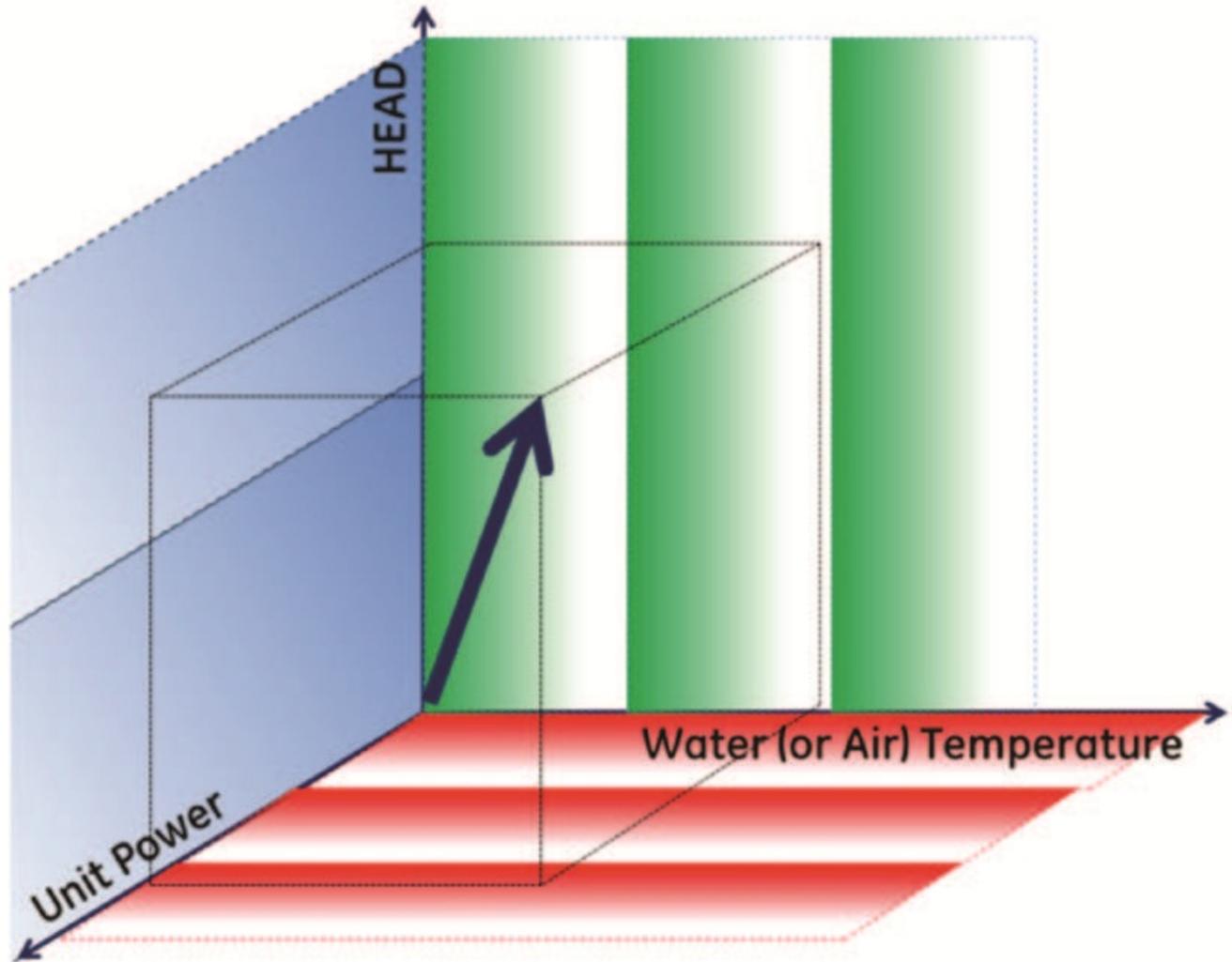# Orbit Magazine

Multi State Analysis

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Multi State Analysis in Condition Monitoring Systems (CMS)

In condition monitoring and protection systems, it is often possible to establish two separate alarm levels for each measured parameter. In Bently Nevada* systems, for example, the lower severity alarm is called the "Alert," while the higher severity alarm is called the "Danger" alarm. Crossing these alarm thresholds provides information about a minor deviation of the measurement from normal conditions (Alert), and a more serious deviation (Danger).

