Simplifying

Predictive Maintenance

Ahmet Duyar, PhD, ME
Artesis
ahmet.duyar@artesis.com

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.

When the Artesis team was first challenged to find a way of solving this problem, customers said that it would require an innovative approach to avoid the shortcomings of traditional systems. So the solution had to be very simple and inexpensive, easy to install, and able to provide flexible links to existing systems. And importantly, it had to avoid putting a heavy setup and analysis burden on busy maintenance staff.

Artesis responded by focusing an intense development effort on the most common form of machine – the whole range of equipment driven by three-phase electric motors. The resulting product is AnomAlert, a device that combines inward sophistication with outward ease of use. It brings the benefits of predictive maintenance to the widest possible range of users.

The “model-based fault detection” approach used by AnomAlert is not only innovative, but unique in its field. This approach was originally developed and used for applications in the aerospace industry [References 1, 2, 3 & 4]. The advanced algorithms used in the product are the subject of careful patent protection. Developing this mathematical process into a practical tool required a considerable effort, which included tests on several million electric motors to ensure the accuracy and repeatability of the diagnostics.

Artesis has succeeded in harnessing an innovative advanced technology to provide a simpler, more effective, and more affordable condition monitoring solution that has sparked a predictive maintenance revolution [Reference 5]. It is a fitting addition that complements the suite of Bently Nevada Asset Condition Monitoring products.

Overview

Traditional techniques for predictive maintenance have relied on observing trends in the levels of a number of key measurements over time. By carefully selecting the range of measurements, a skilled analyst was able to spot significant changes and to develop an idea of the fault that might be causing them. However, the analyst was often confused when the measurements were altered as a result of operational changes, such as speed or load changes, rather than by a developing fault. Setup and analysis costs have typically pushed such systems beyond the reach of many potential users.

AnomAlert takes a completely different approach, based on the use of 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 learning process requires no input from the operator, and includes all operating states experienced during training, such as different speeds and loads.

When the reference model is complete, AnomAlert switches to a monitoring mode in which a new model of the system is created every 90 seconds. This new model is compared statistically with the reference model, and potential faults are identified and characterized. The system is then able to assess the severity of the problem and produce a series of local indications to suggest what is wrong, what action should be taken and how soon it should be done. 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.

Key to the successful development of AnomAlert was to ensure that the advanced technology being used was invisible to the user. In fact, once the system has been installed the user has very little to do other than respond to information being provided to him by the system. Such information can be communicated as local traffic lights, control system inputs, computer displays, or e-mail messages, accommodating virtually any physical location.

So successful has AnomAlert proved at monitoring motor-driven systems, that the core technology has now been extended to provide equivalent cover for generators and alternators through the introduction of the AnomAlert for Generators solution.

Challenge

In today's competitive business environment, manufacturers are faced with growing production demands while at the same time cutting the cost of manufacturing. One pervasive cost that drags down productivity is low asset effectiveness resulting from breakdowns and unnecessary maintenance interventions. In the US alone, the combined cost of excess maintenance and lost productivity has been estimated at $740B, so the potential justification for implementing better approaches is huge.

The predictive maintenance approach has long been recognized as being capable of reducing such costs, and a wide range of condition monitoring technologies have developed to allow it to be implemented in industrial environments. Such technologies work by analyzing data gathered from the equipment in order to recognize fault characteristics sufficiently early to minimize both failures and unscheduled interruptions in production.

Vibration analysis is the most common method of condition monitoring, representing 85% of all systems sold. Other technologies include infrared (IR) thermography used to detect temperature changes in bearings and shafts; tribology or lubricating oil analysis; motor current signature analysis for electric motors; and ultrasonic analysis of bearing wear.

