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ABSTRACT

In order to reliably and safely operate a nuclear power plant, it is necessary to continuously monitor the performance of numerous subsystems to confirm that the plant state is within its prescribed limits. An important function of a properly designed monitoring system is the detection of incipient faults in all subsystems (with the avoidance of false alarms) coupled with an information system that provides the operators with fault diagnosis, prognosis of fault progression and recommended (either automatic or prescriptive) corrective action. In this paper, such a system is described that has been applied to reactor coolant pumps. This system includes a sensitive pattern-recognition technique based upon the sequential probability ratio test (SPRT) that detects incipient faults from validated signals, an expert system embodying knowledge bases on pump and sensor performance, extensive hypertext files containing operating and emergency procedures as well as pump and sensor information and a graphical interface providing the operator with easily perceived information on the location and character of the fault as well as recommended corrective action. This system is in the prototype stage and is currently being validated utilizing data from a liquid-metal cooled fast reactor (EBR-II).

INTRODUCTION

The objective of this paper is the presentation of a general purpose monitoring and diagnosis system based upon modern artificial intelligence techniques that has been applied to the surveillance of a nuclear reactor coolant pumping system. During the development of this system, the primary criteria that were deemed essential to its acceptability and usefulness to an operator included: ease of use (e.g., runs in the "background" of the data acquisition system, DAS, and does not interrupt the operator unless a fault is detected, does not require understanding of the details of the programming, utilizes a graphical user interface, etc.); continuously validates all signals monitored prior to processing (rejects the use of malfunctioning sensors in the diagnosis of system behavior but identifies these sensors and diagnoses their fault); excludes false alarms and missed alarms to a preset certainty as well as detects faults extremely early in their development well prior to any potential damage (this effectively excludes the use of simple high/low limit testing methods); permits directed and immediate access to appropriate detailed procedures; offers explanations of diagnostic, prognostic and corrective conclusions; does not adversely interact with the normal and safety functions of the data acquisition system; and permits easy evolution of the system as operating experience is accumulated. In addition, the system should be tested and validated using data in real-time from an operating power plant to provide confidence and experience in its use by the operators and supervisory personnel prior to its final implementation in the control room.

Since it is essential that only validated data be sent to any diagnostic program and also that alarms should be detected early and not be missed or falsely indicated, it was felt that the use of nominal, smoothed sensor data with high/low limit tests was inadequate and could not be directly used. Thus, a technique was adapted from an extremely sensitive statistical test, the sequential probability ratio test (SPRT), that examines the noise characteristics on signals from identical pairs of sensors deployed for redundant readings of continuous physical processes from a particular subsystem or component. The comparative analysis of the noise characteristics of a pair of signals as opposed to their mean values permits an early identification of a disturbance prior to significant (grossly observable) changes in the operating state of the process. For example, a change in the skewness, bias or variance of the signals can be detected by the SPRT and used to initiate the automatic diagnostic program and annunciated to the operators. The use of two or more identical sensors also permits the validation of these sensors, i.e., determines if the indicated disturbance is due to a change in the physical process or to a fault in either of the sensors.

In addition, it is desired to permit the operators to focus on the current problem and not to overwhelm

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them with large amounts of data. This leads to the use of an embedded expert diagnostic system that embodies operational experience of the relevant physical processes and sensors. Once a disturbance is indicated, the expert system reads in the pertinent data from the DAS (after validation by SPRT), performs a diagnosis of the fault, and after informing the operator of the problem, offers prescriptive actions as well as direct access to the proper operational procedures through the use of hypertext files.

This system is in an advanced prototype stage and is currently being tested and validated on a sodium-cooled fast reactor (EBR-II) located at Argonne National Laboratory - West in Idaho. This reactor is operated by Argonne for the Department of Energy and is currently the only electrical power producing reactor of its type in the U.S. The primary mission of EBR-II is to serve as a test bed to demonstrate the advanced technological capabilities of liquid-metal-cooled and metal-fueled fast reactors for potential future commercial application. These capabilities include enhanced and inherently safe operational characteristics, a closed fuel cycle with no need for fissionable material to leave the reactor site, capability to "burn" high level waste from commercial light water reactors to generate power and to drastically reduce the high-level radioactive waste disposal problem, and the capability to test advanced monitoring, diagnostic and control technologies in a "real" environment. In addition, the reactor plant is well instrumented with temperature, pressure, flow, radiation and other sensors, particularly along its principal heat transport circuits.