The Danger alarm usually indicates that a significant change in physical condition of the monitored asset has occurred. When the monitoring system is configured to interact with a protection system,

the Danger setpoint is normally selected to actuate protective trip logic, which shuts down the protected machine without human intervention. Of course, such a protective trip impacts the production process, but this outcome is preferable to allowing the machine to be damaged by continued operation.

With diagnostic systems that do not provide automatic protective functions, it is often possible to use more than two thresholds for each measurement. Consequently, the diagnostic system can distinguish between more subtle changes in physical condition of the monitored assets. In this Hydro Corner article, we will describe typical measurements (and symptoms) that are used specifically for evaluation of physical condition of hydro turbine-generator machines. However, the approach presented here can be used for any other assets covered by a diagnostic system as well.

Operating Conditions

Ideally, observed symptoms should only depend on actual condition of the monitored asset, and unambiguously describe failure modes. However, in the real world, production assets can operate in various challenging environments with different operating conditions. Observed symptoms can be significantly affected by these factors, rather than indicating the true physical condition. Many observed symptoms are functions of not only the physical condition of the asset, but also of the following variable factors:

- Process Variables, and
- Environmental Variables

Process Variable Dependence
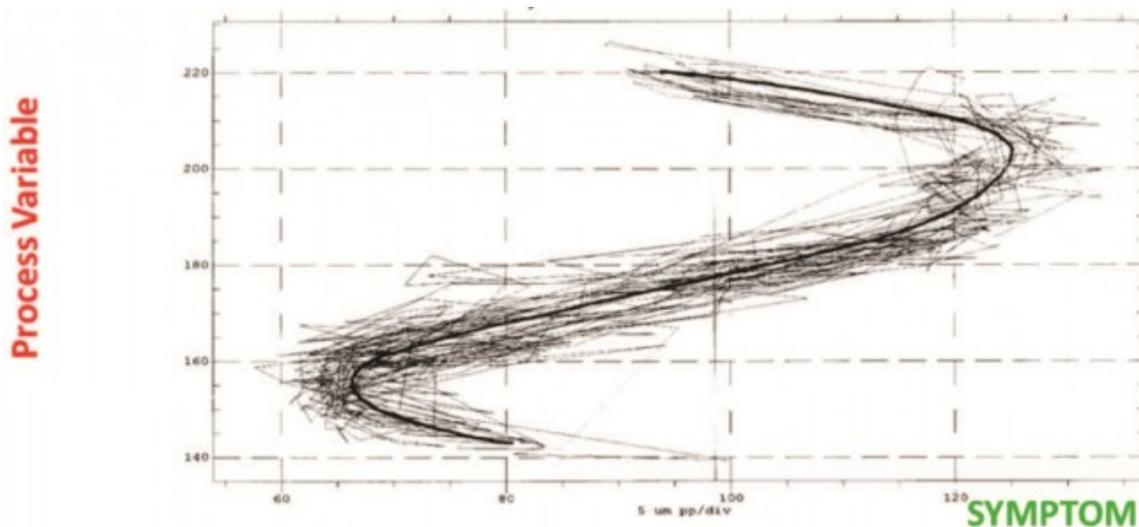
In this example, a 220 MW generator was instrumented with a 3500 monitoring and protection

system. Generator shaft vibration Danger alarms were established with setpoints of 140 ?m. During normal unit operation, operations personnel noted significant variation of shaft vibration levels. The vibration values at the generator bearings ranged from approximately 50 ?m up to almost the alarm setpoint of 140 ?m.

Based on vibration data collected from XY displacement transducers for various operating conditions, it was observed that the varying levels of rotor vibration depended significantly on generator load. An example of such correlation analysis for a chosen transducer is shown in Figure 1. This vibration data was collected during one week of typical unit operation, and based on the experience of station personnel, it shows a representative relationship between vibration and load for their generator when it was in good (normal) physical condition.

> Note: This x-y plot tool is a standard feature of Bently Nevada System 1* software. It is very useful for correlation analysis, to observe relationships between vibration from various transducers dedicated to condition measurement and the selected process or environmental variable.