These traditional approaches have been deployed successfully in a number of key industries. However, they suffer from important limitations that have made them inaccessible to the great majority of the organizations that should be able to achieve the benefits of predictive maintenance. In fact, industry estimates suggest that somewhere between one in a hundred and one in a thousand potential users have been able to effectively deploy condition monitoring up to this time. So why, despite the universally acknowledged benefits of predictive maintenance, have so few companies achieved successful deployment?

Firstly, the diversity of condition monitoring components has made it very difficult for most people to configure monitoring systems. Correct selection of different types of sensor, cabling, data acquisition and processing equipment, and software has been a complex and daunting process even when only one vendor is involved. With multiple vendors, this task requires an effort level that few companies are willing or able to address.

Secondly, the implementation of such systems is far from straightforward. Online systems require sensor installation, significant cabling often involving long cable runs, and complex integration of data processing systems. Even portable systems typically require the installation of many transducer mounting points to be effective. Setting up the condition monitoring software system is also a cumbersome activity. It often requires long manual entry of asset, sensor, and data processing information and the establishment of “baseline” levels that can be taken to represent normal behavior for the equipment being monitored. This then allows alarm levels to be painstakingly set up for each measurement. This largely manual process becomes even more burdensome when baselines and alarms must be configured for a range of different speeds, loads, or operating conditions – a situation encountered in most installations.

Thirdly, even when all these tasks have been completed, the system requires considerable time and effort to deliver results. The required outputs are quite simple from the user’s standpoint: a clear indication of which items of equipment are developing faults, the type of fault, the action that should be taken, and the timescale for that action. However, obtaining these outputs requires time for rising trends to be detected and considerable analysis and interpretation by the user. The skills and person-hours needed to do all this are often not available to a typical maintenance organization.

System costs have typically been unacceptably high. Portable systems have been relatively inexpensive to buy, but prohibitively expensive to operate. Online systems have avoided the high personnel costs of portable systems, but are very expensive to buy and install. Automated, “intelligent” systems have sought to reduce the analysis burden, but have been extremely expensive and difficult to set up.

As a result of these problems, there has been an increasing demand for simple, effective, and inexpensive condition monitoring systems that allow the great majority of organizations to benefit from the adoption of predictive maintenance without sacrificing diagnostic capability. Satisfying this requirement has been the cornerstone of the development of the Artesis system.

Response

AnomAlert was developed to meet a market requirement for a condition monitoring product that can provide simple and accurate maintenance scheduling information, without the need for interpretation by highly trained personnel. It aims to be very simple to install, set up, and operate, and to require little or no user intervention until an equipment fault is detected.

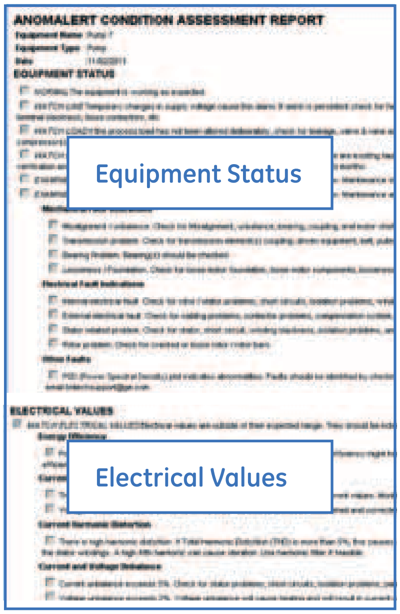
The benefits of the Artesis approach can best be summarized by taking a look at the contrast with conventional technology in each of the three problem areas previously described.

Firstly, the AnomAlert system is extremely simple to configure. AnomAlert monitor units are available for fixed or variable speed drives, and for high or low voltage power. For low voltage installations, only current transformers or transducers are required, while for high voltage systems, suitable voltage transformers are added. A suitable standard adaptor is then selected to link each unit to the software package, typically using network or wireless devices.

