A DATA-DRIVEN FRAMEWORK FOR PREDICTING THE REMAINING USEFUL LIFE OF HYDROELECTRIC EQUIPMENTS

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Abstract. *In this paper is presented a framework based on the OSA-CBM (Open System Architecture for Condition Based Maintenance) architecture for prognostic and health management of hydroelectric power equipments. This framework is a modular, scalable and integrated architecture that will provide comprehensive solutions to the end users. The architecture has seven hierarchic layers that represent a logic transition from data acquisition, signal processing, condition monitor, health assessment, prognostics, decision support, to the presentation layer. The data acquisition layer manages signals from sensors and databases; in the two next layers the signals are processed and evaluated the operational condition. Artificial intelligence techniques are applied in the health assessment and prognostic layer. The diagnostic algorithms calculated the degradation index of equipments, subsystems and systems. The prognostic algorithms are advocated to estimate the remaining useful life and predict the failure numbers. In the decision support layer is used fusion approach algorithms to generate the most accurate maintenance suggestions. The maintenance system developed will be implemented and installed in the hydroelectric power plants of the north of Brazil. This paper identifies specific benefits of the artificial intelligence techniques application into of a modular framework to offer benefits and comprehensive solutions for a hydroelectric power.*

Keywords: *Condition-based maintenance, data-driven prognostic, artificial intelligence, Open Standards, OSA-CBM.*

1. INTRODUCTION

Nowadays, the maintenance efficiency of power plants is an important economical and commercial issue. The size and complexity of hydroelectric power plants contribute to arise problems. The maintenance department performs different maintenance techniques in order to maintain or improve their equipments reliability. In order to optimize the maintenance cost, it is necessary to perform condition based maintenance to prevent failure occurrence.

Condition Based Maintenance (CBM) involves the prediction of potential failures (diagnostics) and the prognostics RUL (Remaining Useful Life) to determine when to perform maintenance. Diagnostic and prognostic assessments are based on measurements of equipments state, when the processing is performed by algorithms, models, or techniques based on knowledge experience. The introducing of monitoring devices has been taken to improve the reliability of the critical equipments in Power Plants. Although CBM (Condition Based Maintenance) conception is well known as its effectively in overcoming the problems of insufficiency or caused by traditional scheduled maintenance (Bengtsson *et al.*, 2004; Thurston and Lebold, 2001).

A complete CBM system comprises a number of functional capabilities: sensing and data acquisition, signal processing, condition and health assessment, prognostics, and decision support. Additionally is required a Human System Interface (HSI) to provide user interface with the system. The application of CBM usually requires the integration of a variety of hardware and software components including: communication and integration with systems installed, protection of proprietary data and algorithms, and the necessity for a upgradeable systems. Standardization of specifications drives CBM suppliers to produce interchangeable hardware and software components.

Software technologies which support systems of distributed software components have developed rapidly over the last decade and the technology continues to advance. In order to cover the broadest range of CBM systems, common core architecture is being defined with specific implementation standards for several key implementation technologies. It is clear that the Internet will be around for quite a while, and Web-based software technologies will continue to evolve. A open standard that is widely adopted will result in a free market for CBM components and algorithms. The benefits of a robust open standard include: improved ease of upgrading for system components, a broader supplier community resulting in more technology choices and increase of technology development.

The MIMOSA (Machinery Information Management Open Systems Alliance) has developed open information standards for the CBM (Mimosa, 2011). The standards provide a layered approach to CBM. The standard OSA-CBM (Open System Architecture for Condition Based Maintenance) defines the data types associated with the layers and the interrelationships using the UML (Unified Modeling Language) notation. It also provides data structures for the processing elements comprising the layers.

This paper will propose a PHM framework based on the open standard OSA-CBM architecture, the develop of CBM software components is according the seven layers of the framework proposed. The benefits after the framework implementation will include reduced maintenance and logistics costs, improved equipment availability, and protection against failure of mission critical equipment.

2. EVALUATION OF OPEN SYSTEMS

The CBM systems are nowadays emerging issues and are widely solicited to carry out specific studies or background analysis in mechatronic systems which are of increasing complexity. Actually, industrial maintenance appears to be both a source and a target of scientific developments which account for many action partnership industry company and research academy and for major projects such as the IMS center in USA which is an Industry / University Cooperative Research Center for Intelligent Maintenance System, supported by NSF (National Science Foundation) (NSF, 2011). As another clue, the IFAC (International Federation of Automatic Control) has accepted the construction of a new working group within the Technical Committee (IFAC, 2011).