Observe that the normal range for load regulation for this generator is between 140 and 220 MW. Interestingly, vibration levels initially drop as load is raised above 140 MW, falling to a minimum at about 155 MW, then rising and peaking at about 200 MW before again falling as load is raised to maximum.

The range of vibration levels for the analyzed measurement point (bearing #2 – transducer Y) is from around of 60 ?m up to 130 ?m. The black line represents empirical correlation between the measured Symptom (rotor vibration) and the Process Variable (generator load).

Suppose the plant operators observe vibration levels around of 80 to 85 ?m (approximately 60% of the Danger setpoint of 140 ?m). Does this mean that the generator physical condition is normal? Maybe – but maybe not – depending on actual generator load at the time of the vibration measurement.

One way that maintenance specialists can assess generator condition is to determine the normal variation of measured vibration with load, and establish the empirical correlation curve as a baseline during normal operation. If the observed vibration ever deviates significantly from the established curve, it is indication of an anomaly that may reflect a change in physical condition of the asset.

Operating States

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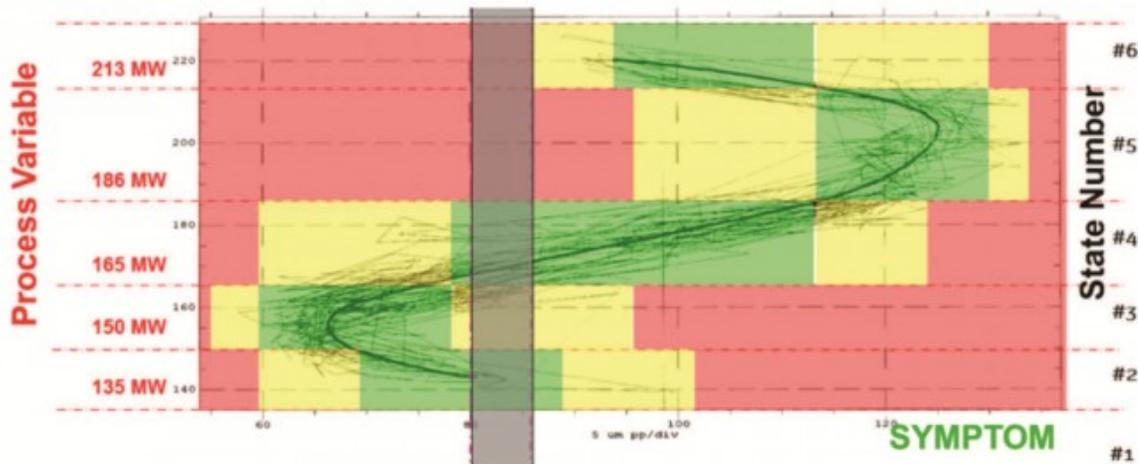
Defining several different operating zones as "states" allows us to more easily establish alarm settings that indicate normal vs. abnormal conditions. As an example, Figure 2 shows the same data from Figure 1, only with six different states defined by various ranges of generator load. For each state, we have indicated normal conditions (green), slightly abnormal (yellow), and highly abnormal (red). Establishing these states makes it easier for maintenance personnel to recognize whether or not the 80 to 85 ?m vibration level is normal at any given generator load. As shown in Figure 2, this vibration would be:

- Completely normal for states #2 and #4,
- Somewhat abnormal for the state #3,
- Significantly abnormal for states #5 and #6.

  Note: We have no sense for normal vibration during state #1, because this particular generator only operates at these low loads very briefly during loading and unloading.

Logic Rules

Now that we have developed this set of empirical relationships describing the expected vibration for various power ranges, it is easy to convert them into a set of logic rules for use in System 1 Decision Support tools (Figure 6). These logic rules can be created in Rule Desk tools, or installed as pre-configured HydroX™ RulePaks (Reference 1) that will detect when abnormal conditions (anomalies) are identified:

- for particular machine bearings,
- for particular transducers or measurements,
- for particular states such as the example in Figure 2

Environmental Variable Dependence

ISO Standard 7919 (Reference 2) includes guidelines for evaluating shaft vibration for Hydro-Turbine-Generator (HTG) machines during normal operation. The vibration values presented in the guidelines are described as being independent of "time, head and power." For very basic plant maintenance programs that have not evolved past Predictive Maintenance (PM) methodologies, these guidelines can be appropriate for determining setpoints for monitoring and protection systems.