Secondly, during installation each AnomAlert unit only requires connection to the motor supply cables and so does not have to be positioned close to the equipment being monitored, which might be in a hazardous or remote location. This provides all the benefits of having an online system without the cost and complexity of extensive cabling. The AnomAlert units are typically installed in the motor control center by means

connected system is established. This process accommodates the full range of speeds and loads that are experienced by the system, and accommodates electrical, mechanical, and operational characteristics of the motor, coupling, and any type of driven equipment (typically including pumps, fans, compressors, and conveyors).

When the learning period is complete after a few days, the Artesis system creates a complete Condition Assessment Report for the connected equipment. This report identifies any existing mechanical, electrical, or operational problems and recommends corrective actions



Artesis has succeeded in harnessing an innovative advanced technology to provide a simpler, more effective, and more affordable condition monitoring solution that has sparked a predictive maintenance revolution. It is a fitting addition that complements the suite of Bently Nevada Asset Condition Monitoring products.

of a square cutout in the front panel, following which connections are made to sensors, power supply, and communication devices. A relay output is also available to control visual or audible alarm equipment, or to provide a simple input to a plant data acquisition system.

Once the AnomAlert unit is switched on, it requires minimal user configuration before entering an automated "learn" mode during which the complete normal operating condition of the

and how soon such actions should be carried out. Unlike conventional systems, this information is provided to the user immediately without having to wait for data trends to be collected and analyzed over an extended period. From this point on, the AnomAlert system provides automated condition monitoring cover for the connected equipment.

Thirdly, the Artesis system is almost entirely automatic in normal operation. Every 90 seconds it compares the current operating condition of the equipment with the normal condition established during the learn mode. If a problem is detected, "traffic lights" on the front panel of the AnomAlert monitor unit change color to indicate the type and severity of the fault. More detailed information is presented by the AnomAlert stand-alone software package which provides the user with a concise, accurate description of any developing faults, recommendations for maintenance actions, time to failure, and a wide range of electrical characteristics.

Condition Assessment Report

ANOMALERT CONDITION ASSESSMENT REPORT

Equipment Name :Pump 7

Equipment Type :Pump

Date :11/02/2011

EQUIPMENT STATUS

- [ ] *NORMAL* The equipment is working as expected.
- [ ] *WATCH LINE* Temporary changes in supply voltage cause this alarm. If alarm is persistent check for har terminal slackness, loose contactors, etc.
- [x] *WATCH LOAD* If the process load has not been altered deliberately, check for leakage, valve & vane ad compressors). If the process is altered deliberately, AnomAlert should be updated.
- [ ] *WATCH EXISTING FAULTS* The operation of the equipment is NORMAL although there are existing fault verification and corrective action at the next scheduled maintenance but no later than six (6) months.
- [ ] *EXAMINE 1* There are developing mechanical and/or electrical fault(s) as shown below. Maintenance sh
- [ ] *EXAMINE 2* There are developing mechanical and/or electrical fault(s) as shown below. Maintenance an

Mechanical Fault Indications

- [ ] Misalignment / unbalance. Check for Misalignment, unbalance, bearing, coupling, and motor shaft
- [ ] Transmission problem. Check for transmission element(s) coupling, driven equipment, belt, pulley
- [ ] Bearing Problem. Bearing(s) should be checked.
- [ ] Looseness / Foundation. Check for loose motor foundation, loose motor components, looseness

