Using Expert Systems for Fault Detection and Diagnosis in Industrial Applications

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Abstract: This paper intended to motivate the introduction of the expert systems within the supervisory systems used in the automatic control of the industrial processes. Some concepts related to the problem of supervision and diagnosis, as well as the functions and principles associated are briefly presented. Emphases is given to the use of expert systems for diagnostic purposes. Some results obtained by the author in implementing an expert shell and using it in building real time expert systems for performance analysis and diagnosis are presented. The contribution shows how the fault detection and accommodation can be achieved through a proper integration of in process on-line monitoring and diagnosis expert system.

Key Words: Diagnosis, expert system, graphical user interface, performance analysis, real time.

Introduction: An expert system shell can be used as a base for the implementation of a real-time expert system for performance analysis and diagnosis of an industrial process. It assures a mechanism able to simplify the operator's job of recognition of the emergency state, diagnosis of the fault and initialization of the necessary corrective actions, offering him the alarms list and messages to define the primary cause as well as a list of priorities of potential solutions [1].

The use of such a system has the following results: prevent key components damages, extend critical components life-time, improve overall system performance and reliability, minimize off-line analysis efforts and maintenance costs, assist the maintenance activities, generating functional reports, and allow remote plant diagnosis and evaluation.

Basic Concepts of Fault Diagnosis: Due to the increasing complexity and risking of modern control systems and the growing demands for quality, cost efficiency, availability, reliability and safety, the call for fault tolerant in automatic control systems is gaining more and more importance [4].

Within the automatic control of technical systems, supervisory functions serve to indicate undesired or non-permitted process states, and to take appropriate actions in order to maintain the operation and to avoid damages or accidents. The necessity of such functions is required by the increasing complexity and risking of the modern complex control, process supervision in order to provide control enforcement via fault accommodation capabilities, and process management.

Fault Detection Methods: There are three types of methods which can be applied for fault diagnosis:

1. The *signal- based methods* are well established in practice. In this case, the maximum advisable information concerning the faults, which could appear in the system, is carried by directly measured signals or by the corresponding symptoms extracted from the system. These symptoms are directly used for fault detection and localization or after the data processing is performed. Such typical symptoms are: time variable magnitudes of the measured signals, maximum or average values, limit values, statistical moments of amplitude distribution, spectral power densities or frequencies, correlation coefficients, covariances, etc. The efficiency of the signal-based methods is limited, these methods being used for the early detection of the faults which can appear in the dynamic of the systems under consideration.

2. The majority of fault detection approaches uses knowledge about the physical processes in the form of mathematical models (*fault detection based on analytical models*). This approach is more efficient than the signal-based one. In this case, the actual behavior of the system is compared with that of a normal fault-free model driven by the same inputs. The dynamic behavior of the system is described using the relationship between the measurable quantities in the form of a quantitative (analytical) model. If available, a perfect analytical model describes the most detailed and concise knowledge about the process.

3. However, it is very difficult to obtain accurate process analytical models, being practically impossible in the case of complex systems. The *knowledge- based methods* represents a complementary solution for the analytical methods used for fault detection. They provide a new dimension of the fault diagnosis of the complex processes, where the knowledge is generally incomplete. In this case, the system behavior is specified using both heuristic symptoms and qualitative descriptions in the form of rules and facts, obtained from empirical human observation.

The combination of these strategies allows the evaluation of all available information and knowledge of the system of fault detection.

Motivations for the Use of Expert Systems in Process Supervision and Diagnosis: The traditional methods - (1) and (2) - are well established and provide a rapid development, but are limited in their efficiency. The role of the knowledge-based approach in process supervision and diagnosis is to provide some interesting solutions for the supervision problems. It is necessary to consider this approach not as a substitution of the traditional methods, but as a supplementary tool for an engineer who has to find a solution to a specific problem. The role of the knowledge-based approach for fault diagnosis can be considered from several points of view [6]:

- *declarative*: the implementation of several reasoning strategies (prediction, postdiction, diagnosis, etc.) is permitted and is not based on the existing knowledge;
- *explicative*: the man-machine co-operation is enhanced, using causal reasoning as a base for diagnosis and explanations;
- *management of different types of data*: imprecise (measurement noise), incomplete (sensor faults), non-homogenous (logical and analogical data), dependent of the context, temporal, etc. These data are used in order to include in the system all the available information, even the heuristic one.