However, for more advanced programs that use Condition Based Maintenance (CBM) or Predictive Maintenance (PdM) techniques, it is necessary to have a monitoring system that is capable of performing more advanced diagnostics. These systems fall into two general categories:

- Expert Systems: Represented by the HydroX™ RulePaks, and
- Anomaly Detection Systems: Represented by the AnomAlert monitor, Proficy* SmartSignal software, etc.

It is important to realize that various environmental variables – including head – can influence vibration levels of a HTG. Although head is one of the most important environmental variables, others can also influence the vibration readings. These include water temperature, when the range is significant. With some plants, the annual change of water temperature may be as small as 2 °C, with negligible influence on vibration. Other sites may have changes in water temperature of up to 20 °C, in which case the water temperature influence on vibration is usually quite visible.

For a turbine at a different power plant, shaft vibration was observed to vary with significant changes in head (Figure 3). These three plots each show the relationship between shaft vibration and generator load for the Turbine Guide Bearing (TGB) over the normal range of operating load. For this machine, it is clear that the lowest vibration levels occur when head is nominal. When the head deviates from nominal (either higher or lower) by several percent, observed vibration values increase significantly – in some cases by as much as 50%!

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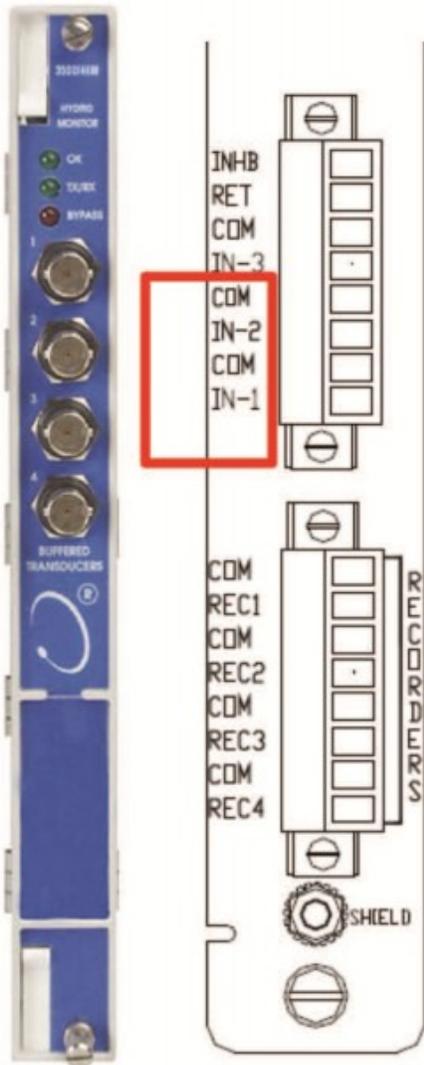
CMS Hardware

As we described in the previous issue of Orbit, the Bently Nevada [3500/46 Hydro Monitor](#) incorporates a unique "Multimode" feature (Reference 3). This allows you to establish up to eight distinct machine modes, each with its own unique set of alarm parameters, including Alert and Danger thresholds.