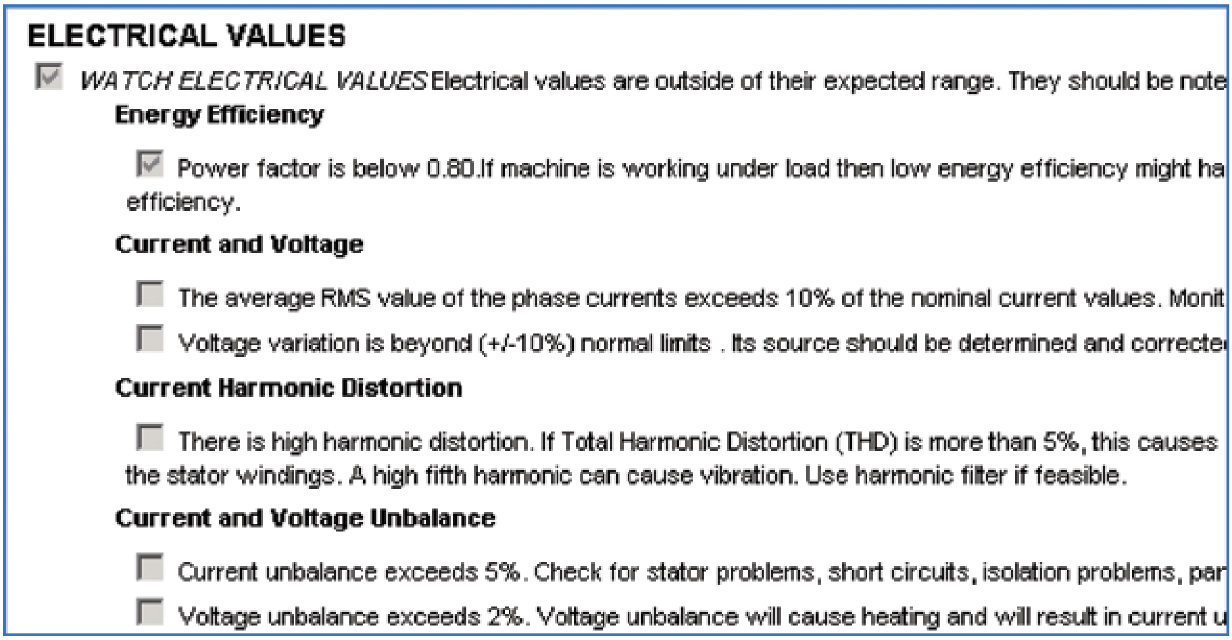
Electrical Fault Indications

- [ ] Internal electrical fault. Check for rotor / stator problems, short circuits, isolation problems, windir
- [ ] External electrical fault. Check for cabling problems, contactor problems, compensation system,
- [ ] Stator related problem. Check for stator, short circuit, winding slackness, isolation problems, anc
- [ ] Rotor problem. Check for cracked or loose rotor / rotor bars.