OVERVIEW OF THE SPRT TECHNIQUE

The theoretical basis of the SPRT technique has been previously described (Ref. 1) and hence, only a brief overview will be presented here. The basic approach taken by this technique is to analyze successive observations of a discrete physical process by a comparison of the stochastic components of the signals generated by similar sensors monitoring the process. If Y_K represents a discretized difference sample from two sensors at time T_K, the set of values $\{Y_K\}$ should be normally distributed with a mean of zero if the system is operating normally and the sensors are functioning within their specifications. Note that if the two signals being compared have different nominal means (due, for example, to differences in calibration), then the input signals will be pre-normalized to the same nominal means during initial operation.

The goal of the sequential measurement of Y_K is to declare that the system is degraded if the set $\{Y_K\}$ exhibits a non-zero mean, e.g., a mean of either +M or -M, where M is a pre-assigned system disturbance magnitude. The problem is to decide between two hypotheses: H_1, the set $\{Y_K\}$ forms a Gaussian[1] probability distribution function with mean M and variance σ^2; or H_2, the set $\{Y_K\}$ forms a Gaussian probability distribution function with mean 0 and variance σ^2. The SPRT technique provides a quantitative framework that permits a decision to be made between these two hypotheses (for both the physical process and the sensors) with specified (input) misidentification probabilities. Specifically, the user must input an acceptable false alarm probability (α, the probability of accepting H_1 when H_2 is true) and missed alarm probability (β, the probability of accepting H_2 when H_1 is true). Utilizing these input values, it can be mathematically demonstrated that a decision strategy can be based upon the comparison of a statistical quantity developed in Reference 1 (based upon a sequential measurement and comparison of the values Y_K and defined here just as S) with a function of α and β as follows:

if $S < \ln(\beta/(1-\alpha))$,	accept H_2;
if $\ln(\beta/(1-\alpha)) < S < \ln((1-\beta)/\alpha)$,	continue sampling;
if $S > \ln((1-\beta)/\alpha)$,	accept H_1.

The value S is sequentially computed at each discrete time interval that a value Y_K is determined and its value is monitored (within the program) relative to the above criteria in order to determine whether or not an alarm should be annunciated and the expert diagnostic system automatically initiated.

Based upon the theoretical work presented in Reference 2, it has been shown that a decision test using the SPRT method has an optimal property; that is, for given probabilities α and β there is no other possible procedure with lower error probabilities or expected risk and with shorter length average sampling time than the SPRT. It is because of this property of the SPRT and its inherent simplicity that it was chosen as the disturbance detection tool for this monitoring and diagnostic tool.

DESCRIPTION AND OPERATION OF DIAGNOSTIC SYSTEM

An overview of the diagnostic system is shown in Figure 1. As indicated earlier, although the system has been developed in a generalized manner so as to perform monitoring and diagnostic tasks of any system, the current prototype has been restricted to reactor coolant pumps. The basic data utilized by the system include the signals generated by seven sensors attached to each of two pumps. These sensors measure the pump impeller rotational speed (with three redundant tachometers), the vibration of the pump housing (with two redundant accelerometers), the electrical power drawn by the pump and the coolant discharge pressure from the pump. These signals are sent to the DAS from the sensors where they are converted into engineering units and then fed into the artificial-intelligence-based inference engine and finally to the display media in the reactor control room.

The diagnostic system (referred to in Figure 1 as the AI inference engine) consists of several modules

[1] If the probability distribution function is not Gaussian, the SPRT technique can still be used, but its mathematical basis is substantially modified. The work demonstrating this application will be the subject of a forthcoming paper.

written in the C programming language and linked together in a structure that permits unidirectional goal-driven logic as well as recursive searching. Its overall architecture is shown in Figure 2 where it is seen that the user interfaces with the system only at the front-end (simply to initiate the system and to identify the particular sub-system to be monitored) and at the back-end (where the diagnosis, prognosis and corrective action(s) are provided as well as access to explanations, procedures, etc.).

