# A METHODOLOGY BASED IN CASE-BASED REASONING TO BUILD A KNOWLEDGE-BASE APPLIED TO FAILURE DIAGNOSIS SYSTEM OF HIDROGENERATORS MACHINERY

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***Abstract.*** *This paper proposes the application of the approach of Case-Based Reasoning (CBR) to build a knowledge-base of an intelligent system for maintenance predictive of hydropower equipment. The CBR approach is an important area of Artificial Intelligence (AI) to solve problems from the previously accumulated knowledge of known scenarios that can provide a solution to new problems arise. The CBR cycle is characterized by have four stages known as 4R: recovery, reuse, revision and retention. Each of these steps involving the knowledge-base, which is know how case-base. The case-base contains the information on abnormal situations presented in the equipments encoded in format of cases according to a structure standard for each case: problem-solution. The architecture and development for obtain the relational model of the knowledge-base according to the CBR approach can be summarized in the following 4 stages: first, identification and classification of hidrogenerators machinery, according to the type or the family for each equipment; second, search and collection of information related to situations of failure or abnormal events occurred in the equipment of the hydroelectric power plant: historical fault records, abnormal events, work orders and others informations as: preventive maintenance, FMEA (Failure Modes and Effect Analyses) tables, experience of operators, supervision on-line and off-line; third, definition of the structure of the cases focused to the diagnosis of equipment failures and support in taking decision. The final step is the coding of cases and their implementation in a relational database, constituting the knowledge-base of the intelligent system. The results obtained, are related in obtain a format and structure of cases for a intelligent system according to the approach CBR, that can be applied to any equipment or system, whose objective of intelligent reasoning is the fault diagnosis and support decision making. The model of the relational database to implement the knowledge-base of the intelligent system is obtained from the information of the case study.*

***Keywords****: case-based reasoning, hydroelectric power plant, maintenance predictive, knowledge-base.*

## 1. INTRODUCTION

The computational intelligent system SIMPREBAL (Predictive Maintenance System of Balbina) (Amaya and Alvares, 2010), emerges as a product of a methodological proposal raised by Amaya (2008), Souza (2008) and Tonaco (2008) that is based in the open architecture OSA-CBM (Open System Architecture for Condition Based Maintenance) for the design and construction of a predictive maintenance system applied to the equipments in a hydroelectric power plant (HPP). SIMPREBAL is a computational tool intelligent, built in JAVA that applies techniques of AI specifically rule-based systems or expert systems to develop diagnosis of failures associated with the equipments of a hydroelectric plant, allowing generate suggestions of maintenance for the operators, key aspects within the paradigm of predictive maintenance. In this paradigm of maintenance the objective is anticipate to the failure to establish and decide what corrective actions taken. SIMPREBAL born as result of the research project entitled “Modernization of the Process Automation Areas of the Power Plants of Balbina and Samuel” whose main objective is “develop an intelligent system for predictive maintenance capable of generate diagnostic and prognostic of failures in order to assist employees of the hydroelectric plant of Balbina in making decisions regarding maintenance actions”, Souza (2008). The case of study of SIMPREBAL was the HPP of Balbina, located in the state of Amazonia, to 220 km of the city of Manaus in the northern of Brazil.

Therefore in order to give continuity to the project of implementation of an intelligent system of maintenance predictive applied to HPP and specifically to the SIMPREBAL system, this paper analyze an alternative and complementary approach related with the generation and representation of knowledge of the intelligent system. The CBR approach will be analyzed as a complementary and parallel technique to be applied to the SIMPREBAL system. This application is based on typical CBR concepts for knowledge representation and reasoning of the intelligent system. Therefore the basic concepts of CBR are presented below as well as the steps for obtaining a generic form of cases focused on fault diagnosis and support decision making and a model of relational data base that will be the knowledge base according with the technique of CBR.

## 2. CASE-BASED REASONING (CBR)

The CBR is an important application of the AI that is emerging in many applications, methodologies, algorithms and systems in many application domains, and that for the case of engineering, is being established as an important tool of user support, principally in the area of predictive maintenance, where can be development intelligent systems that assist the user in the diagnosis of failures and support in the decision-making equipment maintenance in industrial environments (Kim *et al*. (2009), Yee *et al.* (2009), Na *et al.*(2008)).

The CBR approach provides a solution to new problems from past situations. A certain similarity measurement allow set a similarity between cases, allowing reuse or adapted the solution of the case(s) more similar(s) to the new case in question (Aadmont and Plaza, 1994, Wangenheim and Wangenheim, 2003).