It also allows a control system to automatically tell the monitor which mode exists at any particular time so the correct alarm settings will be used automatically. The selection of various operation modes is executed by three contacts located in the Input/Output (I/O) module of the monitor (labeled IN-1, IN-2, and IN-3 in Figure 4).
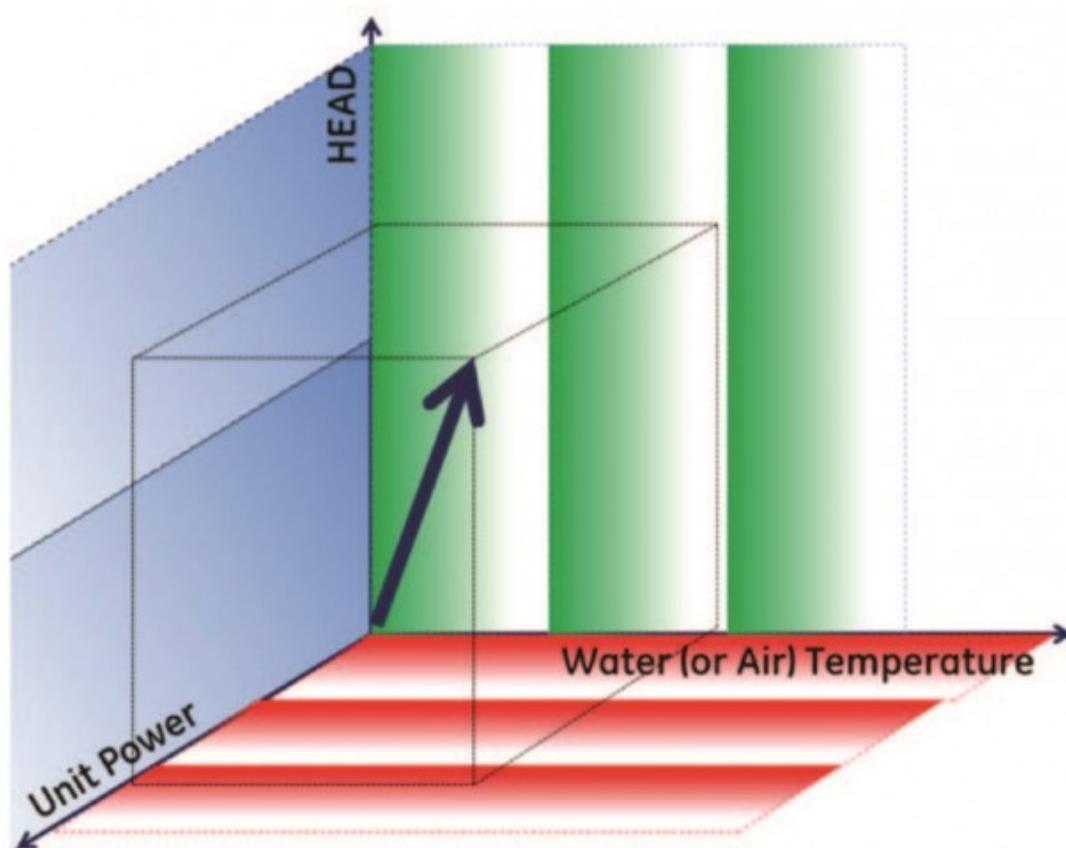
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The monitor can be used for HTG machines that have strong correlations of vibration to process or environmental variables. It can be programed specifically to accommodate the most important variables that accompany operation in situations such as: various load ranges, generation versus pumping mode (for pumped-storage units), synchronous condenser mode, and so on.

It is sometimes possible that seemingly obscure environmental variables may not be recognized as important factors that can impact generator rotor dynamics In one example of a run-of-river hydro power plant with vertical Kaplan turbines, it was observed that the vibration level actually depended on direction of the wind!

For some wind directions (coming from one side of the river or the other), the difference in head from one end of the dam to the other was more than 0.5 m (1.6 ft), which was enough to introduce significant errors to the average head measurement – with puzzling impact on rotor vibration. Once the plant staff recognized this effect, they implemented individual head measurement systems for each unit. With more accurate head measurements available, it became possible to increase the sensitivity of the Alert threshold. When this was accomplished, an accurate correlation curve was created to compare Rotor Vibration (Symptom) with Head (Environmental Variable) – similar to the Rotor Vibration vs. Load correlation curve that was created at the plant in the earlier example.

CMS Software

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Bently Nevada [System 1 software](#) offers a unique System Extender application called State-Based Analysis, which is dedicated to monitoring of assets with more than one mode of operation. This application allows you to define any requested number of dimensions of the analysis, and for each dimension, establish a designated number of ranges.

The first example in this article used 1-Dimensional (1-D) analysis. The dimension was that of generator load, which was divided into six separate ranges. Now, we will go a little bit deeper using the advanced analytics features of System 1 software, and define a 3-Dimensional (3-D) case for a hydro turbine generator. This space is described by the following parameters (Figure 5):

- Generator load (3 ranges, shown with red shading),
- Head (2 ranges, shown with blue shading), and
- Temperature (3 ranges shown with green shading).