With the advent of various technologies responsible for data acquisition, signal processing and communications, it becomes important to establish some sort of openness for enabling interoperability and integration. The operating costs of any type of maintenance are mainly driven by the cost to manage the diagnostic and prognostic information in an efficient and accurate manner. MIMOSA is an association dedicated to developing the adoption of open information model in manufacturing, fleet, and facility environments with information standards which enable collaborative asset lifecycle management. There are many researchers that contribute standardizing methods in order to organize information required in the developing of CBM system.

The IMS (Intelligent Maintenance Systems) Watchdog Agent tool kit (Djurdjanovic *et al.*, 2003; Lee *et al.*, 2006) is a toolbox of algorithms for assessment and prediction of a machines' performance. This describes aspects of modeling and forecasting indicators and leaves out decision support. No integration with enterprise systems or MES (Manufacturing Execution System) is included. Hence, the reaction to predicted failures involves much human interaction and manual synchronization between the Watchdog Agent instances and the enterprise systems.

SIMAP (Garcia *et al.*, 2006) is a predictive maintenance application designed for industrial processes. It is based primarily on neural networks for modeling and forecasting indicators. SIMAP also contains functionality to schedule maintenance actions. However, it has only been deployed in a rather small setting for a wind turbine so far. Also, no integration with enterprise systems or MES is included. Such an integration was realized in the European PROTEUS project (Bangemann *et al.*, 2006 and ITEA, 2011). PROTEUS is a generic platform for e-maintenance that integrates various sub-systems, thanks to a unique and coherent description of the equipment, a generic architecture based on the Web Services technology.

Another large integration project is PROMISE (promise, 2011). It aims at developing a comprehensive product life-cycle management platform to capture, manage, and analyze product data from all life-cycle phases of the product. The overall scope of PROMISE is large and also involves research into hardware components, so-called product-embedded information devices that can be used for measuring indicators. TATEM (tatemproject, 2011) is an ongoing project that aims at improving aircraft operability and safety and at reducing maintenance costs through the detection of present and incipient faults. TATEM covers all aspects of predictive maintenance but focuses exclusively on the application in aircraft.

DYNAWeb develops a CBM system based on OSA-CBM standard over MIMOSA comprising broad of capabilities like sensing and data acquisition, signal processing, health assessment, prognosis, etc. This platform ensures the integration of software and hardware components using different technologies and providing them with agents and Web Services to allow the integration and the reuse among different applications (Gilabert *et al.*, 2007).

The application of CBM architecture with three key elements: monitoring and forecasting, diagnosis and prognosis and maintenance decision-making. This ICMMS (Intelligent Control Maintenance Management System) was applied to a hydroelectric generating unit (Fu *et al.*, 2004). An application of the OSA-CBM framework and toolset for building IVHM (Integrated Vehicle Health Management) architecture to allows the creation of truly integrated, comprehensive solution for vehicle CBM (Dunsdon and Harrigton, 2008).

3. OSA-CBM ARCHITECTURE

The implementation of CBM systems has a necessity of integrating a wide variety of software and hardware components as well as developing a framework for these components. OSA-CBM simplifies this process by specifying a standard architecture for implementing CBM systems. This architecture contains seven layers as show in the Fig. 1: data acquisition (sensors and databases), signal processing, condition monitoring, health assessment (diagnostics), prognostics, decision support, and presentation. The standard describes the information that is moved around and how to move it. The OSA-CBM model was used by Amaya *et al.* (2007b), Thurston (2001) and Lebold *et al.* (2003).

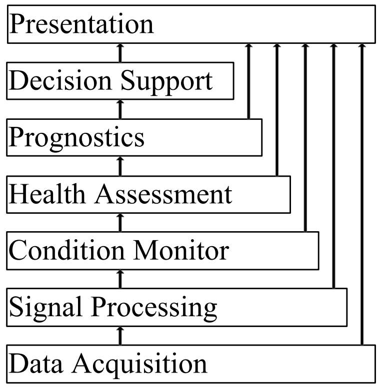

Figure 1. OSA-CBM Functional Layers.

3.1 OSA-CBM layers

3.1.1 Data Acquisition

Information collected from sensor, transmitter, database or another data source. The system capture through this signal the dynamic effect caused by the incipient failure. This layer is developed using the standard IEEE 1451 (Bengtsson, 2004) and provides to the CBM system with digitized information.