According with Aadmont and Plaza (1994) a CBR cycle has four stages known as 4R: retrieve, reuse, revise and retain. If a new situation or problem is detected, a computational system based on a CBR process, start the search of cases more similar within their knowledge-base in the stage known as **retrieve**, once found, can reuse or adapt the solution of similar cases to establish a solution to the problem in question in the stage known as **reuse**. The solution obtained by the system can be subject to correction in the stage of **revision** and finally the new experience is saved in the case-base in the **retain** (Fig. 1).

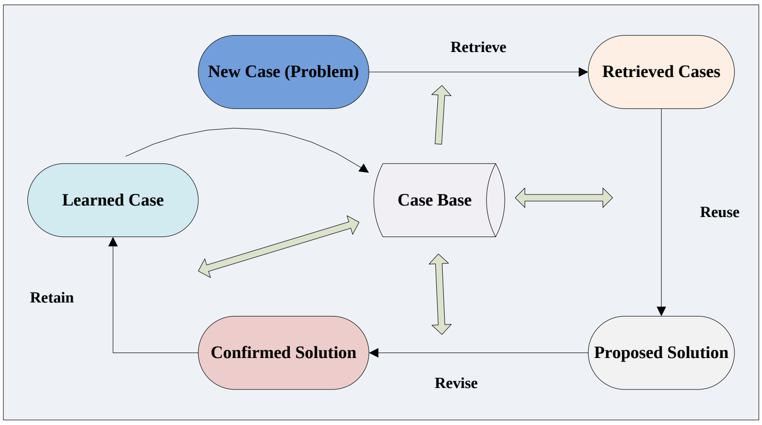


Figure 1. Cycle CBR (4 R)

A very important feature of a CBR system is the possibility of learning. When a new problem is resolved, corrected or modified this is retained in the database, remaining available to solve similar problems in the future. This fact allows that the knowledge in a system CBR remain constantly update, learning of new cases occurred (Wangenheim and Wangenheim, 2003).

A case, according to the CBR approach, is a unit of knowledge where is store all the information of the situation or problem occurred together with its solution. Therefore, a case denotes a problem situation already identified and resolved. A new case will be, therefore, a problem situation without the solution.

## 3. METHODOLOGY PROPOSAL

Before starting with the methodological proposal must be define the objective of the CBR system. For the application domain discussed in this article, the objective of the proposed intelligent system is focused to support decision making of maintenance actions when a failure is detected or identified. The alternative and complementary approach to be applied to SIMPREBAL proposed in this paper is based in two key aspects:

- Built a format of cases that stores the information of the fault situations and the action carried out when it occurred in the equipment.

- Obtain a model of relational database as a proposed scheme for the knowledge-base system.

Given that SIMPREBAL is an example of application of condition-based maintenance, based on open architecture OSA – CBM (Alvares *et al.* (2009), Alvares *et al.* (2007a)), the alternative methodology proposal for the construction of intelligent maintenance system based on approach CBR is shown in the Fig. 2:

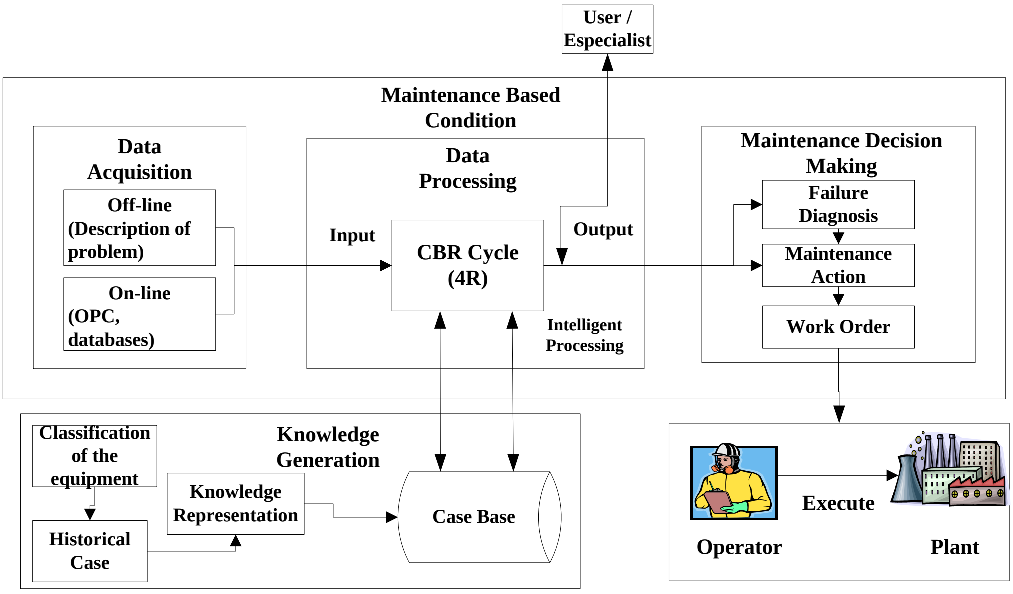


Figure 2. Intelligent maintenance system based in CBR approach

In the Fig. 2 in the module for knowledge generation, are defined 3 stages for finally obtain the model relational of the case-base. The steps correspond to the proposed methodology in this article and are described below (Fig. 3):

- **Identification and classification of equipment:** classification of equipment presents at the hydroelectric plant.
- **Historical case:** capture and collection of historical information about the machinery equipment.
- **Knowledge extraction and representation:** definition, format and construction of the cases.
- **Case-base:** construction of the case-base according to the model relational.