In the knowledge-based techniques, any symptoms can be used instead of output signals and the robustness can be attained by restricting to only those symptoms that are not or not strongly dependent upon the system uncertainty. This technique can be applied in all three phases of fault diagnosis, the theory of diagnosis being developed from first principles (system structure and behavior descriptions).

The residual evaluation is a complex logical process which demands intelligent decision making techniques like fault trees. Therefore, knowledge-based methods are a quite natural approach in fault diagnosis and the *expert systems (ES)* are applied more successfully in this field that in the control domain. This was the result of an analyze of about 2500 expert system (Durkin, 1994). Figure 1 proves that the diagnose is a field in which the ES role is predominant because ES plays the same role as an human expert and are easy to develop, the number of possible solutions and information being finite.

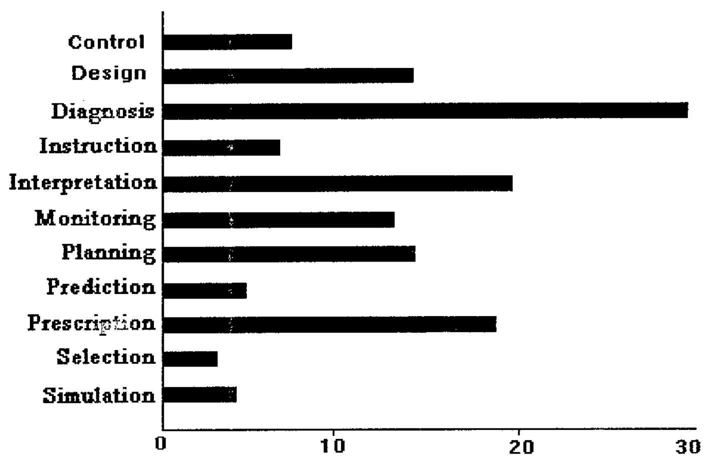

Fig. 2 - % Applications (Durkin, 1994)

The Architecture Of Fault Detection And Diagnosis System: The architecture of the fault detection and diagnosis system is presented in Fig. 2. The core is an on-line expert system which complements the analytical model-based method with the knowledge-based methods using heuristic reasoning. The resulting overall fault detection system consists of the following architectural components:

- *knowledge-base* with heuristic (qualitative) process models expressed in form of rules related to the physical cause-effect relationships;
- *data-base* with information (facts) about the present state and the history of the process;
- *inference engine* which combines heuristic reasoning with algorithmic operations in terms of evaluation of the analytical redundancy;
- *explanation component* used to inform the user on why and how the conclusions were drawn;
- *co-ordinating routines* which assures reliable communication with the monitoring application, internal synchronization and data-base and knowledge-base consistencies;
- *user interface* which is a windowing type interface used for both building and exploitation of the system. Some major characteristics are: representation of the structure of the system; automatic alarming of the operator, on-line displaying of data and messages, high speed in providing the system reaction to fault conditions.

The knowledge of the system is acquired from an expert who might be not the same person as the user.

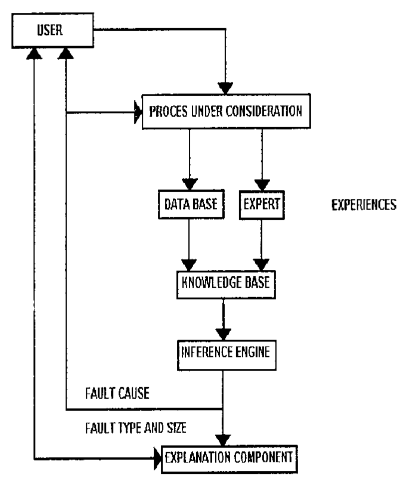

Fig.2 - Architecture of the fault detection and diagnosis system

Expert Systems for Performance Analysis and Diagnosis in PV Plants: The paper aims to present the results obtained in the implementation of an expert shell that can be used to develop a real-time expert systems. This expert shell was used as a base for the implementation of a real-time expert system for performance analysis and diagnosis of a PV plant, in the frame of a Joule II European project. The results obtained using this expert system in Zambelli PV plant (near Verona, Italy) are also presented in the paper.