3.1.2 Signal processing

The purpose of signal processing in diagnostic applications and CBM is: (1) remove distortions and restore the signal to its original shape, (2) remove sensor data that is not relevant for diagnostics, and (3) transform the signal to make relevant features more explicit (Bengtsson *et al*., 2004).

3.1.3 Condition Monitor

This layer compares on-line data with its expected values. The condition monitor should also be able to generate alerts based on preset operational limits. The condition monitor could be developed using the standard ISO 13373-1 (Bengtsson, 2004).

3.1.4 Health Assessment

The primary focus of the health assessment layer is to prescribe if the health of the monitored item has degraded. The health assessment layer should be able to generate diagnostic records and propose fault possibilities. The diagnosing should be based upon trends in the health history, operational status and maintenance history. According with Bengtsson (2004), this layer could be developed using the standard IEEE 1232 and ISO 13373-1.

3.1.5 Prognostics

This layer requires data from the previous layers. The function of the prognostics layer is to project the current health state of equipment into the future, taking into account estimates of future usage profiles. In reference Thurston and Lebold (2001) is present a proposal for a generic prognostic module in which input requirements cover historic data in the form of health, failures, mission, maintenance history, model information, and spare part assets. The prognostics layer may report health status at a future time, or may estimate the remaining useful life (RUL) of an asset given its projected usage profile. Assessments of future health or RUL may also have an associated diagnosis of the projected fault condition.

3.1.6 Decision Support

The previous layer should be integrated into a decision support for the best possible solution. The primary function of decision support is to provide recommended maintenance actions. Additional information such as production scheduling and labor should be applied.

3.1.7 Presentation

The presentation layer receives data from the previous layers. The most important are the data from the health assessment, the prognostic, and the decision support layer. The presentation module could be built into a user interface.

3.2 Steps for building an OSA-CBM system

The main steps necessary to develop an OSA-CBM system are now discussed. First, choose a technology for the implementation. Since OSA-CBM is defined only in UML, it may be implemented in any middleware programming language such as Web Services, CORBA, Java, DCOM, etc. After the technology type has been selected, the OSA-CBM UML needs to be converted into an appropriate usable format. In this work has been chose to implement the standard using Java, DCOM and Web Services. Finally we decided how the different layers in the OSA-CBM system will communicate with one another. The OSA-CBM specification defines four types of communication that may be used: synchronous, asynchronous, service, and subscription. In the Fig. 2 gives a description of each communication type.

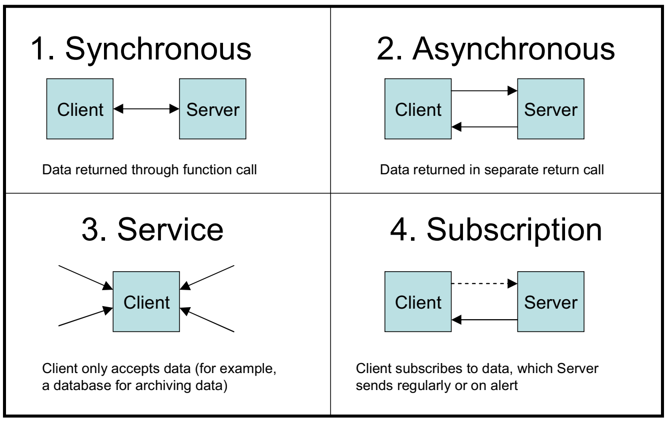

Figure 2. OSA-CBM Communication Types.

4. DATA-DRIVEN PROGNOSTIC FRAMEWORK

This CBM system will be introduced to a Kaplan HGU (Hydroelectric Generator Unit) in the hydroelectric power plant of Balbina located on Uatuma River in Presidente Figueredo city, Amazonas state, Brazil. There are 5 HGU, the rated output power is 250 MWh, the rated descriptive rotary speed is 105.88 rpm and the rated water head is 21.85 m. The system will be developed based on the OSA-CBM architecture. Its structure involves the OSA-CBM layers, adapted to a client-server computational framework. The developed of this computational system in Use Case diagram was presented in Amaya *et al*. (2007a).

The PHM framework is implemented on seven layers. Each layer is implemented applying different technologies in order to achieve satisfactory prognostic indicators. The implementation flow information is described in Amaya and Alvares (2010a), Amaya and Alvares (2010b) is detailed and show in the Fig. 3.