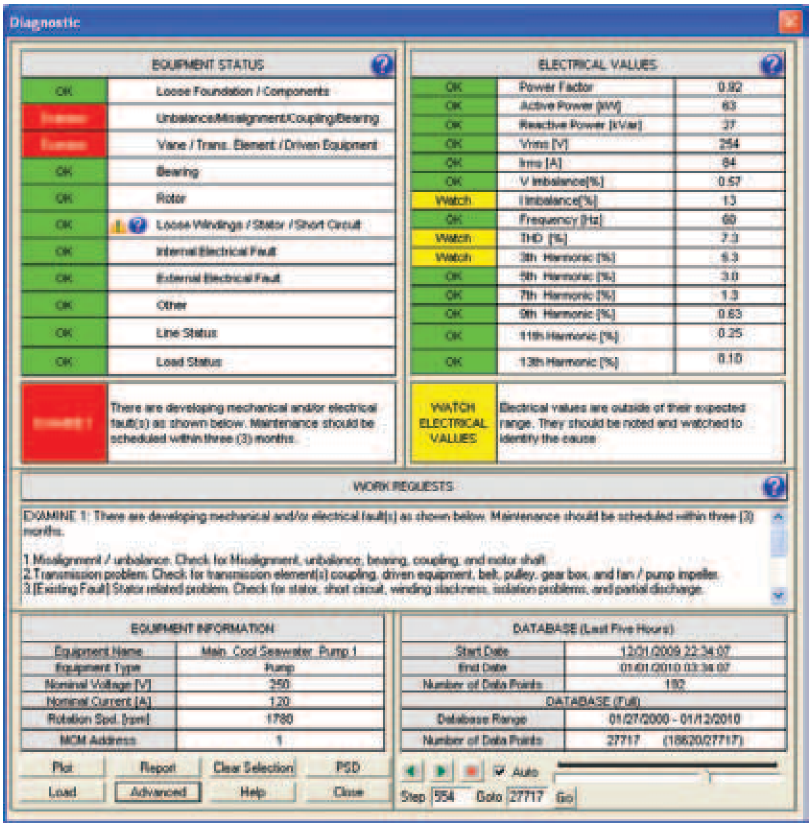
Other Faults

- [ ] PSD (Power Spectral Density) plot indicates abnormalities. Faults should be identified by checkin email bntechsupport@ge.com

The Equipment Status section includes indications of mechanical, electrical and other faults.



The Electrical Values section includes indications of various electrical problems.



Diagnostic Display

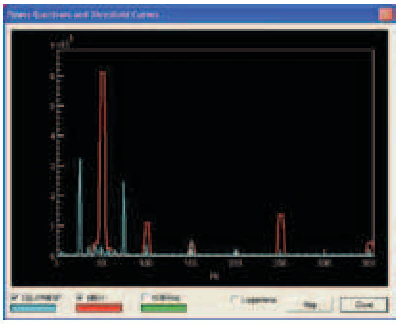
This diagnostic display gives also maintenance planning information with timing based on the severity level assessed by the system as *"within 6 months"*, *"within 3 months"* and *"as soon as possible"*. Such recommendations are based on the results of many similar assessments in the field and represent an average behavior for similar types of equipment.

Many users of the AnomAlert system spend much of their time in the field, away from their office workstations. To keep them up to date with the condition of their equipment, AnomAlert for System 1 can send email messages when a new fault is detected. These messages contain a summary condition report, prompting the user to check details in the software.

Although AnomAlert for System 1 excels at providing the user with actionable information in a concise, practical form, some advanced users choose to make use of the more complex displays that it can also provide. Trend plots can be used to show how faults have been developing over time for example, and Power Spectral Density (PSD) displays indicate the way the system has used information about the frequency content of the measured signals.

Power Spectral Density (PSD)

In this example, sidebands around the power supply line frequency (50 Hz) are shown in the figure, below. These ± 25 Hz sidebands represent modulation at shaft rotation speed (1X frequency for a 4-pole motor) and typically indicate machine unbalance or misalignment.



Power Spectral Density (PSD) display.

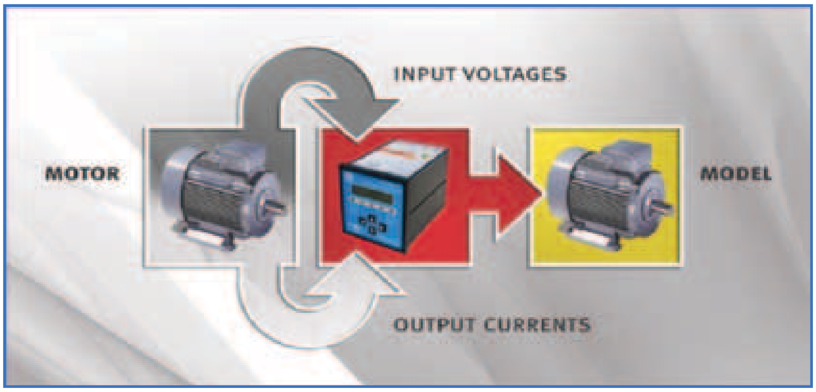
Technology

Although the AnomAlert system is simple to implement and operate, the technology behind it is both sophisticated and unique. By combining advanced model-based fault detection and intelligent diagnostics, the system is able to deliver outstanding results with minimal user intervention.