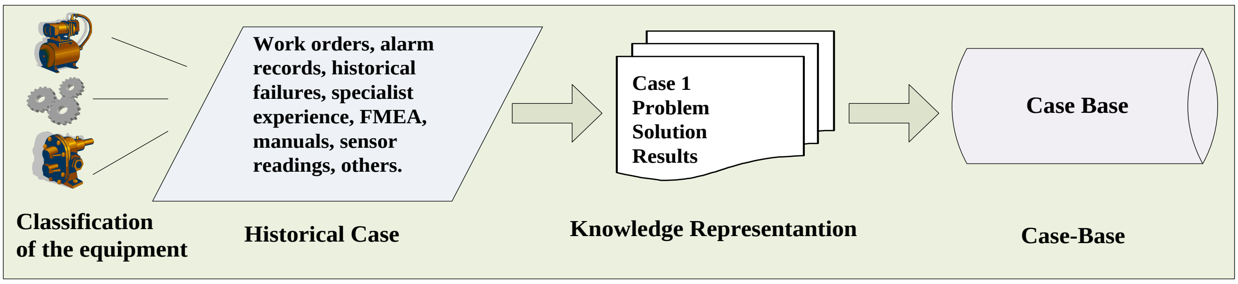


Figure 3. Steps for the construction of the case-base

### 3.1 Identification and classification of equipment

Identify and classify the devices in a HPP has a purpose collect all the information available and sufficient for a specific type of equipment. The foregoing is with the objective of generate a domain of knowledge about a class or particular type of device. Each particular type of equipment will have a unique identification code, and him belong all the information and cases occurred in specific machines according to a particular family or class.

For example, if an information concerning with a fault in a particular pump is found, this information goes to form a historical record relating to a subdomain of the application called "pumps". Then, each information found in a determined device referring with a family of equipment, goes to form a small knowledge-base relating with the mentioned subdomain. Therefore, must be identified the multiple subdomains of the area of application according to the family of each equipment (Fig. 4).

### 3.2 Historical case

According Kim *et al.* (2009) a system diagnosis failure require of information such as systematizing heuristic, diagnosis and maintenance procedures, FMEA, FTA (Failure Tree Analysis) and decision tables. Yao *et al.* (2009)

proposes that an intelligent maintenance system requires a large amount of information such as structural data, performance data, spare part data, operating data, maintenance data, fault data, maintenance decision data, maintenance plan data and so on, that reflect equipment maintenance status, for later use such information in the development of the case-base.

In the case of maintenance, the information about the equipment or system is available through of sensors or intelligent instrumentation that transmit data of critical variables. In addition to this information, manuals and tutorials on operation equipment is available. There are also methodologies and analytical methods for identifying potential failure modes and effects in products and processes. Such methodologies can be: FMEA, FTA and decision trees. Expert knowledge is another important factor in the building of knowledge-base of an intelligent system. The experience of the human operator and the reasoning about a problem that occurs in a process or equipment make it the kind of information more difficult to codify. Databases, SCADA (Supervisory Control and Data Acquisition) software, work orders, preventive and corrective maintenance, alarm records and abnormal events, are another type of information that can be added as data encoded in the knowledge-base. All this information is summarized in the Fig. 5.

In the case of building of an intelligent system based on the CBR approach, the type of information or knowledge has preference for past situations or events that occurred and was recorded and its solution is known.