4.1 Data Sources

The system acquires information from online (OPC server) and historic (database) tendency stored. The instruments installed send the information to an OPC server. The system collects this data using a library JOPCClient, this library is implemented in Java and use DCOM to communicate with the OPC server.

The database is accessed using JDBC (Java Database Connectivity) and is used to storage failures, variables related to failures and decisions. The database also includes information of the maintenance and operation personnel. The system is foresee for communicate to another database in order to have in the future an integrated system with ERP (Enterprise Resource Planning) system, MES ((Manufacturing Execution Systems) and others systems.

4.2 Condition Monitor

The primary function of the condition monitor is to compare features against expected values or operational limits and output enumerated static condition indicators (e.g. normal, alert, alarm, trip, etc). The condition monitor may also generate alerts based on defined operational limits. The process variable value is compared with the values established previously. In case of dynamic limit is calculated the rate of a variable change.

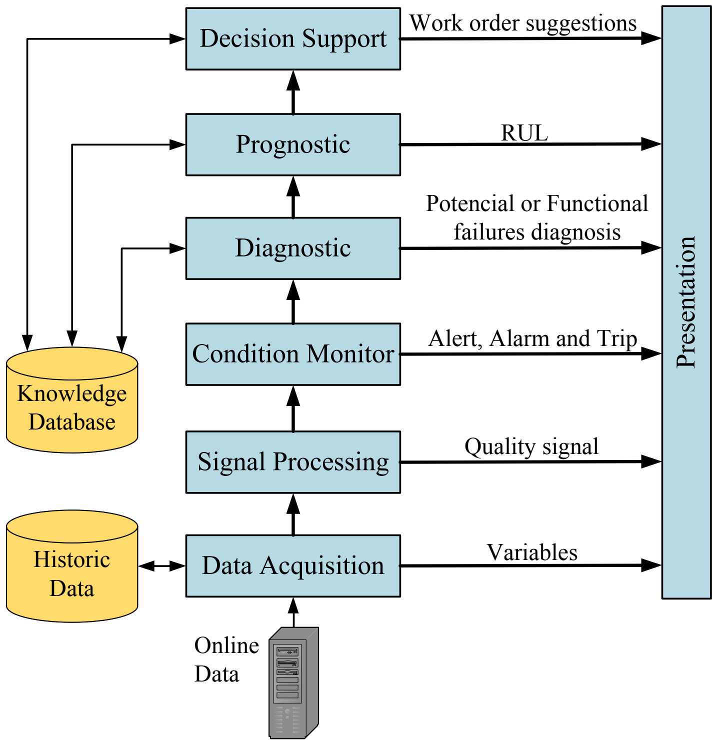

Figure 3. PHM Framework.

4.2.1 Static Limits

There are four states proposed (Fig. 4) characterize the condition monitor using defined static operational limits.

NORMAL - The values are inside of the normal operation of an equipment.

ALERT - In this state the monitored values show an incipient default in the equipment. This state was established to find any alteration of the normal condition.

ALARM - This state was previously established by the maintenance, operator and automation managers of the process plant. This state indicates the risk situation of the equipment monitored. When is arrived to this state is require to take preventive actions in order to prevent achieve the failure stage that can produce unexpected stops.

TRIP - Values in this state is considered inacceptable in the equipment operation of the process plant. When is achieved to this state as a security measure is turned off the equipments.

4.2.2 Dynamic Limit

Dynamic limits will be applied to detect a variable value change in real time. The dynamic limit is used to measure the speed of a variable change and permit to know how quickly will arise to a static operation zone as show in the Fig. 4.

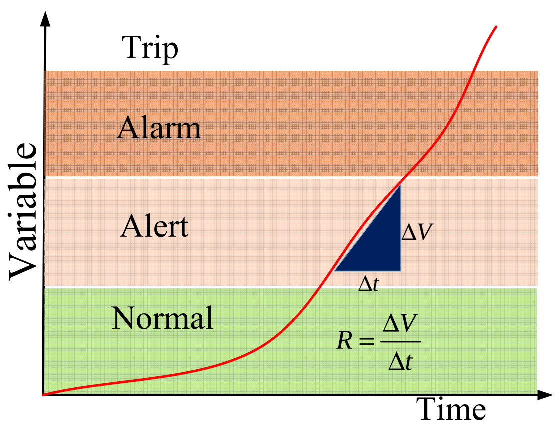

Figure 4. Operation States.