Once initiated through the front-end driver, the system actuates the fault-detection system which has a buffered interface with the plant data acquisition system. The digitized signals from the specified sub-system (the reactor coolant pump in the present application) are read into computer memory from the DAS and passed through a logic structure incorporating the SPRT technique. Essentially, the algorithms in this structure perform the SPRT analysis on each pair of sensors, determining if any degradation is present. If all sensors show normal, then the time step is incremented, a new set of data from the DAS is read, and the process repeats with a passive notice appearing on the monitor indicating that the system is operating normally. However, if degradation of a signal is observed, the particular sensors are first validated; if they fail the validation, a sensor fault is declared and control passed to the sensor diagnostic system. If all the sensors are validated, then a fault in the pump operation is declared and control passed to the pump diagnostic system. Once the pump or sensor diagnostic systems complete their assessment of the fault, the resulting information is passed to the operator through a display on the monitor and a complete report of the event recorded in a file on hard disk for future reference.

The pump and sensor diagnostic systems were both developed using the 1st-CLASS Hypertext expert shell supplied by the 1st-Class Expert Systems Corporation. This product was chosen for several reasons, including its ease of embedment within a larger code structure written in the C language, its ability to utilize both shallow and deep knowledge within and linked to the shell, the ease of linking exterior data bases to the final system and its inclusion of hypertext features.

A more detailed description of the overall system is shown in Figure 3 where most of the intermediate and critical steps in the data handling and logic flow are indicated. The user initiates the system through a front-end graphic-interfaced driver system where choices are made relative to which plant subsystems or components are wished to be monitored. At the present time, only the reactor coolant pumps in the primary pumping system are implemented. Once initiated, data from the pre-selected sensors (the particular choice of sensors is made internally based upon the user selection of the subsystem to be checked) are read from the plant DAS for continual processing and surveillance. Due to the stringent configuration and function control placed on the DAS of a nuclear power plant, it is necessary to buffer the system from the DAS resulting in an effectively read-only access to the plant data.

The signals from the selected sensors are passed through a net utilizing the SPRT algorithms searching for either sensor or process disturbances. If normal operation is confirmed, a notice is generated on the monitor screen to indicate that the pumps are within their normal operating state and then a new set of data are read and the search for disturbances repeated. This internal iterative looping is continued until either the operator terminates the diagnostic system operation or a fault is detected. If a fault is detected, the SPRT-based algorithms then identify the source of the fault, i.e., a sensor mal-function or a disturbance in the physical process (pump operation). Based upon this determination, control is then passed to either the pump or sensor diagnostic program. In addition, the data that will be needed for the final diagnosis is generated (additional data may be read from DAS and existing data converted into the format needed for subsequent handling) and written to a separate file for access by the downstream programs.

If the disturbance was identified by the SPRT algorithms as originating in one of the sensors, an expert diagnostic system specific to that sensor is activated. This system initiates a search for the root cause of the disturbance in the identified sensor by a combination of forward and backward chaining in the rule-based logic structure accompanied by data input read from the file(s) generated in the fault detection/sensor validation phase as well as execution of mathematical models (in external codes) of the sensor behavior. Typical faults searched for by this system include signal drift, change in signal bias (offset), increased stochastic content in signal, complete or partial loss of signal, etc. It was necessary to develop a separate knowledge base and expert system for each sensor type since the dynamics and failure modes of the diverse types of sensors involved precluded a generalized and unified approach. Of course, conditional branches leading to individualized knowledge bases contained within a single system could have been utilized, but the approach taken results in a more flexible system relative to its amenability to upgrading and transferring to other applications.