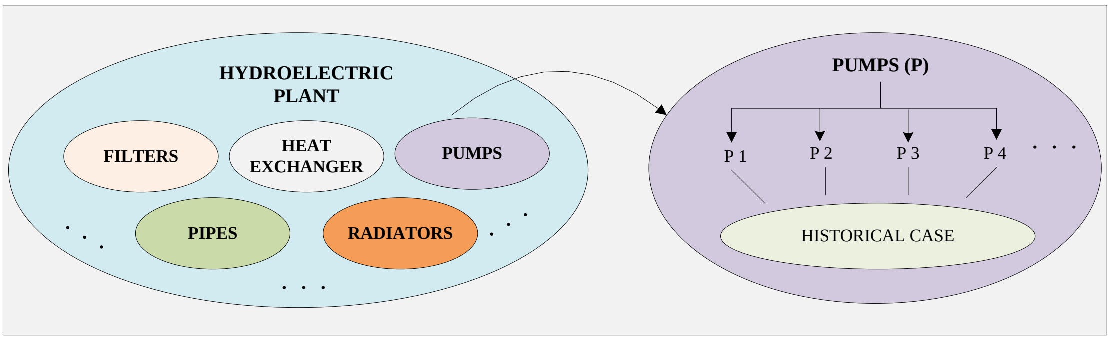


Figure 4. Identification and classification of equipment

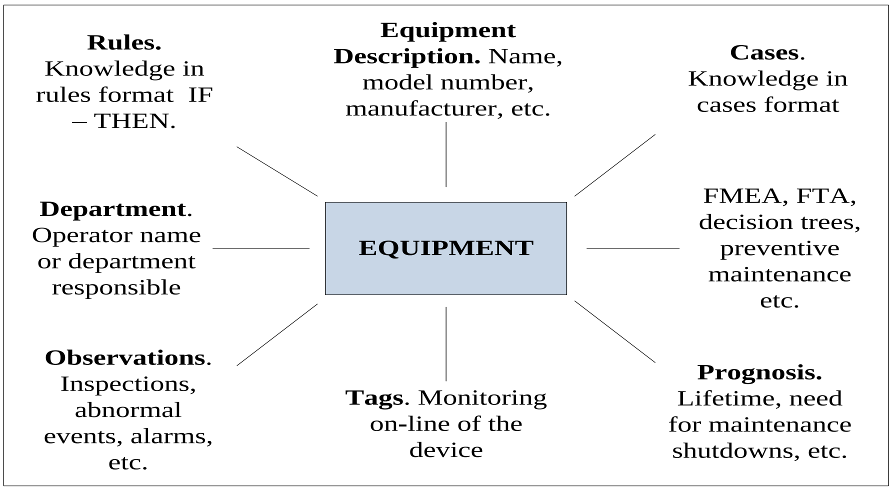


Figure 5. Information model for the devices on the hydroelectric plant

### 3.3. Knowledge representation

A case can have different contents and representations depending on the area of application and purpose of reasoning, well as specific information for its implementation, but the minimal structure that a case must have is the description of the problem and its solution (Wangenheim and Wangenheim, 2003).

The representation of the cases, have multiples and varied forms, some of them are: semantic nets, frames, object oriented, trees, trees K-D. Whatever the representation used, the coding scheme should also represent information about fault condition and correctives actions that can be expressed qualitatively and quantitatively. For example, a fault condition can be expressed quantitatively “the temperature is exceeding 100ºF” but also in qualitative terms such as “The vibrations levels are very high” (Vachtsevanos *et al.* (2006)). Figure 6 show a case format for the situation of failures diagnosis in equipments.

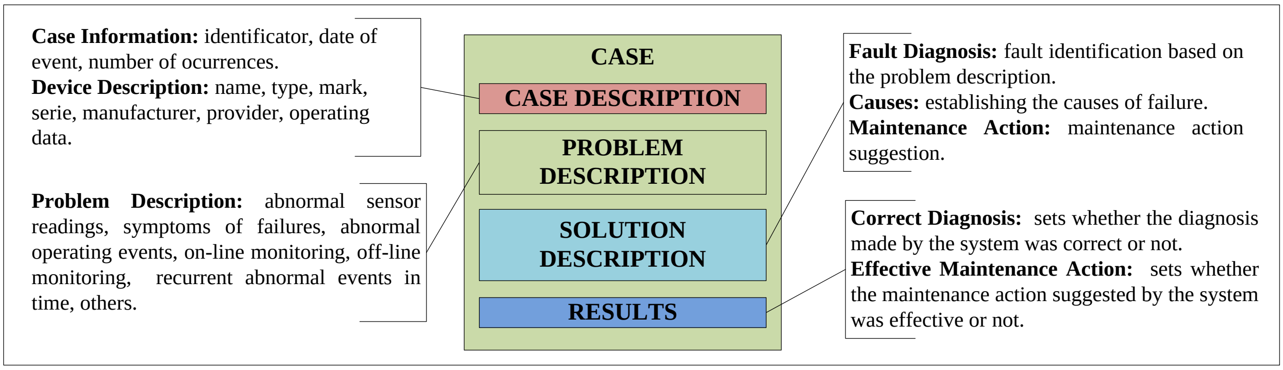


Figure 6. Case structure for diagnostic equipment failure

### 3.3.1. Case description

This field specifies a unique identification code, the date of occurrence of the event, the description of the equipment (mark, model, number series, manufacturer, type, among others), and some other additional information as number of occurrence of the case and department or operator who carried out the maintenance task. Identification code for each case is essential, and is related to the recovery stage and the concept of indexing to facilitate or accelerate the search on the case-base of similar situations.

### 3.3.2 Problem description

In this field, are specified each and every one of the symptoms that allow describe the fails that presents the device: abnormal sensor readings, problems detected by the operators, recurring problems in time, among others. The symptoms must be precise in the description of the problem, with sufficient detail to his description; hence the concept of abstraction takes on enormous importance. The abstraction at this point of the design has to do with the fact of “reduce” the problem so that we can identify the salient features of this, and also include sufficient details to identify the problem. Represent the cases at appropriate levels of details, it is a real challenge. The capacity of abstraction of the designer will determine how many details need to be represented to describe the problem (Zhou *et al.* (2010)).

The abstraction leads to a concept that Wangenheim and Wangenheim (2003) define as “information entity”. An information entity is a part atomic of case. All cases are formed by units of information, for example: name of equipment, date of case, system, cause, failure and so on. Therefore the problem description must be represented according to these units of information.

### 3.3.3 Solution description

The solution for the domain of application currently under analysis and according to the objective for the intelligent system has to do with the fault diagnosis and the suggestion of a possible action or maintenance task for the failure in question (Wangenheim and Wangenheim, 2003). Diagnose a fault is identify the damage that is affecting the device. The identification of the failure is very important because allow to decide that type of actions taken to avoid the consequences of this.

The maintenance actions are also suggested by the system. This support in decision-making is one of the most important features of an intelligent maintenance system based on the CBR approach, since it allows recommend a maintenance action to the operator or user to be executed in the device or plant.

In the solution also is common to add which is the cause of problem presented.

### 3.3.4 Results

According to the problem domain this field is optional. For the case of failure diagnosis this field is fundamental, because allow evaluate whether the diagnosis suggested by the CBR system was correct and the maintenance action was effective or not. In this field is presented that occurred when executing the proposed solution, if the solution given by the system was successful or not. With this information the specialist can anticipate potential problems and predict the consequences of a particular proposed solution. This field also is part of the learned of the system (Wangenheim and Wangenheim, 2003).

Evaluate the result of a case may take some time. The case can remain in the case-base and be reused for new situations, but the evaluation is made once the solution proposed by the system was applied in the equipment or plant (Aadmont and Plaza, 1994).

### 3.4 Case-base

After of process of abstraction, a set of relevant attributes are identified for the description of the problem, besides of the description of solution, information of equipment and results, the components of a case. Therefore, a CBR system is reduced to the identification of significant attributes (Na *et al.* (2008)). In these sense, the set of information of the cases can be organized and retained in a database according to model relational forming the case-base. Can be used any commercial database or available for the application (Waheed and Adeli, 2005). Given that a case is a structure that contains fields detailing specific situations through different attributes, this information can be organized in tables and linked by indices, as posed by the design of relational databases. The representation of data using relational data tables offers advantages such as (Vachtsevanos *et al.* (2006), Elmasri and Navathe (2007)):

- Representation of the information through tables (rows and columns), where the rows represent a case and the columns represent attributes or fields of the case.
- The databases have advances techniques for managed large volumes of historical cases. The indexation for example, is a method used for the CBR systems that permit a fast and efficient search of cases from attributes identified as indices in the database. An index is an information entity that is a attribute key and that is not necessarily a primary key but that is fundamental for the identification of the cases similar.
- The redundancy of the information is avoided. A minimum amount of storage space is used for store information.
- The database and the organization of the information as well as its maintenance, are more understandable and easy to implement, since its organization in tables and their relationship through primary or secondary keys.

## 4. CASE STUDY

The case study for implement the proposed methodology is the machinery of the HPP of Balbina. This HPP has five electric generator units generating a total of 250 MWh. Each generating unit has a set of equipment organized in different systems carrying out specific functions. The same machinery is presented in each of generating units.

### 4.1 Identify and classification of equipment

According with the proposed strategy, the first stage is to identify and classify the machinery present in the installation, according to the family or the type of equipment to which they belong. The Fig. 7 list the more common equipment found in a hydroelectric plant.

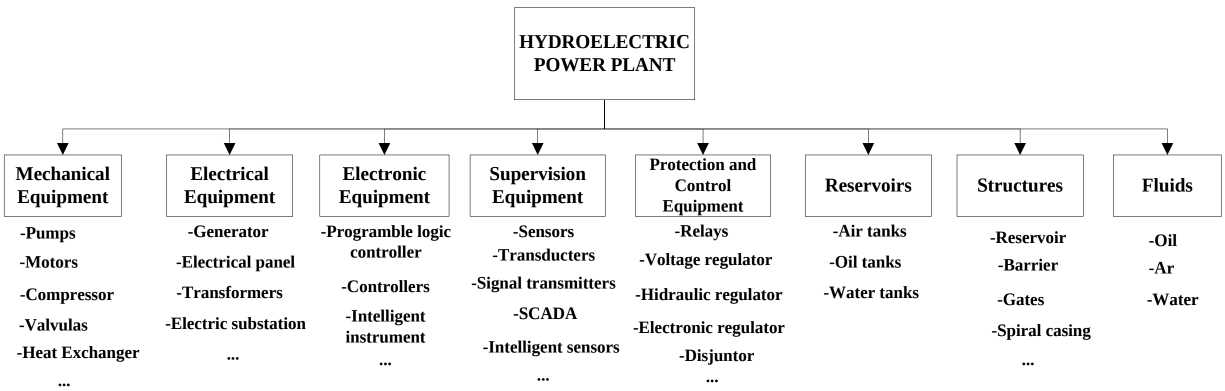


Figure 7. Typical equipment in hydroelectric power plant

Defined the family of the equipments, the next step is the identification of the devices that are part of each type identified. The equipments family's can be: pumps, heat exchanger, relays, filters, motor and so on. For the case of a generating unit of the HPP of Balbina, the equipments family of pumps has the devices listed in the Tab. 1.

Table 1. Identification and location of pumps of HPP of Balbina

| HPP of Balbina | | | | | | |
|---|---|---|---|---|---|---|
| Equipment description | | | Supervision on - line | | | Typical problems |
| Type of equipment | Equipment (Name) | Location (System) | Tags (Pressure) | Condition | | Symptom |
| | | | | Value (Bar) | Thresholds | |
| Pumps (P) | P. AE – AF | Speed regulation system | | | | |
| | P. AH – AG | Bearing system | 63LW | ≥50 | Normal | |
| | | | | 50>, ≤35 | Alert | • Leaks |
| | | | 63LV | 35> | Trip | |
| | P. AI – AJ | Bearing system | 63LX | ≥2.0 | Normal | |
| | | | 63LY | 2.0>, ≤1.2 | Alert | • Abnormal sound |
| | | | | 1.2> | Trip | |
| | P. AK – AL | Drainage system of the turbine | 63BAKL | ≥2.0 | Normal | |
| | | | | 2.0>, ≤1.5 | Alert | • Defect in the pumping |
| | | | | 1.5> | Trip | |
| | P. 01 - 02 | Drainage system guide | 63B1 | ≥6.0 | Trip | |
| | | | | 6.0>, ≤5.0 | Alert | • Low pressure operation |
| | | | 63B2 | 5.0>, ≤ 2.5 | Normal | |
| | | | | 2.5>, ≤2.0 | Alert | • High pressure operation |
| | | | | 2.0> | Trip | |
| | P. AN - AR | Common systems for generating unit | SAS63 | ≥2.5 | Normal | |
| | | | | 2.5>, ≤2.0 | Alert | |
| | | | | 2.0> | Trip | |
| | P. CT1-CT2 | Watergates | 63PBA | ≥153 | Trip | |
| | | | | 153>,≤120 | Alert | |
| | | | | 120>, ≤ 60 | Normal | |
| | | | | 60>, ≤30 | Alert | |
| | | | | 30> | Trip | |

### 4.2 Historical information equipment

The HPP of the Balbina offers historical information on abnormal events and actions of corrective and preventive maintenance that run on different equipments of the power plant. Some of the historical information is recorded in work orders to be executed by the operator. A work order describes the equipment and the failure that is reported, the action that execute the operator and the time it takes to be conducted. An example of the format of some work orders reported for the pumps in the year of 2009 in the HPP of Balbina is shown below:

Table 2. Work orders for the pumps of HPP of Balbina

| Order | Decision | Number | Type | Start date | Start time | End date | End time |
|---|---|---|---|---|---|---|---|
| Check the oil leakage in P. AL | Was replaced the mechanical seals and lubrication of bearings of pumps. | 30027394 | O | 8/3/2009 | 08:36:00 | 8/3/2009 | 22:15:00 |
| Make preventive maintenance in P. AG-AH | Lubricate the bearings and make cleaning of oil on site. | 30027594 | O | 19/3/2009 | 08:45:00 | 19/3/2009 | 10:20:00 |
| Check fails in the departure of the P. AL and reserve | Was made change of contactor interlock that was defective in interconnecting the pump AL | 30033118 | O | 19/7/2009 | 10:00:00 | 20/7/2009 | 09:30:00 |
| Check abnormal sound in P. AK | Verify defects in the pump couplings and lubricated the bearings | 30029690 | O | 30/6/2009 | 08:40:00 | 30/6/2009 | 14:35:00 |

Work orders are a domain of facts or past events that is fundamental to the development of cases. This information can be complemented with the failure analysis methods such as FMEA. In the development of SIMPREBAL the FMEA table was fundamental for the construction of rules and is a very important methodology in general for the entire project development (Alvares *et al.* (2007b), Souza (2008)). An example of format FMEA applied to pumps is shown in the Tab. 3 (Amaya and Alvares, 2010).

Table 3. Table FMEA for pumps

| Component | Function | Failure Mode | Effects | Cause | Control |
|---|---|---|---|---|---|
| Pumps | Oil Pumps | Alert pressure operation | -Turn off the priority pump and turn on the alternative pump in Low pressure.<br>-Lubrication and cooling failure. | -Oil leaks by the mechanical seal.<br>-Coupling damage<br>-Corrosion by contamination Oil<br>-Cavitations by presence air in oil | Oil pressure transmitter in the pump out |
| | | High pressure operation | -Turn off the priority pump and turn on the alternative pump in high pressure.<br>-Pump failure risk.<br>-Crack tubes and leaks<br>-Falha na lubrificação e refrigeração | -Incorrect adjustment | Oil pressure transmitter in the pump out |
| | | Abnormal sound | -Pump failure risk | -Bearing wear<br>-Bad bearing lubrication | Sound inspection |
| | | Insufficient cool of oil | -Lost oil's physic-chemist characteristics<br>-Cooling failure<br>-Oil contamination risk | -Plate pack with noise<br>-Stud bolt wear | Temperature transmitter |

### 4.2.1 Equipment supervision on-line and off-line

*Supervision on-line.* HPP of Balbina has instrumentation for monitoring and control important and critical variables within the central. The instrumentation manages the protocol Foundation Fieldbus that monitors variables such as pressure, temperature, leaks, density, among others, in various equipment and systems of the HPP. The pumps have pressure readings (tags) that establish any abnormal behavior in these devices (Tab. 1). There are four threshold that characterized the condition monitor: **normal**, the values are inside of the normal equipment operation; **alert**, condition out of normal operation; **alarm**, indicate the risk of the equipment monitored to achieve a failure stage; **trip**, values in this state are inacceptable (Amaya and Alvares, 2010).

*Supervision off-line.* If the device or system does not have a set of sensors for monitoring, the problem description must be performed by the operator. Here is where the concept of abstraction is fundamental. From the historical information of the equipment, must be indentified the facts, symptoms, or problems that occur more frequently in the equipment. For the case of pumps, the problems that occur more frequently are listed (Typical problems) in the Tab 1.

### 4.3 Format of cases

A general case format that codifies the information previously submitted to the pump is presented below.

<table>
<tr><th colspan="4">CASE</th><th colspan="3">ID</th><th colspan="3">DATA CASE</th></tr>
<tr><td rowspan="3">Case description</td><td rowspan="3">Equipment</td><td colspan="2">Name</td><td colspan="3">UGH</td><td colspan="3">Manufacturer</td></tr>
<tr><td colspan="2">Family</td><td colspan="3">Subsystem</td><td colspan="3">Time operation</td></tr>
<tr><td colspan="2">System</td><td colspan="3">Reference</td><td colspan="3">Others</td></tr>
<tr><td rowspan="6">Problem Description</td><td rowspan="4">Supervision on-line</td><td colspan="8">Tags (Pumps)</td></tr>
<tr><td>63LW</td><td>63LV</td><td>63LX</td><td>63LY</td><td>63BAKL</td><td colspan="2">SAS63</td><td>...</td></tr>
<tr><td colspan="8">1.Failure condition (1)</td></tr>
<tr><td colspan="2">(50>, ≤ 35), (35>)</td><td colspan="2">(2.0>, ≤1.2),( 1.2>)</td><td>(2.0>, ≤1.5),(1.5>)</td><td colspan="2">(2.5>, ≤2.0),( 2.0>)</td><td>…</td></tr>
<tr><td rowspan="2">Supervision off-line</td><td colspan="8">Typical failure</td></tr>
<tr><td colspan="2">2.Leaks</td><td colspan="2">3.Abnormal sound</td><td>4.Defect in the pump</td><td colspan="2">5.Low pressure operation</td><td>6. High pressure operation</td></tr>
<tr><td rowspan="2">Solution Description</td><td>Supervision on-line</td><td colspan="3">Diagnosis<br>1.</td><td colspan="2">Causes<br>1.1<br>1.2</td><td colspan="3">Task<br>1.1<br>1.2</td></tr>
<tr><td>Supervision off-line</td><td colspan="3">2.</td><td colspan="2">2.1<br>…</td><td colspan="3">2.1 …</td></tr>
<tr><td rowspan="2">Results</td><td rowspan="2">Evaluation Specialist</td><td colspan="4">Correct diagnosis?</td><td colspan="4">Effective task?</td></tr>
<tr><td colspan="8">Comments: add maintenance task, add new case, remove causes that do not correspond, others.</td></tr>
</table>

(1) : measured at Bar

Figure 8. Case format according to the approach CBR applied to pumps.

### 4.4 Case-Base

The information of cases can be represented in a model relational applied to databases. In this model, the information is represented in tables and linked according to model relational (Elmasri and Navathe, 2007).

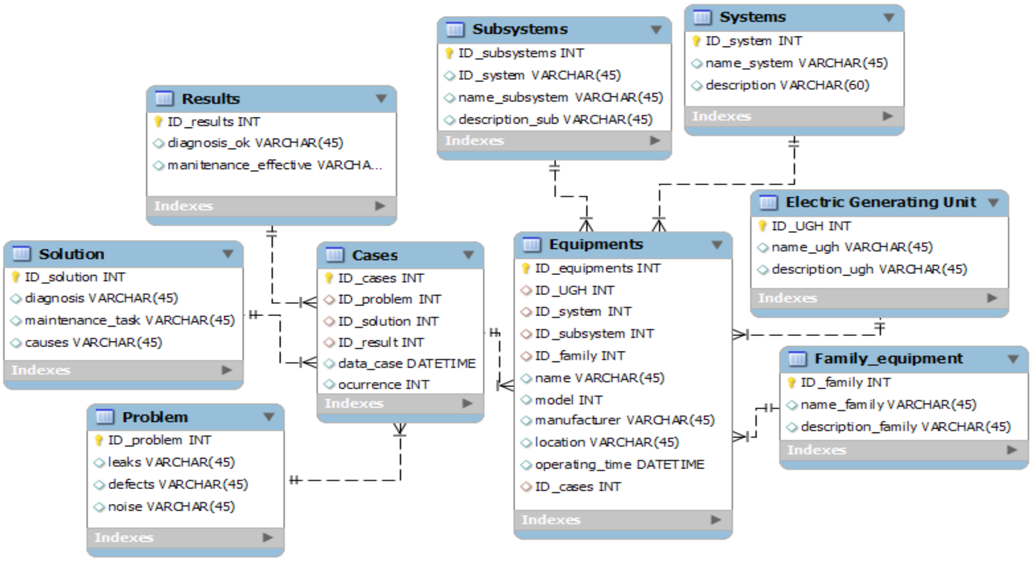


Figure 9. Knowledge-base representation in a relational model

The case-base obtained meet with an essentials features for a process of recovery of cases in the CBR cycle. Some of them are:

- Avoids data redundancy.
- In the description of the equipment, every system, subsystem, type of equipment and generating unit have tables, where can be easily added such information, without need of alter full registers.
- There are key fields that cannot be null. Each equipment belong to a generating unit, to a system, a subsystem and belongs to a type of equipment. Any equipment is isolated.
- In the tables of “cases” and “problem” are used indices to facility the search of cases in the step of recovery, in the cycle of CBR. The concept of indexation is fundamental in this stage of reasoning.

## 5. CONCLUSION

In this article, was presented the development process for the generating of a model of knowledge-base for a failure diagnosis intelligent system and support decision making of hydrogenerators machinery according to the CBR approach. The methodology presented is based in the approach of cases and is alternative and complementary technique to be applied in SIMPREBAL system, which is entirely based on rules approach.

A CBR system based its reasoning from the past situations, occurred in the application domain, to provide solutions to new situations that may arise. In these sense, the collection and search of past situations that occurred in the equipment together with her solution, is fundamental for the knowledge-base. Work orders, FMEA and human expert knowledge are used for the creation of the knowledge units or cases. A case has a structure that depends of the objective and domain of application. For the case of failure diagnosis in hydrogenerators machinery is shown a format case with the equipment description, the problem description, the solution and results, taking into account, the supervision on-line and off-line of the equipment, increasing in this way, the domain of knowledge of the SIMPREBAL system, based completely in the supervision on-line.

The set of cases corresponds to domain knowledge where the model of relational databases is ideal for its representation. A model for the organization of the cases in a format of relational databases also is presented in this paper, obtaining the knowledge-base of the CBR system, where in future works will be adapted to the framework jCOLIBRI (Recio-Garcia *et al.* (2009)) to complete the reasoning cycle of the system and adaptation to SIMPREBAL system.

## 6. ACKNOWLEDGEMENTS

The first (Proc. CNPq 133960/2009-9), third and four author's are thankful to Eletronorte, Manaus Energia and CNPq for the financing support of this research work.

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