4.3 Health Assessment

This layer uses the FMEA (Failure Mode and Effect Analysis) tool in order to find relations between the monitored variables and the equipment failures. The operation and maintenance personnel contribute to indentify the maintenance problems in the power plant. Also were used documents like Technical Operation Instructions (TOI), Technical Maintenance Instructions (TMI) and Maintenance Planning Autonomous (MPA). The documents contain functional description of the equipment and condition state. Other documents are maintenance service order, in this case is analyzed in detail the failures occurrence and the maintenance procedure realized. With all this information will be elaborated a complete analyze of the possible FMEA (e.g. see the Table I).

Table 1. FMEA Worksheet

System in Analysis: Guide bearing cooling and lubrication system
Function: Lubrication and dissipate heat of the guide bearing
Component: Heat exchanger
Function: Cool the oil

Failure mode	Effects	Cause	Control
Insufficient cool of oil	-Lost oil's physic-chemist characteristics -Cooling failure	-Plate pack with noise	Temperature transmitter
Oil leaks	-Oil contamination risk -Lost oil's physic-chemist characteristics -cooling failure	-Stud bolt wear -Plate pack connections slack	Oil flow transmitter
Water leaks	-Cooling failure	-Slack tubes connections of water	Water flow transmitter

4.3.1 Knowledge Base

The knowledge base is constructed from the FMEA table. Also is required information from documents of the power plant. Important information is the experience of the maintenance personnel. The integration of all of the information is realized by knowledge engineer. A format is established to structure the information and is stored in a database. The flow diagram of the process is show in the Fig. 5.

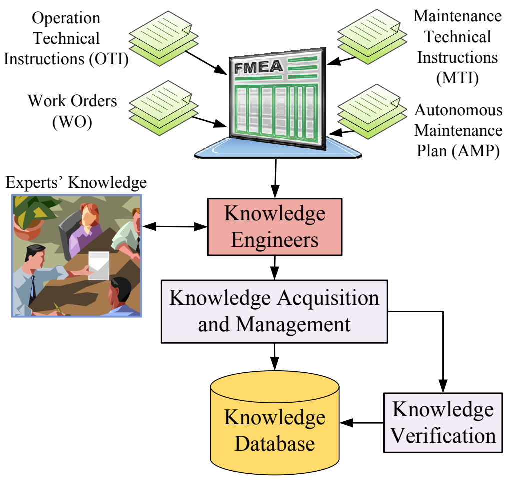

Figure 5. Knowledge base construction.

4.3.2 Failure Isolation

Information from knowledge base and historic data is used to train a neural network using backpropagation algorithm. The testing phase is performed using online data. In the Fig. 6 is show diagram of the information required to isolate four failure modes.

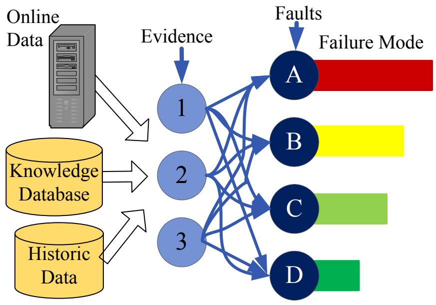

Figure 6. Failure mode isolation.

4.4 Prognostics

The continuous prognostics is aimed at detecting failure condition in development rather than failure reporting, whereby the aim is to reduce maintenance time and as a consequence increase operational time. This assessment generates recommendation for repairs or part replacement required to carry out maintenance. This framework showed in the Fig. 7 use process information, operational condition data and knowledge base to predict the RUL.

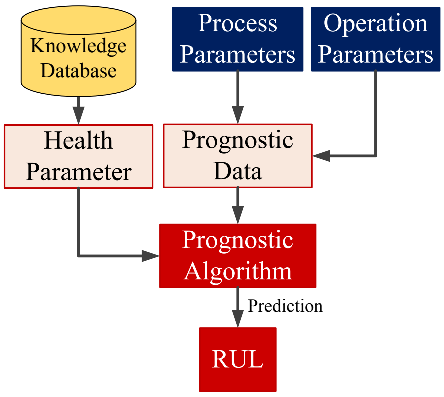

Figure 7. Prognostic Layer Framework.

4.5 Decision Support

The decision support is a maintenance service order and will be integrated with ERP systems. All the decision support associated to an eventual failure diagnostic was previously storage in the database.

