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PSAD: CONDITION-BASED MAINTENANCE THROUGH PERMANENT MONITORING

ABSTRACT

Since the beginning of the French nuclear program, Electricité De France (EDF) has looked for ways to improve the availability and safety of its nuclear units. Therefore, monitoring systems on turbo-generators, reactor coolant pumps, primary circuits and core internal structures were designed by the Research and Development Division and implemented on 56 Pressurized Water Reactor units (PWRs) with technologies available during the 1970's.

The overriding goal of optimizing maintenance costs in power generating plants has led to the design and implementation of the PSAD condition monitoring system. Its main objectives are:

Prevent major failures: early and automatic detection of any abnormal behavior in critical equipment (turbo-generators, reactor coolant pumps, inlet valves, ...) using advanced continuous on-line vibration, hydraulic and thermal monitoring.

Predict and plan maintenance: provide plant maintenance operators and experts with powerful tools to diagnose the wear and other phenomena, identified or not, that characterize aging machinery; this should help them lower costs by reducing current preventive outage schedules.

Each component of a nuclear unit is monitored by its own fully autonomous Monitoring Unit. This rack-mounted system performs periodic or event-triggered acquisitions of plant signals, computes more elaborate data, triggers warning and alarm messages when a malfunction is detected, and applies intelligent data reduction to archive only significant information.

The Diagnosis Workstation centralizes the data storage for all monitoring units through a Local Area Network and provides the user interface to all control and diagnostic functions.

Warning messages are processed and sorted by seriousness then displayed in lists to optimize operator acknowledgment. A wide selection of graphical displays and plots let the user view the data in the most suitable and meaningful way. Other tools, such as statistical analysis, rely on the historical database information to detect long-term condition trends.

Plant operators can access monitoring databases covering machine lifetime, data import and export capabilities for comparisons and the opinions of experts sharing the data through the PSAD network and thus have the most information available for establishing an accurate diagnosis.

Designed using Object-Oriented methodology and based on recognized industrial standards, the PSAD is intended to perform over the whole plant lifetime. Its open structure lets it evolve towards new monitoring strategies such as Loose Part Detection in the primary circuit and Core Internal Structure Monitoring, both to be soon integrated.

PSAD systems are currently operating on four French nuclear units and it is projected that they be installed in all the others.

INTRODUCTION

Since the beginning of the French nuclear program, Electricité De France (EDF) has looked for ways to improve the availability and safety of its nuclear units. Therefore, monitoring systems on turbo-generators and reactor coolant pumps were designed by the Research and Development Division and implemented with technologies available during the 1970's.

The data processing modules which were designed for these two systems have proven their efficiency regarding incipient failure detection. The data collected and processed with this equipment was found to be very valuable for diagnostic purposes.

In addition, a recent study has shown the economic benefit of such monitoring systems for heavy components.

However several limitations to the existing systems have been identified:

- difficult data interpretation by plant personnel
- time consuming tasks in routine operation and maintenance of monitoring equipment
- heterogeneous technologies and programming languages
- "black box" type of equipment with no extension capabilities
- difficulty transmitting data between the plant personnel and centralized experts.
- EDF thus decided to design and develop a new generation of Monitoring and Diagnostic System called PSAD ("Poste de Surveillance et d'Aide au Diagnostic" in French), integrating all this background through state-of-the-art data acquisition and processing equipment, advanced computers, and artificial intelligence.

CONDITION-BASED MAINTENANCE With psad

The main objectives of a condition-based maintenance strategy using the PSAD system are:

- prevent failures before they occur,
- predict and optimize maintenance costs,
- reduce downtime through improved maintenance organization,
- increase plant efficiency.
- The PSAD provides plant personnel and experts with an efficient and user-friendly tool to assist decision making upon incipient failure detection on the main components of nuclear power plants.

For plant maintenance teams, the PSAD is primarily a condition-based maintenance tool. It provides accurate data acquisition, powerful data processing and automatic detection of abnormal conditions of the monitored components. Various data graphical displays and coupled expert systems provide operators with valuable diagnostic tools.