If all of the sensors were validated, i.e., confirmed as operating within their normal specifications, and a disturbance was indicated to exist in the physical process (pump), then the expert diagnostic system for the pumping system is initiated. This system operates similarly to those used for the sensors, but includes not only information on the pump itself, but other plant parameters that are affected by or contribute to the operation of the pump. Since the EBR-II plant has two reactor coolant pumps that provide flow through independent piping systems that ultimately merge in a mixing plenum, it is necessary to include a considerable amount of information on the hydraulic characteristics of this plant system in order to interpret the measured data relative to potential faults. This can be accomplished either by a detailed mathematical model of the hydraulic circuit including the pumps, or through an extensive set of "if-then" rules. The approach taken here was a combination of these, where a simplified thermal-hydraulic model was used in conjunction with a shortened list of rules.

Once either of the expert diagnostic systems reaches a conclusion as to the cause of the disturbance, the operator is immediately notified through an annunciated message on the monitor screen and a detailed report is written in a file on the hard disk for future reference. Through a graphically-displayed screen message, the operator is also informed of the exact problem, its cause, recommended corrective action and is offered the option of requesting an explanation of the logic and information used by the system to arrive at its conclusions. In addition, the operator can directly access the appropriate operating or emergency procedures or system design descriptions of the affected sensor or pump. Since these documents have been largely converted to a hypertext format, the pertinent sections of the documents (as well as specific key words or phrases within the documents) can be immediately accessed by the firing of rules related to the identified fault or by manual action of the operator at the keyboard.

LOGIC FLOW WITHIN THE SPRT-BASED DISTURBANCE NET

Since an essential aspect of this system is the use of a disturbance net through which the data are passed, a brief description of the use of the SPRT technique within this net will be presented. Referring to Figure 4, the measured impeller rotational speeds from both pumps (averaged values from three sensors) are initially passed through the SPRT algorithms searching for a disturbance. If normal operation of these sensors is confirmed, the other sensor signals are sequentially evaluated; if all sensors indicate normal conditions, a new set of data are read from DAS and the process is repeated. However, if a fault is detected in any pair of signals, more detailed SPRT evaluations are performed. Only the branch for impeller speed sensors is shown in Figure 4 where comparative tests of combinations of sensors A1, B1 and C1 from pump 1 are made searching for faults in these sensors. If a fault is confirmed, then the operator is alerted and the diagnostic expert system for the identified sensor is initiated. If all speed sensors from pump 1 are shown to be operating properly and their signals validated, then the process is repeated for the same set of sensors from pump 2.

If the SPRT analysis of the three signals from pump 2 also confirms normal operation, then all pump speed sensors from both pumps will have been validated and the only possible conclusion is that there is a disturbance in the operating state of the pumping system. The operators are alerted and the expert diagnostic system for the pump system is initiated. On the other hand, if a fault is detected in one or more of the pump 2 speed sensors, then the expert diagnostic system for the affected sensor(s) is initiated.

Experience accumulated to date on the performance of this SPRT net, using actual data from EBR-II from archival digital tapes, indicates that faults can be detected in real time and in advance of any observable disturbances in the mean signals. This conclusion and supporting evidence has been presented in Reference 3.

SUMMARY AND CONCLUSIONS

In this paper, a technique utilizing a statistical-based pattern-recognition approach (the sequential probability ratio test or SPRT) coupled with expert system-based diagnostic tools that can be used for the surveillance, validation, fault detection, diagnosis, prognosis, and prescriptive corrective action of a dynamic system has been described. Although this technique has application in almost any system that includes redundant instrumentation, the prototype currently under test and validation has been focused upon nuclear reactor primary coolant pumps. The fully validated system will provide operators extremely early notification and diagnosis of disturbances in the operation of coolant pumps along with recommended corrective action based upon existing plant operational and emergency procedures through the use of hypertext files. Successful implementation of this system has the potential of avoiding damage to the reactor coolant pumps as well as contributing to improved plant availability through the early detection of incipient disturbances and the avoidance of false alarms. Preliminary testing of this system has been conducted utilizing archival data tapes from the EBR-II fast reactor. Plans are currently underway to install the system directly within the EBR-II plant data acquisition system in order to evaluate its performance in a realistic operating environment in order to qualify it for potential permanent use in the control room.