4.6 Presentation

This layer is conceived to be a web application make available through of the power plant intranet. This application has been developed in HTML pages into of this is inserted an applet Java, JavaScript and PHP structures. This layer presents the information of the previous layers. When the system detects one fault, information about the type of fault is send to the user through email, storage in database and advisory in the synoptic window. The database tables containing relevant information on the pieces of equipment considered by the knowledge base. The window, as shown in the Fig. 8 display the five HGU, each one display the fault and failure in its components. This screen contains explanatory messages intended to inform the user about faults advisory in the five HGU.

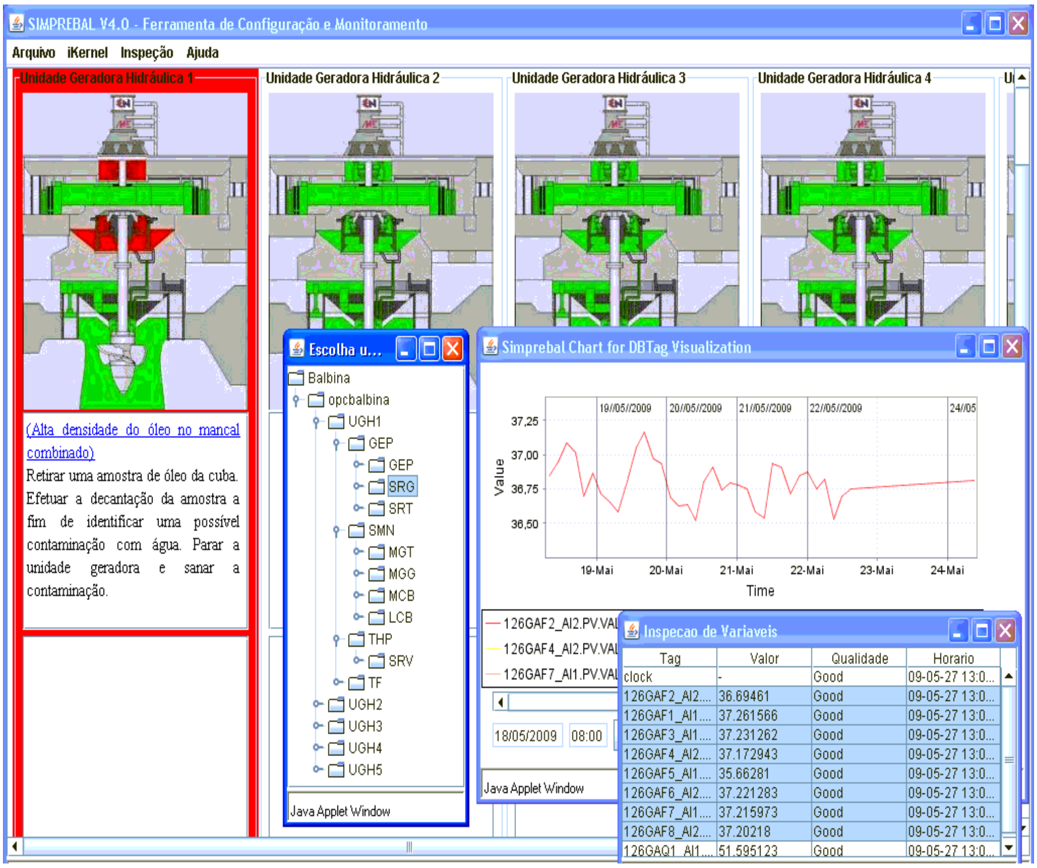

Figure 8. presentation layer.

5. CONCLUSION

The OSA-CBM architecture used to develop the SIMPREBAL can be implemented in modular way, the distributed processing architecture is easily scalable. Each layer can be implemented independently. Each layer can be developed using different kind of technology, in this case will be used to get information in real time, the OPC technology in the acquisition layer, Java in the computational system and web service in the presentation layer.

The major difference of this framework is to fuse knowledge information, process and operational data. The benefits of this system include: reduction in machine down time, reduction in skill level for maintenance activities, ease of maintenance, speedy response and affordable cost. The reliability of diagnosis is highly dependent on the accuracy information from online and historic sources.

This study dealt with the design and development of a knowledge-based system for the evaluation of industrial equipment in terms of fault diagnosis. The first phase of the project consisted of a comprehensive knowledge engineering effort to identify the major failure modes associated with the five UGH and equipment used in the hydroelectric power plant.

The system will be installed in the hydroelectric power plant of Balbina, ir will be a helpful tool for the maintenance engineer, and the diagnosis generated is accurate. A future work is to develop the layers using AI techniques that calculate the RUL (Remaining Useful Life) of the equipments.

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8. Responsibility notice

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