Secondly, the PSAD is also designed for condition monitoring specialists who must analyze difficult or not yet identified cases. The communication facilities allow experts at a plant site or on a remote workstation to assimilate data from the entire life of all machines monitored by a PSAD on the network. Then, the open structure allows each PSAD to be updated with any new algorithms and characterization functions developed.

The major features introduced by PSAD are:

- early, on-line detection of operating faults,
- compute of significant complementary data in real-time for an efficient diagnosis,
- assist the maintenance staff's diagnosis through the use of expert systems,
- offer a homogenous user interface for all of the monitoring functions,
- ability to transfer any data to the EDF national analysis center for further diagnosis by experts,
- ability to modify the machinery descriptive configuration without stopping the whole system.

The PSAD is designed with a flexible hardware and software architecture to be open to new monitoring functions in the future.

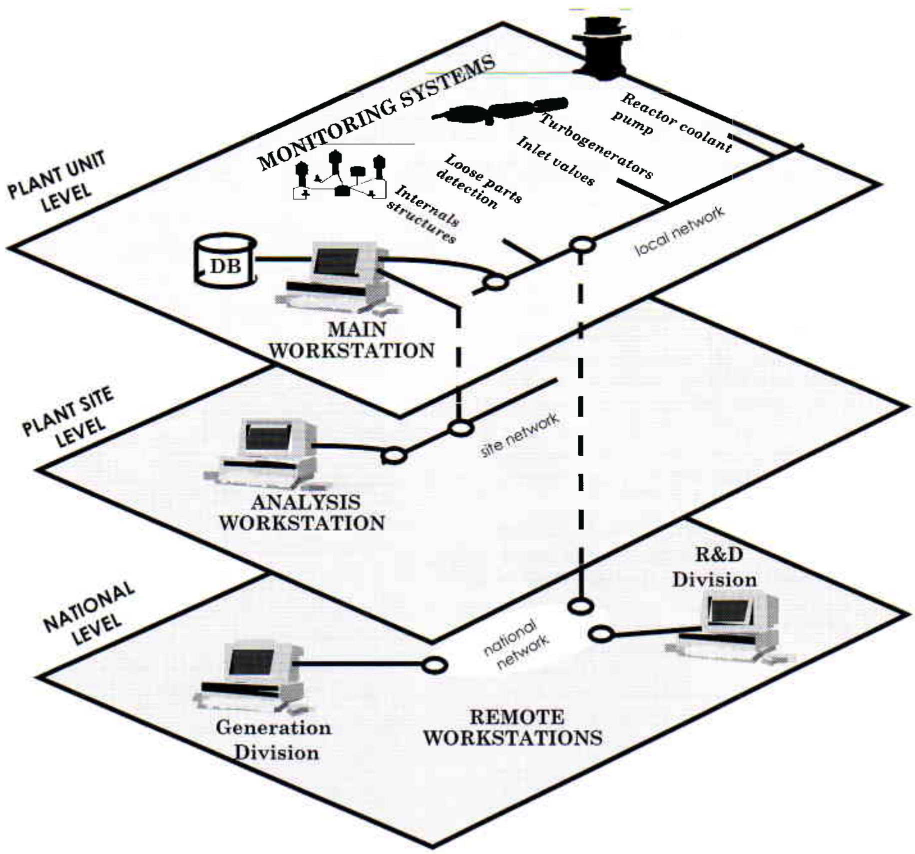

Figure 1: The PSAD's overall hardware architecture

The first version of PSAD performs the on-line monitoring of:

- the turbo-generator shaft line; up to 40 typical faults can be detected: unbalances (mechanical, thermal and rubbing), misalignment (bearings and supporting structures), lubrication defects (oil-whip), rotor faults (cracks, blade loss), coupling faults, etc...
- steam inlet valves to detect tightness defects, sticking, seat-body separation, stem break, etc...
- the reactor coolant pumps; up to 50 typical faults can be detected on the shaft and seals: bearings and motor like unbalances (mechanical, thermal and rubbing), misalignment (bearings and supporting structures), rotor faults (cracks, windings), damaged or sticking seals, etc...
- the generator where up to 10 typical faults can be detected such as ventilation problems, rubbing, short-circuits, rod defects, etc...