A photovoltaic system can be represented by a transfer function with the solar irradiance as input and an electrical value (power, etc.) as output [7]. The components of a *PV plant* are PV array (made by monocrystaline or polycrystalline cells), batteries (usually Pb batteries) and power conditioning block (converters, rectifiers, switches and inverters). The PV pilot plant Zambelli is a part of the water pumping station for Verona city and consists of PV arrays of 70 kW and 360V, two inverters of 35 kWA with variable frequency, two strings of batteries of 300 Ah.

In global supervision of a PV plant, an important amount of data is measured and calculated by the monitoring system in order to analyze the system performances and to detect and diagnose the possible faults. These data are inhomogeneous (logical and analogical data), temporal, imprecise (affected by measurement noise) and incomplete (due to sensors' faults). There are hundreds data linked by complex relationships. Heuristic and qualitative observation (i. e. for meteorological conditions) have to be used. That is why the utility and validity of analytical models is quite uncertain, especially in case of faults. The expert systems provide new interesting solutions for supervision problems, and taking of intelligent decisions.

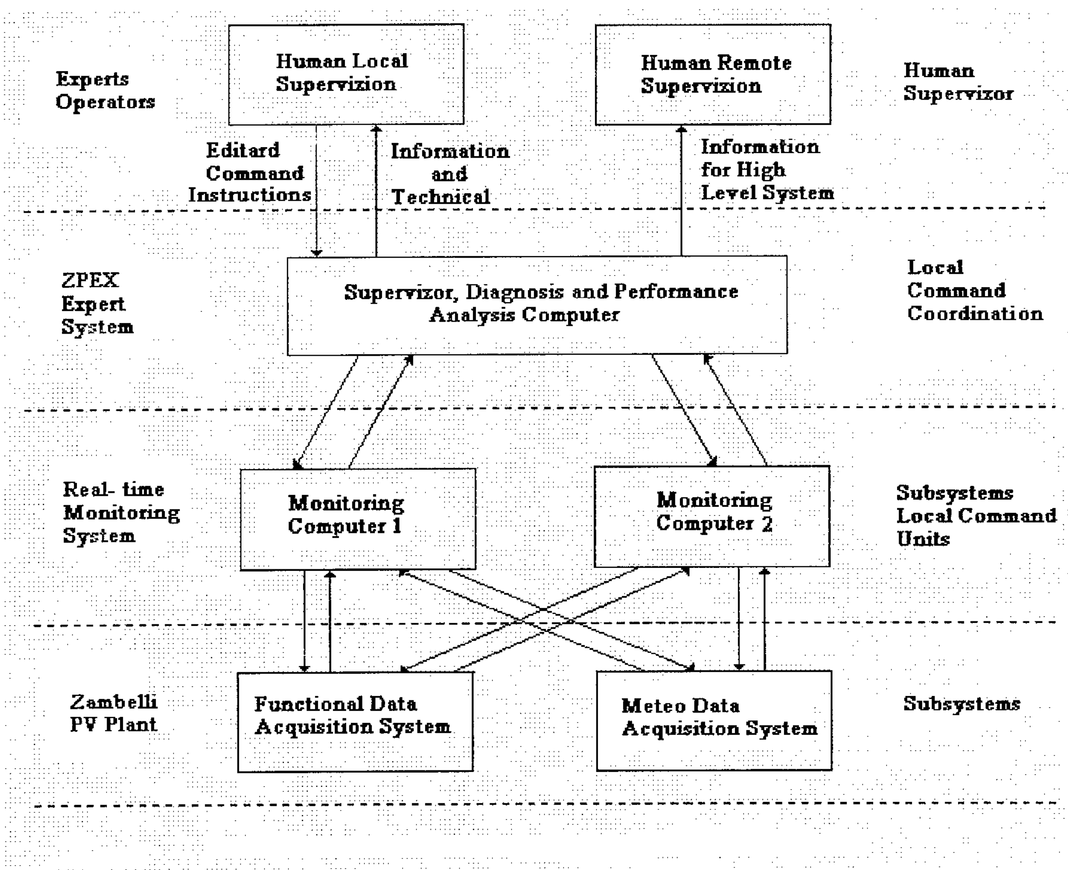

Fig. 3 – The hierarchical structure of a supervision system

ZPEX (Zambelli Plant Expert System) is a real time expert system for faults detection and diagnosis, performance analysis and consulting for appropriate counteractions destined to the operators of a PV plant. It can be included in the frame of the hierarchical man-machine concept. The acquisition of the functional data of the PV plant and of the meteorological data via sensors are under the coordination of a real- time monitoring system. The hierarchical structure used for an automatic system is generalized towards supervision by integrating ZPEX in level 3 of the structure (see Fig. 3). This system is designated to assist the human level 4, where the local operators and remote operators (from AGSM, Verona) are included. The man-machine cooperation, in this case operator/ expert- ZPEX, is a vertical cooperation.

The design of the supervision system was performed in parallel with the design of the monitoring and man- machine systems. Thus, ZPEX became a decisional partner for the operators.