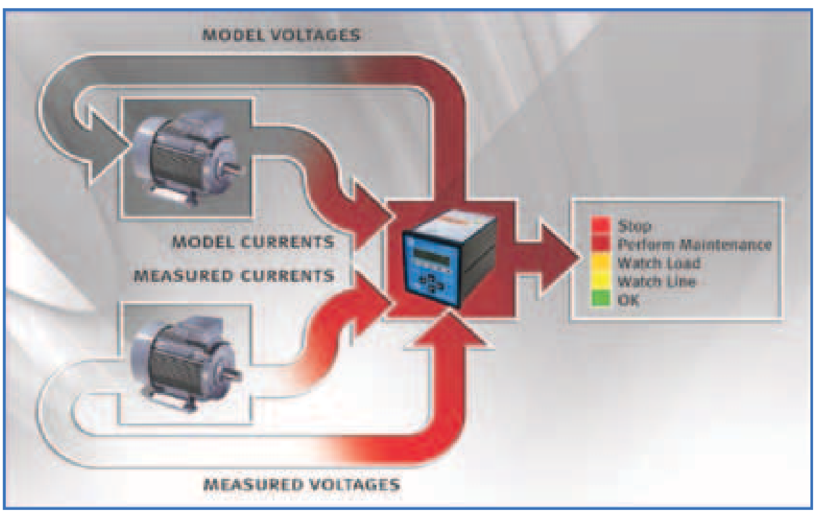
The principle of the AnomAlert approach is to build a mathematical model of the motor driven system that it is connected to, and then to compare the dynamic behavior of that model with the actual, measured dynamic behavior. The model consists of a set of differential equations, which describe the electromechanical behavior of the motor driven system, including the full range of mechanical, electrical, and operational characteristics.

During learn mode, AnomAlert acquires real-time data from the physical equipment before applying advanced system identification algorithms to calculate a set of model parameters. The mathematical model takes into account all speed and load variations experienced during the learn mode, eliminating the need for manual set up of multivariate alarms. When completed, this model represents the normal operating condition of the connected equipment. In normal operation, AnomAlert produces a series of new mathematical model of the system and by comparing the parameters in this new model with those in the reference model, developing faults can be accurately detected and diagnosed. This model-based approach effectively allows the motor itself to act as an advanced condition monitoring sensor, and is not confused by preexisting faults in the equipment.

AnomAlert monitors and compares 22 different model parameters, which are 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,



Learning Phase



Operating Phase

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, while at the same time being immune to false alerts.

In addition to its diagnostic capabilities, AnomAlert also provides the user with a wide range of electrical parameter measurements – including real and reactive power – which allow the system to be used for energy consumption assessments. Other parameters, such as total harmonic distortion, supply harmonic content, and voltage imbalance, also provide a valuable power quality analysis capability.

References

[1] A. Duyar and W. C. Merrill, "Fault Diagnosis for the Space Shuttle Main Engine", AIAA Journal of Guidance, Control and Dynamics, vol. 15, no. 2, pp. 384-389, 1992.

[2] A. Duyar, V. Eldem, W. C. Merrill, and T. Guo, "Fault Detection and Diagnosis in Propulsion Systems: A Fault Parameter Estimation Approach", AIAA Journal of Guidance, Control and Dynamics, vol. 17, no. 1, pp. 104-108, 1994.

[3] J. Litt, M. Kurtkaya, and A. Duyar, "Sensor Fault Detection and Diagnosis of the T700 Turboshaft Engine", AIAA Journal of Guidance, Control and Dynamics, vol. 187, no. 3, pp. 640-642, 1995.

[4] J. L. Musgrave, T. Guo, E. Wong, and A. Duyar, "Real-Time Accommodation of Actuator Faults on a Reusable Rocket Engine", IEEE Trans. Cont. Syst. Technol., vol. 5, no. 1, pp. 100-109, Jan. 1997.

[5] Innovation Award for "Simplifying Predictive Maintenance", The Institute of Engineering and Technology, United Kingdom, Dec 2007.