HARDWARE AND SOFTWARE DESIGN

The hardware architecture is divided along four levels:

- at the machinery level (turbo-generator, reactor coolant pumps, vessel, primary circuit, ...): several real-time Monitoring Units
- at the nuclear unit level: the Diagnosis Workstation
- at the site level: a plant Analysis Workstation
- at the national level (wherever corporate expert teams are located): Remote Workstations.

The plant-wide components communicate through local area networks and remote sites are connected through specialized communications lines.

On-Line Monitoring Units

The on-line monitoring units are located close to the monitored equipment in the plant and provide continuous acquisition of raw data and real-time processing of physical measurements. Each of them is dedicated to one or more machines, depending on the monitoring instrumentation: one monitoring unit can receive up to 150 sensors.

The PSAD system uses the concept of descriptors which represent a significant facet or characteristic for monitoring a machine.

The raw data make up the **Level 1 Descriptors**, acquired through specialized electronic or data processing boards. They include the values related to immediate machine operation: spectrum analysis, harmonic orders, RMS and peak-to-peak values, A/D conversion for static signals (temperature, pressure, flow,...), position and movements of valves, etc...

More specific data are computed by user-specified real-time algorithms using combinations of level 1 descriptors. These data, called **Level 2 Descriptors**, provide an additional significant description of the process which is not directly available from the sensors, for example rated power.

Level 1 & 2 descriptors are stored locally and monitored to determine if changes occur in the immediate condition of a machine, in which case warnings are generated automatically. Very innovative data reduction mechanisms are then applied to all data so that only significant information is transmitted to the Diagnosis Workstation for storage in the data base.

The Diagnosis Workstation

There is one Main Workstation for each nuclear unit which provides the main user interface for a PSAD system. Its screen display informs operator teams of malfunctions on the monitored components: warnings are displayed in different colors depending on their seriousness.

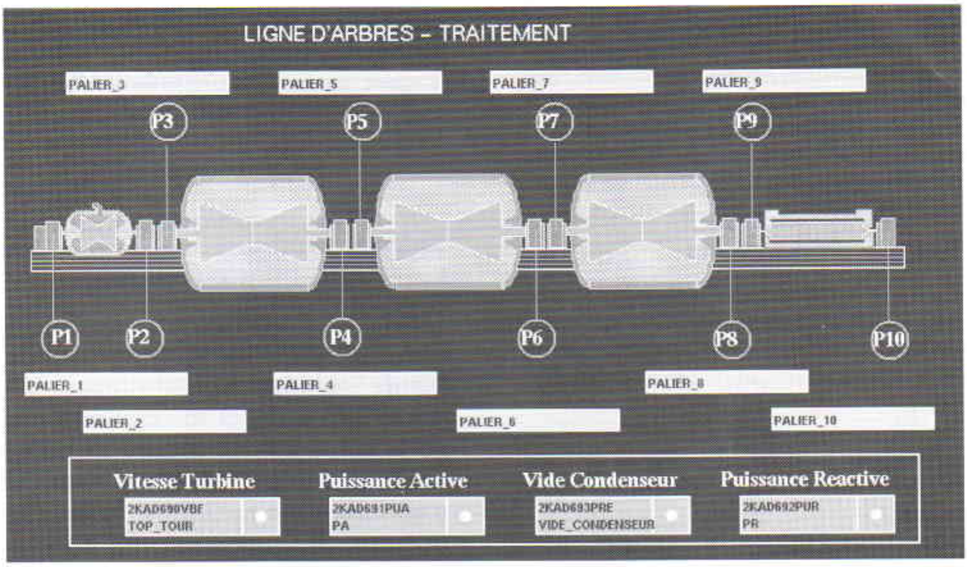

Figure 2: Turbo-generator diagram for descriptor selection

The Diagnosis Workstation also computes more information, called Level 3 Descriptors, based on the history of level 1 & 2 descriptors provided by the different monitoring units. They are used to track long term evolution, of a vibration for example, and perform statistical analyses. This information gives a complete characterization of the machine's operation under normal and abnormal conditions.

All of the descriptor values are stored in a high capacity relational data base resident on the Diagnosis Workstation. Historical data covering the entire machine lifetime are permanently available on disk, allowing immediate on-line access. Fully automatic backup to tape drives prevent any loss of data and guarantee minimal unavailability.