The design of the expert shells is based on an integrated approach of the design and evaluation of Zambelli PV plant supervisory system. It became with the analysis of a PV plant in order to infers functionality and its foreseen disfunctionalities. The analysis became with a bibliographic study [7], [10], followed by meetings and discussions with PV experts from AGSM, Verona and WIP Munchen [2]. Thus the technical constraints and the specific requirements were underlined. Both normal and the abnormal (degraded) functionality were analyzed. This analysis helped at the identification of the objectives to be fulfilled, taking also into account the functional necessities of the operator/expert involved in the system.

In the case of a malfunction, the degraded evolution was identified aiming at the definition of the counteractions which have to be performed by the human operator on order to limit the effects of the abnormal functionality. The method of the fault trees analysis was used in order to write a list with all the possible faults of the system, their combinations, causes and consequences. These fault trees was off- line established, taking into account the faults models, that is the behavior in case of a fault. ZPEX is an hybrid knowledge-based expert system, where both symptom and inputs based techniques (heuristic symptoms, information about the process history, statistical data and real-time acquired data by the monitoring system) and qualitative models based techniques (the rule- based representation of the system structure and behavior) were used. The rules sets were initially established for the functional modules of the system (i.e. PV arrays, inverters, batteries, etc.) and then the sets were expended by interconnections between the component modules.

The conclusions obtained from the process analysis were then used for the designed of operator/expert - ZPEX interface. The design were based on the human mechanisms used to perform the human tasks and on the analysis of the informational necessities of the operator. These lead at the implementation of a Windows based color graphical user interface, which allows:

- definition of the information displayed on- line on the screen (see Fig. 4): graphical images (explicit representation of the PV plant and the connections between its parts), acquired and calculated parameters, results of the system performance analysis (i. e. faults and their causes, etc.);
- images were structured accordingly the operational contents of the process: knowledge base editor (see Fig. 5 and Fig. 6) and real-time diagnostic system to be used in system operation (see Fig. 4);