Now, when the "symptom" data (such as vibration) is collected in the System 1 database, it can be correlated to these three parameters, by indexing it to the 18 different subspaces that we have defined. The State-Based Analysis system extender has no limitations on either the number of dimensions that can be used to define states or on the number of sub-ranges that can be defined for each dimension.
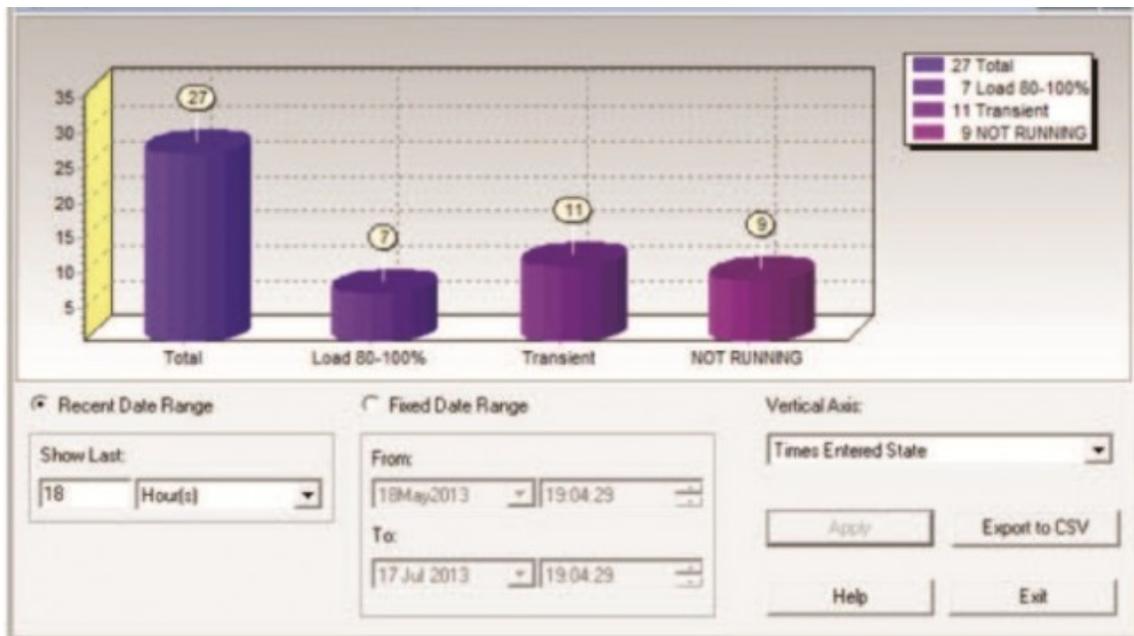
The State Based Analysis tool allows building of State Histograms which can be observed and reported whenever State Indicators have been configured. Figure 6 presents as an example such histogram build for 4 states.

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Note: One hydro-turbine OEM used a software package that allowed them to define approximately 150 different variables for correlation of measured parameters! System 1 software is even more flexible, allowing you to evaluate a practically unlimited number of symptoms, and to define an unlimited number of variables.

Advanced Analytic Software for Predictive Maintenance

The valuable information determined by advanced analytic software can help with more effective implementation of Predictive Maintenance (PdM) programs. Reference 4 describes some of these software tools that can be very useful for improving maintenance in hydroelectric power plants. In addition to System 1 software, these tools include the HydroX™ RulePak that can be used for

some specific hydro-turbine-generators, and Proficy SmartSignal that can be used without any limitations for any hydroelectric power plant asset.

Many standard System 1 RulePaks are available for various assets. The standard RulePaks can be extended by creating additional custom rules that facilitate automatic recognition of changes to machine condition. The new rules can be created easily by using System 1 RuleDesk tools. The new custom rules can be useful for evaluating the condition of monitored assets for which you have established multi-mode correlations with process or environmental variables.

Figure 7A shows the RuleDesk logical functions, while Figure 7B shows part of a screen during the process of building of an expert rule. This particular rule will automatically evaluate generator vibration levels for State #2 (135 to 150 MW), as defined in Figure 2.

> Note: The available logic tools can perform numerical operations, as well as specialized functions for processing dynamic "waveform" data. This data includes mechanical vibration, fluctuating water pressure pulsations, and proportional voltage or current signals that come from sensor systems measuring a wide variety of environmental and process parameters.
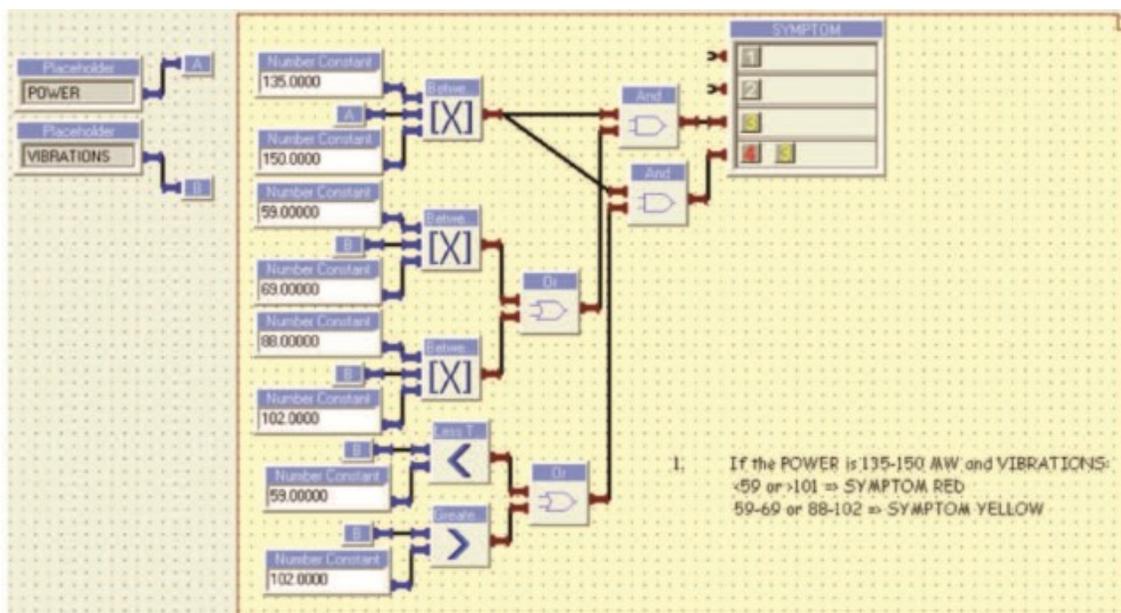
Conclusions

The hardware and software tools described in this article accommodate more precise condition monitoring and protection operation, and more accurate diagnostics than older systems could handle. System 1 software can use MultiMode states from hardware (such as defined in the

3500/46M monitor) or as defined by maintenance specialists in the software itself. Different alarm setpoints can be used - not only for direct vibration, but also for other measurements and analysis (for instance, specific alarms for amplitude vs. phase "acceptance regions" that can vary with changes of selected process variables).

At the expert level of diagnostic software, specific rules can also be created to reduce the "noise" in symptoms that can be caused by the influences of process and environmental variables – thus facilitating more accurate detection and diagnosis of actual changes in asset condition. The custom rules dedicated for each state result in a more efficient PdM approach. Even in an organization that hasn't advanced beyond a traditional Preventive Maintenance (PM) program, System 1 software can provide more accurate diagnostic information, allowing users to detect (and act earlier on) anomalies recognized through the use of state-based analysis techniques.

If an organization recognizes the importance of considering the influence of process or environmental variables but does not have the required expertise, the Bently Nevada team can help. Our specialists can assist with creating appropriate Decision Support rules to perform the needed correlation analysis. In addition to creating custom rules with an optimal number of states in a multidimensional space, our team can help with validity checking and implementation or "commissioning," of the rules in your facility (Reference 5).

References

1. HydroX™ RulePak - Diagnostic Monitoring for Hydro Turbine Generators, GEA-15031C (10/08)
2. ISO 7919-5:2005, Mechanical vibration – Evaluation of machine vibration by measurements on rotating shafts – Part 5: Machine sets in hydraulic power generating and pumping plants
3. M. Snyder, 3500/46M Hydro Monitor – Smart Monitoring for the Intelligent Machine Age, Orbit V34 N1
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5. P. Popaleny, Bently Nevada Machinery Diagnostic Services, An internal GE Report #R-140110

For More Information

The Bently Nevada Hydro Turbine/Generator Condition Monitoring and Diagnostics Application Package brochure (GEA-13902) is available at this link.

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