The operators and experts consult all of this historical data using sophisticated graphic display software and diagnostic functions including:

- quick and simple selection of the descriptors through explicit diagrams of the monitored components (see Figure 2 below); sets of descriptors to be graphed constitute a diagnostic context used to study a specific defect and can be saved and recalled by the various users
- a complete set of tools for graphing data: trends, Bode plots, Nyquist plots, spectra, Waterfall plots, bar charts, etc...

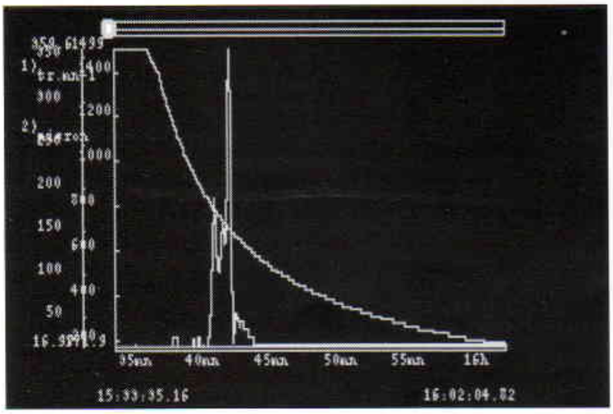

Figure 3: Example of overlaid plots

- identification of critical speeds: at the end of each run-down (or run-up), a modal identification algorithm determines critical speeds, modal damping and modal participation from measurements acquired in the frequency windows selected for each descriptor (e.g. bearing sensor 1, amplitude and phase of the 2nd order harmonic); a warning message will be triggered if these parameters evolve beyond a predefined threshold during subsequent speed-transition phases
- identification of resonance frequencies: while operating under rated conditions, the spectrum analysis of a rotating machine vibration signal makes it possible to highlight both the response to harmonic excitations and modal responses to wide band excitations (fluid, steam, etc.)
- statistical analysis tools: besides monitoring the usual signal levels under nominal conditions, the PSAD implements supervision based on a statistical analysis; its purpose is to define statistical reference states for the behavior of machines and to be able to diagnose mechanical deterioration by following any changes over time
- determine the sensitivity to operating parameters: at a given operating speed, the PSAD system computes the vibration sensitivity of the machine to variations of an operating parameter such as the power or output voltage of a generator; this sensitivity vector is stored and a warning message is generated if its value progresses beyond configured thresholds
- compute a deviation vector: the average vibration vector (1st and 2nd harmonics) of the vibration magnitude is computed continuously and compared with a reference value; several types of messages can be generated, depending on the extent or the persistence of any difference between the two
- measure valve stroke times during openings and closures: through periodic maintenance tests, the PSAD can detect any variations due to abnormal rubbing.

The Site Analysis Workstation

The Analysis Workstation is a central access point to the data stored on the different Diagnosis Workstations of a plant site.

All the graphical and diagnostic functionality of a Diagnostic Workstation is duplicated to provide a parallel assistance with a diagnosis. All data is obtained directly from the PSAD systems being studied through remote queries of their databases.

The maintenance analysts can thus perform behavior comparisons and data correlation between the monitored components of different nuclear units.

Remote Workstations

Any number of Remote Workstations can be connected by specialized communication lines or networks to the PSAD systems available at a corporate level. They are typically located at the headquarters of the Generation and Research & Development Divisions.

Again using remote queries, data are transferred to a Remote Workstation from local databases at the different sites. Data can also be exchanged with complementary expert systems for further analysis.

These workstations are used by national experts or equipment specialists either to perform general studies of component behaviors or to confirm and complete a pre-diagnosis initiated on site.

STANDARDS

The PSAD is an open and evolutionary tool. It has been designed to host new monitoring, processing and diagnostic applications. It is based on widely recognized industry standards:

- sensors are connected to VXI standard (VME eXtension for Instrumentation) acquisition boards
- an ORACLE relational data base management system ensures the storage and retrieval of information and a data export capability to other applications (SQL)
- communications are based on Ethernet protocols (TCP/IP): new monitoring units and analysis workstations can easily be connected to the LAN
- a user interface built upon the X-MOTIF standard
- all software was developed using an object-oriented methodology and is written in ADA and C to guarantee system maintainability and upgradability.

FUTURE MONITORING FUNCTIONS

Loose Part Detection (LPD)

The primary cooling system in nuclear power plants includes a great number of components which are subject to repeated stress. Certain parts can break off and be carried away with circulating coolant until they reach and remain in a specific area called the "trapping zone". Such objects may weigh several hundred grams and can cause major damage incurring costly repairs.

While such incidents are rare, an automatic monitoring system must be able to detect loose parts and alert plant operators when necessary. Loose part detection is based on the observation of acoustic waves produced by these objects as they hit the walls of the primary cooling system:

- when a loose part hits the structure of the extended primary cooling system, the waves produced by the impact are propagated throughout the structure. The appearance of coinciding

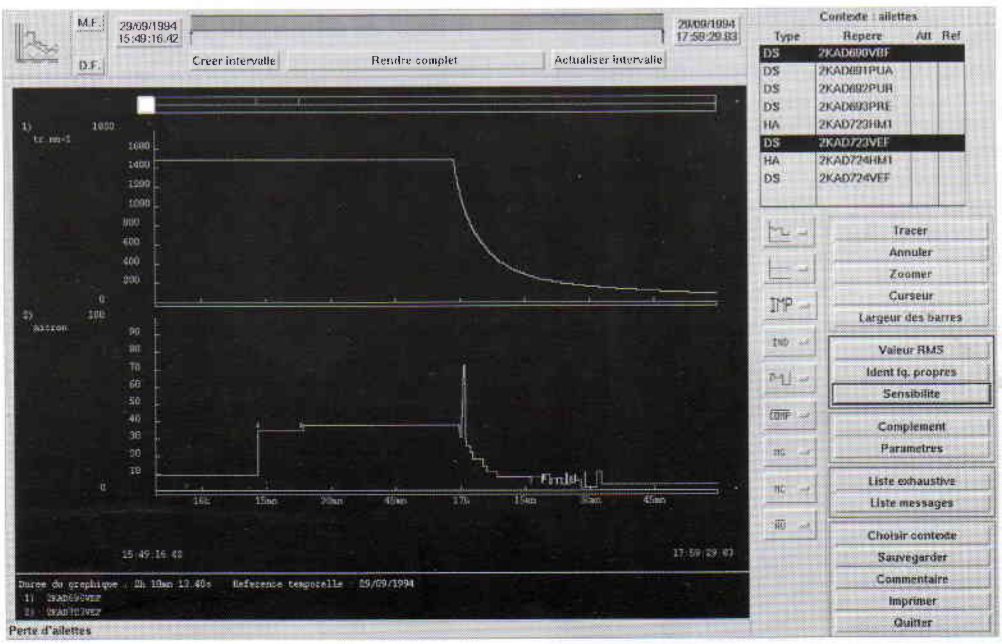

Figure 4: A graphical analysis screen on the PSAD Diagnosis Workstation

transients (called a coincidence) in the signal from the different sensors of a given zone characterizes a mechanical impact.

- as loose parts are trapped, they hit the structure in a repetitive manner. The rate of coincident impacts is therefore characteristic of a loose part.

The objective of the LPD function is to trigger an alarm only for loose parts (using noise filtering to avoid false alarms), while alerting operators of any doubtful cases.

Elaborated signal processing has been developed and automatic detection and characterization of events are performed by a monitoring unit while automatic statistical analysis, localization and graphical analysis of a loose part event, confirmed or suspected, are performed on the PSAD Diagnosis Workstation.

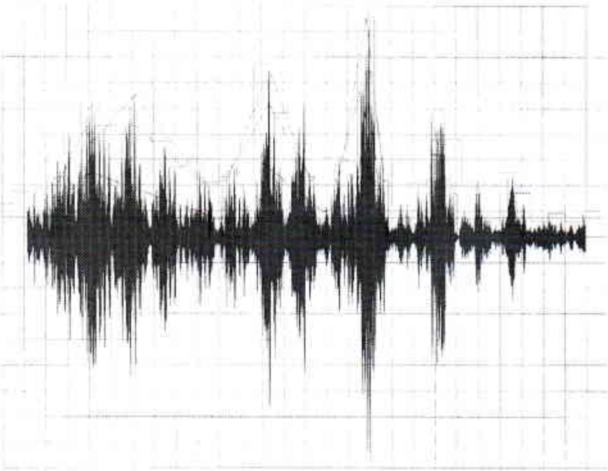

Figure 5: Loose part impact characterization

Core Internal Structure Monitoring (CISM)

Vibration analysis of the core internal structures monitors the good mechanical behavior of the hold-down spring, the attachments of the thermal shield on the core barrel, and the fuel rod assemblies. The potential incidents include loss of functions, rupture of flexures and deformation, or even rupture of fuel rod assembly spring sets and centering pins.

The CISM functionality must be able to discriminate between true vibration events and normal changes in vibration amplitude, indicating the transition from one normal state to another normal state. These different states correspond to different types of contact between internals and the vessel. In addition, CISM must be able to ignore the general increase of the monitoring signal level due to fuel burn up as well as help diagnose any malfunctions not yet observed.

Monitoring is based on spectrum analysis of two types of signals, each from a distinct set of sensors:

- ex-core neutron chambers on which the incident neutron flux varies with the thickness of the water layer between the core barrel and the reactor vessel
- accelerometers which detect forced vibration of internals on the reactor vessel.

Slow mechanical behavior changes imply an increase of vibration levels and decrease of frequencies. The periodic analysis of the vibration of the structures enables detection of such changes. Furthermore, continuous monitoring of vibration levels enables the detection of unusual signal variations, pointing out the beginning of some kind of degradation. This involves monitoring RMS values in frequency bands centered around known phenomena to detect any values which exceed predefined thresholds.

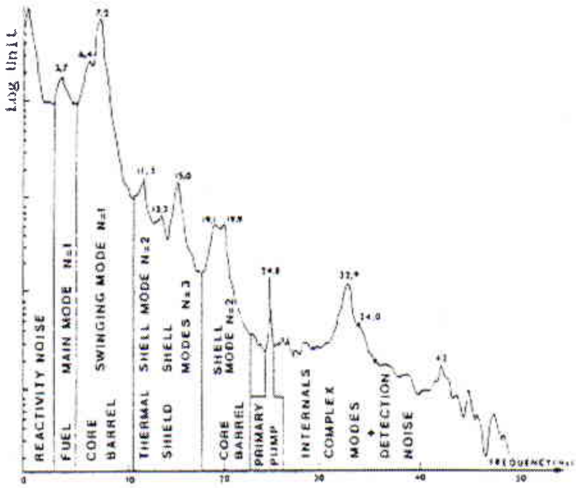

Figure 6: Main modes detected in a neutron noise signature (reactors with cylindrical thermal shields)

The PSAD diagnosis workstation automatically monitors two kinds of core internal structure behavior:

- detection of abnormally low frequencies and diagnosis of current vibration behavior
- detection of frequency decrease and adjustment for the evolution in the vibration behavior since the beginning of the current fuel cycle.

FEEDBACK FROM INSTALLED SYSTEMS

Four PSAD type monitoring systems are currently in operation on French power plants.

Three of them were installed in 1994 on the new 1500 MW nuclear units located at CHOOZ and CIVAUX. They are providing very useful data for two newly redesigned machines in use on these units: the turbo-generator and the reactor coolant pumps. Detailed behavior analysis were performed during machine installation, proving the efficiency of these monitoring systems. Maintenance teams are now using them on a regular basis, especially for determining resonance frequencies, analyzing vibrations and tracking long term evolution.

The latest version of the PSAD system was installed in 1995 on the TRICASTIN 900 MW nuclear unit. A detailed evaluation of the system has been performed at the unit and corporate levels. This feedback went into the final version which will be installed at CIVAUX Unit 2 by the end of the year and could be used for the other fifty French nuclear units.

REFERENCES

[1] *Monitoring and Aid to Diagnosis of French PWR*
A. JOUSSELIN, A. TRENTY, J.C. BENAS, Y. RENAULT, J.L. BUSQUET, B. MOUHAMED SMORN VII Conference, 1995.3

[2] *Monitoring of Large Rotating Machines at EDF*
R. CHEVALIER, G.P. OSWALD, J. MOREL IFTOMM