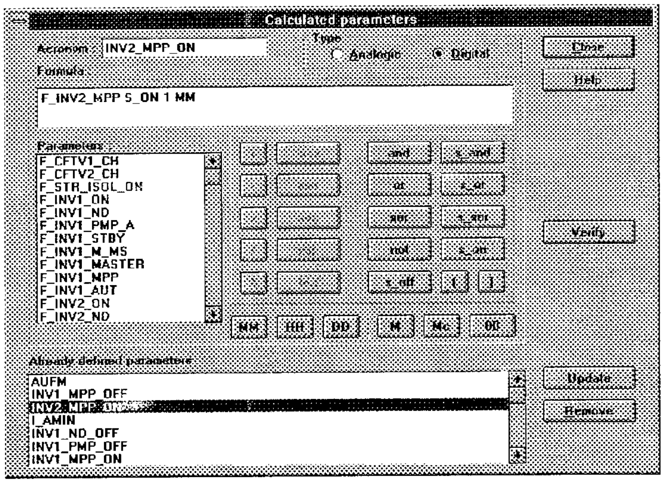

Fig. 4 - Run-time menu

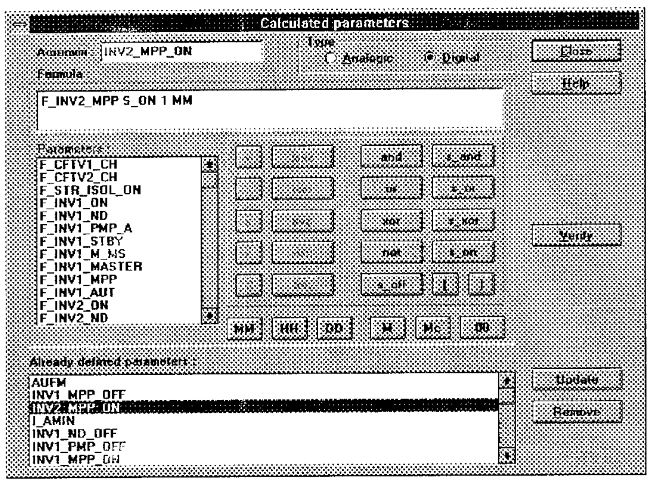

Fig. 5 - Calculated Parameters/ Menu

- definition of the necessary assistance for taking the decisions and actions (automatic alarming of the operator in case of a fault, operator's guide for limit/remove the faults, explanations of the results of the diagnosis process);
- definition of the on-line assistance for ZPEX utilization: start/stop, switch between the two operational contexts, use of the buttons/options displayed in the windows of the screen.

Some of the advantages of such a graphical interface over a command- based interface are: user- friendly interactive by graphical means, quick design of prototypes for windowing applications, and developing of program modules while reusable character. These capabilities are assured by: predefined graphical elements, predefined actions for graphical elements, and separation of the interface description from the source program.

The system implementation was performed using the successive prototypes methods: two versions were installed in Zambelli PV plant (in December 1995 and June 1996).

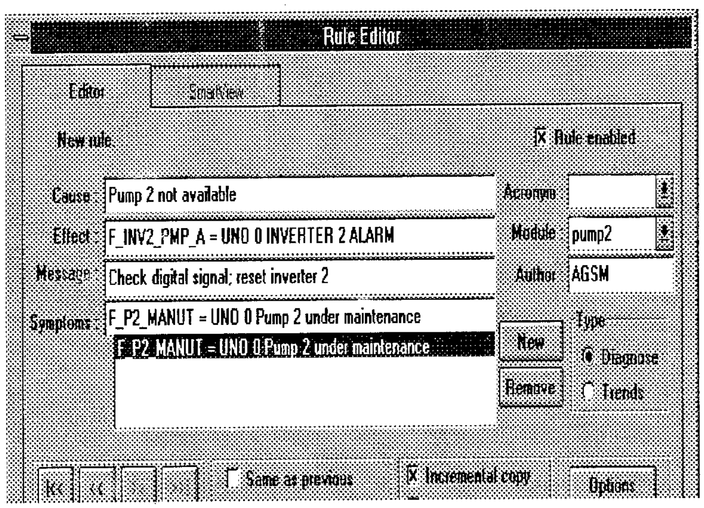

Fig. 6 - Rule Editor

Hardware And Software Requirements: The expert system for performance analysis and fault diagnosis uses the on-line acquired data of the data base built by a conventional real-time monitoring system of the plant. Personal computers became an usual support for expert systems, but memory and performance limits make them available only for small and medium systems.

The hardware configuration for expert system is a IBM compatible PC with at least: 486 DX, 66 MHz, 16 MB RAM, 350 MBB HDD, 3.5" FDD, SVGA video adapter, 14" color monitor, mouse.

The system was developed using Microsoft Visual C++ development environment and runs on Windows NT versions 3.51 or later.

Conclusions: High quality software systems is now-a-days an important request that software technology is confronted with. Expert systems are powerful tools that use artificial intelligence techniques for providing information just like a human expert would. The requests related with superior capabilities of 'reasoning' are motivated by the growing number of potential users of such systems.

A concrete implementation of an expert system based on the expert system shell described in the paper was made at the Zambelli PV pilot plant, near Verona, Italy.

Due to its flexibility this system could be used in the supervision of:

- processes in commissioning phase, normal operation, maintenance and inspection on request and teleservices and telediagnosis;
- production / products for quality monitoring and control;

- high reliable systems design for implementing re-configurable systems to be used in predictive control;
- intelligent systems.

Within the knowledge-based concept, the main difficulty is the knowledge acquisition and the lack of a founded, tried and tested theory.

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