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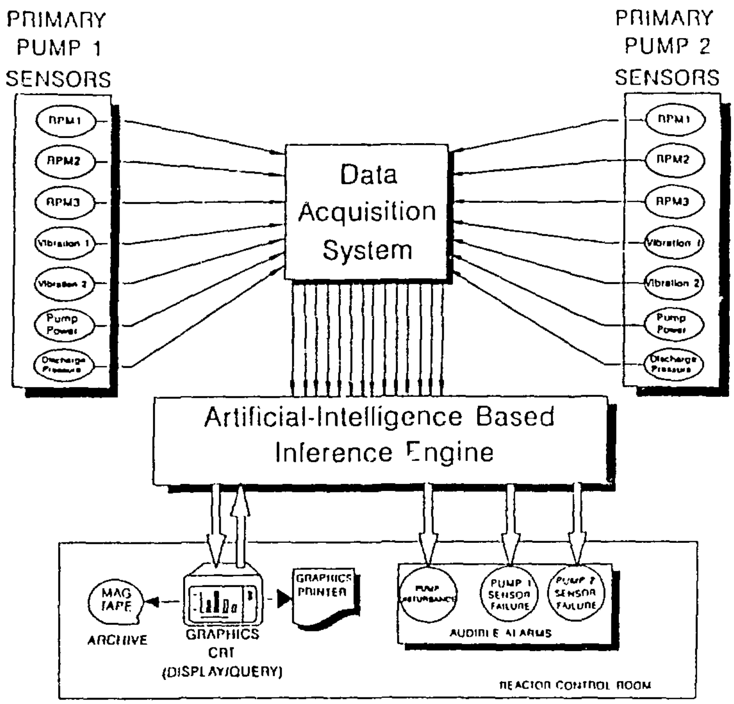

Fig. 1. EXPERT SYSTEM FOR ONLINE SURVEILLANCE OF NUCLEAR REACTOR COOLANT PUMPS

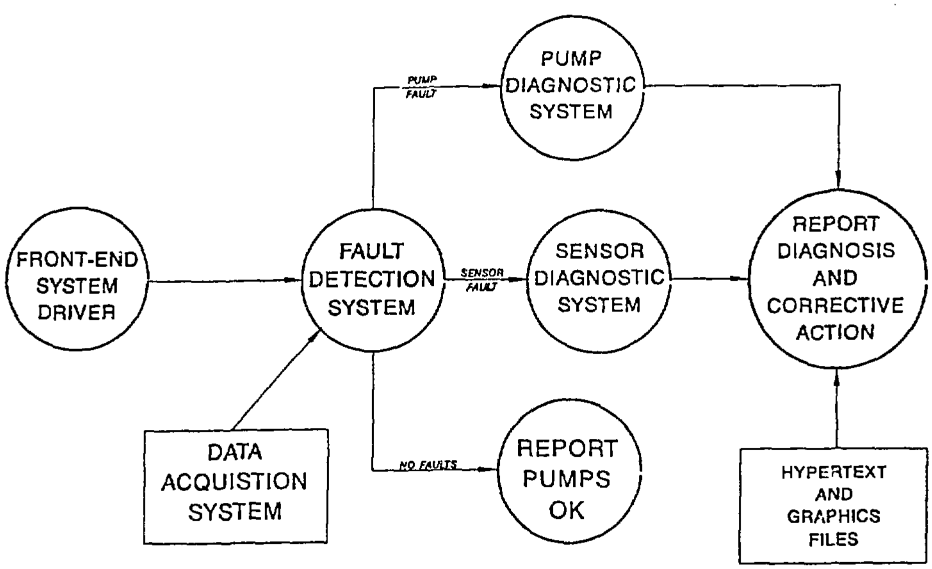

Fig. 2. SIMPLIFIED PUMP DIAGNOSTIC SYSTEM

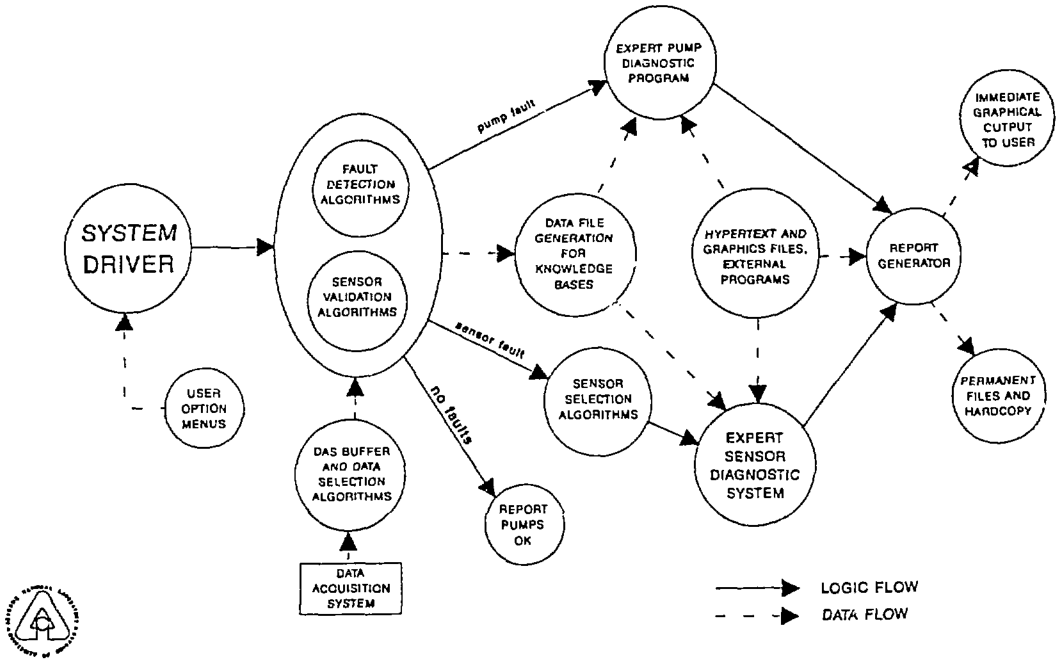

Fig. 3. EXPERT PUMP DIAGNOSTIC SYSTEM

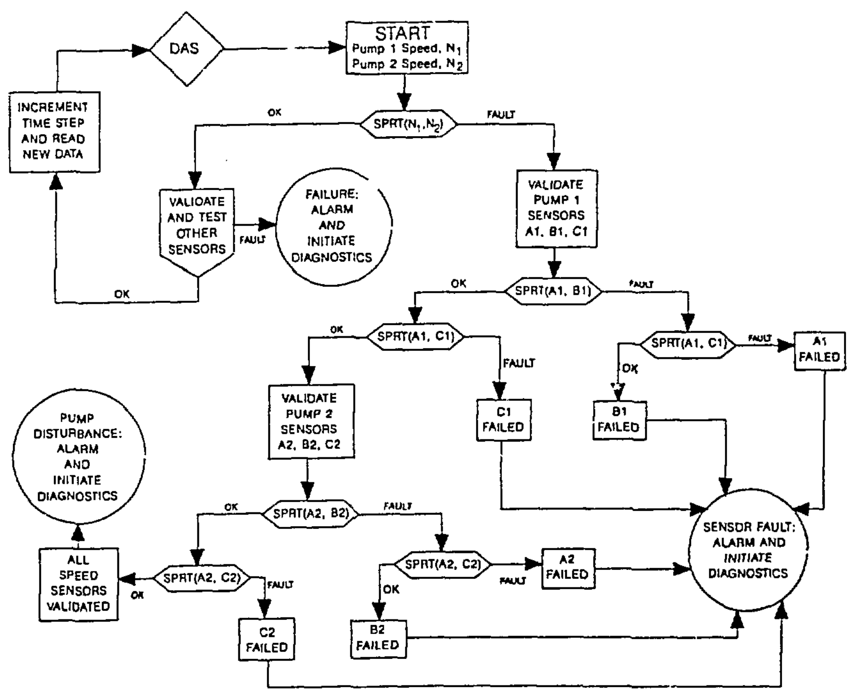

Fig. 4. SIMPLIFIED SPRT LOGIC DIAGRAM