</td>
<td>9th Harmonic [%]</td>
<td>0.08</td>
</tr>
<tr>
<td>OK</td>
<td>11th Harmonic [%]</td>
<td>0.06</td>
</tr>
<tr>
<td>OK</td>
<td>13th Harmonic [%]</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**WATCH ELECTRICAL VALUES** Electrical values are outside of their expected range. They should be noted and watched to identify the cause.

- **Current and Voltage Imbalances**
  - Current imbalance exceeds 3%. Check for stator faults, short circuits, isolation faults, partial discharge, etc.

EEE: **Voltage and current imbalances cause heat and up to 3% loss in energy efficiency.**

EEE: Effects on Energy Efficiency
When there are equipment which performs similar tasks, their power spectral density can also be compared to determine their relative conditions. Such comparison were made for Rotary Kiln Main Drive 1 and 2 as well as Rotary Kiln Fans 1 and 2 as shown below:
The above figures indicate that the transmission fault in Rotary Kiln Main Drive 2 is more advanced than the Rotary Kiln Main Drive 1 and therefore priority should be given for maintenance action. Similarly Fan 2 has priority for maintenance action since it has advanced imbalance fault compared to Fan 1.

The reports for two more cases are also shown below. The first one is for the combustion air fan of a glass manufacturing company. This report indicates developing faults of loose foundation, bearing and stator faults at their early stages. Hence the faults are not at an alarm level but they should be watched. The second report is for a pump at a different manufacturing facility. This report indicates a bearing fault at an advanced level and therefore an alarm is issued. A developing stator fault is also observed at an early level.
WATCH EXISTING FAULTS These faults should be checked for verification and corrective action should be taken at the next scheduled maintenance but no later than six (6) months.

**Mechanical Fault Indications**

- Looseness / foundation. Check for loose motor foundation, loose motor components, looseness or excessive tolerances in driven components. **EEE:** Mechanical faults such as misalignment, physical looseness and imbalance not only adversely affect a motor’s performance and longevity but also its efficiency.

- Bearing. Bearing(s) should be checked. **EEE:** The presence of bearing defects often results in reduced efficiency, or even severe damage, of the motor under consideration.

**Electrical Fault Indications**

- Stator. Check stator for short circuit, winding slackness, isolation faults, and partial discharge. **EEE:** Heating and increased resistance due to stator, rotor and other electrical faults cause deteriorating conditions and reduced efficiency.
CONDITION ASSESSMENT REPORT

<table>
<thead>
<tr>
<th>Equipment Name</th>
<th>Pump</th>
<th>Nominal Voltage</th>
<th>398 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Type</td>
<td>Pump</td>
<td>Nominal Current</td>
<td>41 A</td>
</tr>
<tr>
<td>DB Start &amp; End Date</td>
<td>2013-02-28</td>
<td>Motor Speed</td>
<td>2940 rpm</td>
</tr>
</tbody>
</table>

Frequency 50 Hz

![Equipment comparison with AnomAlert monitored equipment](image)

- **WATCH EXISTING FAULTS** These faults should be checked for verification and corrective action should be taken at the next scheduled maintenance but no later than three (3) months.

**Mechanical Fault Indications**
- ✔️ Vane/Trans. element/Driven equipment. Check for transmission element(s), coupling, driven equipment, belt, pulley, gear box, and fan/pump impeller. **EEE: Efficiency is dependent on pulley size, driven torque, under or over belting, and V belt design and construction. Efficiency deteriorates by as much as 5% over time if slippage occurs.**

**Electrical Fault Indications**
- ✔️ Stator. Check stator for short circuit, winding slackness, isolation faults, and partial discharge. **EEE: Heating and increased resistance due to stator, rotor and other electrical faults cause deteriorating conditions and reduced efficiency.**

- ✔️ Other. PSD (Power Spectral Density) plot indicates abnormalities. Faults should be identified by checking trends, PSD, and diagnostic help.

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**EEE: Effects on Energy Efficiency**
**Continuous Monitoring with AnomAlert**

Continuous monitoring with AnomAlert is the preferred approach for critical equipment since it provides 24/7 monitoring and also has the capability to monitor process changes. Some of the application results in Iron and Steel Industry are provided below.

The first case is for monitoring Run Out Table Rolls in an Iron and steel Industry which is a critical process where a typical one hour down time may cost around $60K. The rollers are subject to high temperature and variable load conditions. AnomAlert is used to monitor 120 of such rollers at a customer facility. A summary of the initial findings with this application are given below:

- Number of equipment that are working as expected: 109
- Number of equipment that need maintenance in 3 months: 3 (stator faults)
- Number of equipment that should be watched (Caution, no alarm): 11 (loose foundation, 7, imbalance 4)

In general the mechanical conditions of the inverter driven roller motors were observed to be good and no alarm for mechanical faults were issued but only caution. However, a waterfall graph of the power spectral density indicated that mechanical imbalance increase with respect to the position of the roller motor as shown in the below figure. This may be due to the design/structural conditions of the ROT and would be the root cause of motors at a position further away to have earlier failures due to increased mechanical imbalance. It is expected that a design change can remedy this issue.

![Waterfall Graph](image)

It was also observed that average voltage imbalance varies with respect to frequency was given in the figure below. This implies that in lower frequencies the variable speed drivers generated voltages that were more imbalanced than they were in higher frequencies. Voltage imbalance will result in imbalanced currents on the order of 6 to 10 times of the voltage imbalance. Consequently, this will lead to a non-uniform temperature increase in the motor windings. Voltage unbalance also causes energy efficiency reduction in motors. A 2.5% voltage unbalance can cause lower efficiency up to 1.5%.
Therefore it was recommended that Variable speed drives should be selected so that they provide acceptable voltage imbalances at the operating frequencies. These results indicates that AnomAlert may be used not only for fault detection and diagnosis but also to determine the root causes of faults and to correct them.
The second case is for a reversing cold milling fume fan in an iron and steel company and demonstrates detection of a dirty filter. This fan discharges dust-laden air out of the factory via a filter. AnomAlert started to warn the user by giving a “Watch Load” alarm on 15th April 2009. Examination of the motor current trend shows that the motor current had been gradually decreasing since 17th November 2008. This indicates that the filter blockage started on that date and had been gradually deteriorating to the point where it exceeded the AnomAlert alarm level on 15th April. This drop off in current shows that the fan had not been extracting the desired volume of air, and hence the ventilation in the plant would be below design levels. The maintenance team attempted to clean the filter with compressed air on 25th April 2009, but it was not fully successful. AnomAlert started giving a “Watch Load” alert again after just 1 month of operation. The team changed the filter completely on 20th August 2009. After this AnomAlert stopped giving alert signals and the motor current reverted to its nominal value. This sort of fault would not have been possible to detect by Vibration analysis.
The third case is for a bearing fault, again, in an iron and steel facility and demonstrates detection of a coupling fault.

References: