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BWR RECIRCULATION PUMP DIAGNOSTIC EXPERT SYSTEM

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ABSTRACT

At General Electric (GE), an on-line expert system to support maintenance decisions for BWR recirculation pumps for nuclear power plants has been developed. This diagnostic expert system is an interactive on-line system that furnishes diagnostic information concerning BWR recirculation pump operational problems. It effectively provides the recirculation pump diagnostic expertise in the plant control room continuously 24 hours a day. The expert system is interfaced to an on-line monitoring system, which uses existing plant sensors to acquire non-safety related data in real time. The expert system correlates and evaluates process data and vibration data by applying expert rules to determine the condition of a BWR recirculation pump system by applying knowledge based rules. Any diagnosis will be automatically displayed, indicating which pump may have a problem, the category of the problem, and the degree of concern expressed by the validity index and color hierarchy. The rules incorporate the expert knowledge from various technical sources such as plant experience, engineering principles, and published reports. These rules are installed in IF-THEN formats and the resulting truth values are also expressed in fuzzy terms and a certainty factor called a validity index. This GE Recirculation Pump Expert System uses industry-standard software, hardware, and network access to provide flexible interfaces with other possible data acquisition systems. Gensym G2 Real-Time Expert System is used for the expert shell and provides the graphical user interface, knowledge base, and inference engine capabilities.

INTRODUCTION

The recirculation pumps and motors are essential equipment for producing power in a BWR nuclear power plant. This system operates continuously as the power plant generates power. Because of its high-use duty and inaccessibility during plant operation, all BWR plants have installed some level of instrumentation to monitor the recirculation pump condition with various degrees of sophistication. However, industry experience has generally shown that these current monitoring systems do not provide the intelligent information needed for quality decision support. To better realize the potential benefits of an existing or newly installed monitoring system, many expert system-style decision-aid tools were developed for use with general rotating equipment. Two different expert system sets, specifically for the BWR recirculation pumps, were developed by GE during the past two years. One is a PC based system using the GEN-X shell (Reference 1). The second system that operates on workstations with a real time graphical expert system shell will be discussed in this paper.

One of the unique features of this BWR Recirculation Pump Expert System is that it uses fuzzy logic and rule sets based on component design specifications and actual field operations experiences. Diagnoses are derived on-line while the plant is in operation using on-line analysis results of monitored vibration and process signals. It is designed to inform plant operators of the current condition of the recirculation pumps. If faults are detected, the system will also show which component is at fault and the degree of certainty for that particular diagnosis using fuzzy terms and combined validity indices.

This Recirculation Pump Expert System is currently being used with the GE Integrated Equipment Monitoring System (GEIEMS), which performs the raw data acquisition, on-line analysis, and monitoring functions. Analysis results obtained by the GEIEMS are written in a file, which is accessed by the Expert System via Ethernet for diagnoses. However, this expert system is also designed to interface with other PC and/or workstation-based monitoring systems. If the data (analysis results) from the interfacing monitoring system are insufficient to drive all the diagnostic rules of the Expert System, each rule can be independently switched off.

GEIEMS

GEIEMS is a workstation-based monitoring system. It is designed to provide BWR nuclear plants with an integrated platform for monitoring various plant equipment such as the recirculation pumps, main steam turbine, motor operated valves, and key reactor components, such as feedwater nozzles. It offers BWR plant monitoring and diagnostics for support of predictive maintenance, plant performance, and plant

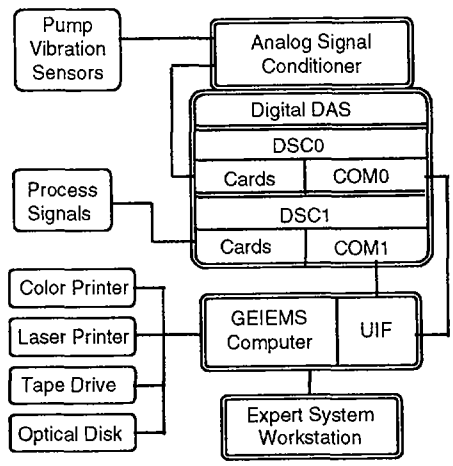

Figure 1a GEIEMS/Expert System Block Diagram with Conventional Digital DAS

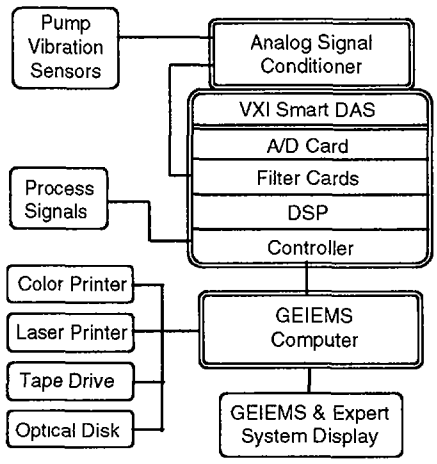

Figure 1b GEIEMS/Expert System Block Diagram with VXI Type Smart DAS

life extension concerns. Within the context of this paper, the GEIEMS system provides the data needed for the expert system to perform diagnostic functions.

Figures 1a and 1b show two different configurations of GEIEMS, one with a conventional digital data acquisition front-end and another with a smart data concentrator front-end. These figures also show that the Expert System can reside on another workstation and obtain the necessary data from the GEIEMS computer via Ethernet (Figure 1a), or the Expert System can be integrated into the GEIEMS workstation (Figure 1b).

EXPERT SYSTEM

The Expert System supplements an on-line monitoring by evaluating the data for the possible causes of abnormal data behavior. It uses the plant and pump process data and the pump vibration data from GEIEMS or a similar monitoring system (see Figure 2 for the Expert System Interface). For BWR Recirculation Pump application, typical process data include bearing temperatures, seal pressures, pump ΔP and flow, pump speed, motor current, etc. Vibration data used by the Expert System include shaft displacements and motor and pump casing velocity and acceleration in terms of amplitudes, spectral components, phases, etc. Therefore, some of the data used in the Expert System are as-measured while others are results of some analyses such as FFT. Over 150 parameters generated from these process and vibration signals for each pump are used by this Expert System.

This Expert System evaluates the data by applying the expert rules. The knowledge base file, containing the expert rules, user interface, and data input/output procedures, is loaded into the G2 Real-Time Expert system shell (Gensym Corp.) for execution. All operator interactions are managed through the knowledge base. It communicates with the GEIEMS Recirculation Pump Monitor though a monitor-result file using G2's data input/output capability. This file is formatted as a text file to allow interface with different data input sources. The input data are read in continuously, and

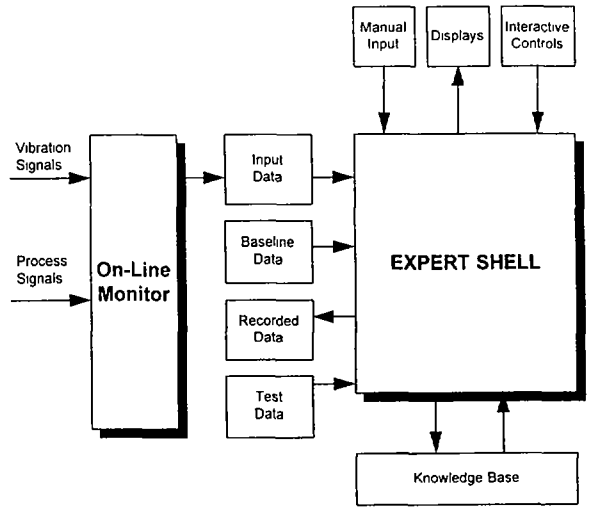

Figure 2 Expert System Interface Diagram

only when a data value change is detected, all rules that act on that particular data will be evaluated. The baseline values are input through Diagnosis Baseline file. The baseline values may be modified by a responsible engineer by using a standard text editor in off-line mode or by using G2 itself in an interactive mode during an on-line operation. Furthermore, this Expert System also allows evaluation of test data, which can be input manually or input through test data file, where a file may be constructed by text editor or by capturing the current data into a file. This test data capability allows user verification of the Expert System operation and it can be used as an off-line diagnosis tool by inputting data from sources other than an on-line monitoring system. The input file, baseline file, test file, and captured data file are all ASCII character text files and use the same format, for convenience of maintenance.

The user interface is a set of graphical screens where a diagnostic message will be automatically displayed. Figure 3 shows a sample screen display with a diagnostic message that indicates which pump has a problem, the type of problem, and the degree of concern. The degree of concern (or diagnosis uncertainty) is expressed throughout the Expert System using validity indexing and color hierarchy. As described later, the degree of concern is not a diagnostic accuracy nor is it a problem probability. It provides operators and other plant personnels with a measurement for confidence factor for evaluating how strong the diagnosis indication is and how much of concerns should be expressed over the equipment condition. The degree of concern is expressed in the following terms:

1) *The occurrence of the indicated* ***problem is impossible*** (green).
2) *The occurrence of the indicated* ***problem is unlikely*** (yellow).
3) *There* ***may be a possibility*** *of the indicated problem* (orange).
4) *The indicated problem is* ***likely to occur*** (pink).
5) *The indicated problem is* ***certain to occur*** (red).

Since the G2 expert system shell is used and since the input interface is through a serial file containing ASCII characters, the system is adaptable with other systems and platforms. The expert system can be connected with other systems such as personal computers, workstation, or other system that can provide the input data in ASCII text in specified formats. The expert system can be loaded and run on any workstation (Sun, HP, DEC, SGI, etc.) that supports G2. No recompilation or linking is needed. This expert system can easily operate on different platforms by transferring the knowledge base to the desired platform and setting up the input file path.

Knowledge Based Expert Rules

The basis of the expert system is a set of rules that frame the knowledge to be used in diagnosing problems for the BWR recirculation pumps. Sets of rules, which are expressed

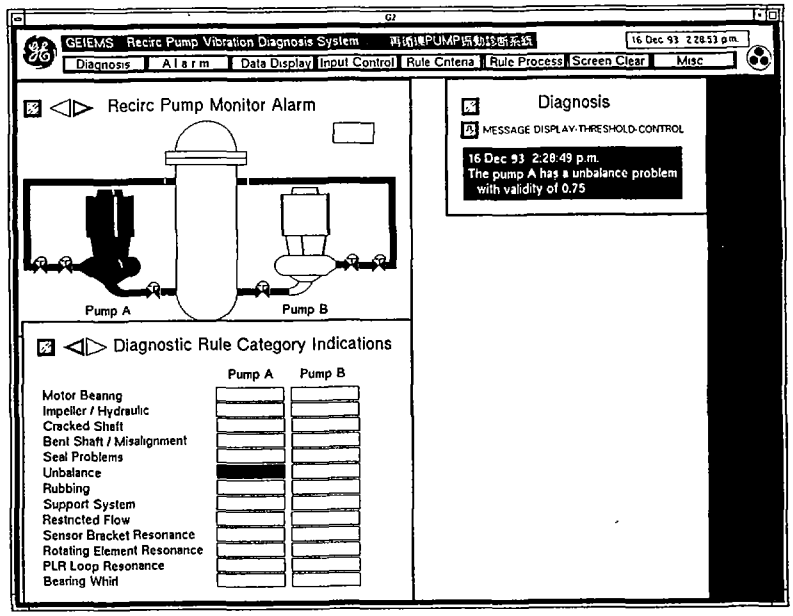

Figure 3 Diagnostic Message Display

in fuzzy IF-THEN format, determine possible problem(s) by evaluating the process data, vibration data, and the recirculation pump operating parameters. The rules can be illustrated by a simple rule for a rotating element balance problem, which is as follows:

If shaft coupling 1X vibration component during steady state is high, then rotating element unbalance is indicated.

In this rule, the shaft coupling vibration displacement signals from horizontal eddy probes in either the X or Y direction are analyzed by GEIEMS to obtain the 1X vibration component. The rule is in IF-THEN format, but the resultant conclusion, related to a rotating element unbalance problem in this case, is not expressed using familiar TRUE/FALSE logic. Instead, the resulting value for each rule is expressed in fuzzy logic membership values (not probability values) using a certainty factor called the validity index. For this particular rule the validity index is shown in Figure 4. This approach avoids an unrealistic Yes/No type of conclusion. As an example, using a rule that states *"If vibration is higher than 200 microns, then there is an unbalance problem."* is unrealistic. That is because it implies that at 200 microns all is normal, but there is a problem at 201 microns.

Validity index is being used instead of traditional fuzzy logic application, where the evaluation of each rule is expressed in fuzzy membership and values, to simplify the evaluation and aggregation of individual rule results. To combine the fuzzy results from several IF-THEN rules into a single expression for a particular problem, the fuzzy terms must be defuzzified into numerical values and processed into one result. The validity index expresses the uncertainty/certainty of the fault being diagnosed at the level of individual rule evaluation and carried through to the aggregation. The Figure 4 example shows that when the 1X vibration components are less than 150 microns, the validity of the conclusion is 0 for

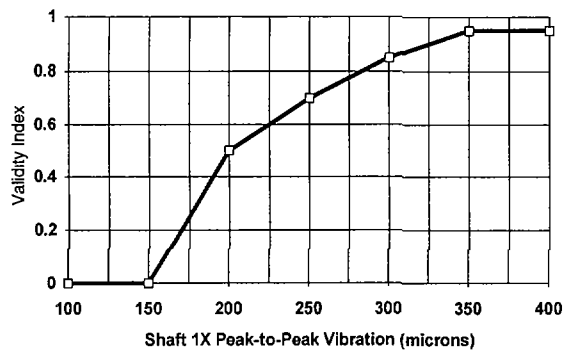

Figure 4 Validity Index for the Rule Example

the rotating element unbalance problem. When the vibration is greater than or equal to 350 microns the validity becomes 0.95. In this rule, the maximum validity index is set to 0.95 because the problem cannot be diagnosed with 100% confidence based on this single rule evaluation. In fact, for the rotating element unbalance problem, seven different rules, which evaluate data from eight different vibration signals are used in combination with other pertinent pump operation information. The validity indices from these seven rules are then combined into a single validity index and a fuzzy expression representing the rotating element unbalance problem. Linear interpolation of validity index is used throughout the rule evaluation, where each validity index table consists of 3 or more points. The use of a more refined curve does not provide added significance. The validity index is usually based on uncertainty of prediction and if available, on empirical data. The index is further adjusted for a particular pump at each site during the installation.

Another aspect of these recirculation pump expert rules is the extensive use of baseline data, which is the data obtained when the recirculation pump condition is NORMAL (steady state). For example, the rotating element unbalance fault is also being detected by the rule *"If the shaft coupling 1X vibration component shows an increase over the baseline value, then unbalance is indicated."* The amount of increase in this case will result in a particular validity index similar to the example described above.

These rules and the validity indices incorporate the expert knowledge from various sources such as plant operations and maintenance experience, test data, design specification, engineering principles, and published reports.

Rule Categories

The current version of the GE Recirculation Pump Diagnostic Expert Rules covers the following fault categories:

- misalignment
- unbalance
- bent shaft
- cracked shaft
- rubbing
- whirl instability
- restricted flow
- pump hydraulics
- pump impeller
- resonance
- structure support
- motor bearing
- pump seal problems
- loose parts

Rules for these fault categories are specifically designed for the BWR recirculation pump. However, the structures of these fault categories are independent and can be easily switched off or new categories can be switched in for other applications or as the problem experience grows.

MAN-MACHINE INTERFACE

This Expert System is designed with an all-graphic point-and-click type user interface that is simple and easy for a plant operator to understand. This design eliminates the need for a user's manual by having an intuitive user interface design. The normal operation screen display shows the status of the system and the pump condition pictorially with color codes. Upon detection of fault(s), the pump color changes from normal green to various colors corresponding to the degree of concern (validity index) for the fault(s). The fault category, diagnostic statement, and the validity index are also automatically displayed upon detection of a fault. If needed, the parameter and the actual data value that triggered the fault condition can be displayed by just three point and click operations.

FUTURE DEVELOPMENTS

This expert system is one of the steps in the ongoing development efforts to improve BWR plant operations and reduce maintenance costs. Some of the features which would further enhance this and other rule based expert systems are:

1) Prognoses to provide plant operators even more concise equipment and component specific information,
2) Root/cause analysis and recommended action for each diagnosis,
3) Integration with equipment monitoring systems for predictive maintenance,
4) Neural network application to automatically update the baseline data and the validity indices with actual in-plant equipment behavior and experience, and
5) Forecasting remaining life of equipment and its components, even when there is no fault.

CONCLUSION

BWR plant equipment monitoring systems provide monitoring of abnormal signals based on data sent from the sensors on plant equipment. Expert systems supplement this by diagnosing equipment operating faults. By designing the expert system specifically for the BWR recirculation pumps, it enables full utilization of all aspects of BWR recirculation pump specific information. Therefore, in addition to general rotating machinery diagnostics information, its knowledge base includes recirculation pump and motor design expertise, plant operations and maintenance experience and diagnostic methods from expert vibration engineers. Compilation of all this recirculation pump and motor specific knowledge also results in more focused diagnoses and allows easier future development in prognoses and neural net application. However, for the current system to be effective, the system must be adjusted for a particular site and any unique recirculation pump operating conditions. Need for this manual adjustment can be further reduced by better use of equipment specific information and neural net application.

REFERENCES

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