

METHODOLOGY FOR THE BUILDING OF A FUZZY EXPERT SYSTEM FOR PREDICTIVE MAINTENANCE OF HYDROELECTRIC POWER PLANTS

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Abstract. *The aim of this study is giving continuity to the evolution of the SIMPREBAL methodology and computer system based on the specification OSA-CBM (Open System Architecture for Condition Based Maintenance). The operation of the SIMPREBAL (Predictive Maintenance System of Balbina) system mainly is based on the collection and analysis of the monitored physics variables in hydroelectric power plants, those variables are obtained from intelligent sensors to be usually installed on the generator units of hydroelectric power plants and on the implementation of a computer system based on diagnosis of the running states of the devices with the objective to help the establishment of decision making and maintenance operational actions of the machines thus, increasing their availability. It will therefore develop a new intelligent system to improve the performance of the SIMPREBAL system. This approach involves the development of a production rules based fuzzy expert system; this model and reasoning mechanisms are implemented using Java, JESS (Java Expert System Shell) and the NRC FuzzyJ Toolkit for the Java Platform Version 1.8. Basically the development of the methodology will be divided in 3 main parts; In summary, first the dates to be obtained from sensors, will be fuzzificated with their fuzzy sets, then those fuzzificated inputs will be matched against the production rules of the system applying the main fuzzy inference techniques such as Mandani-Style, Sugeno-Style, etc. to evaluate the performance of the system and finally the outputs of the system will be defuzzificated applying some appropriate methods of defuzzification (Decoding) such as the Center of Gravity (COG) technique, the Center of Area (COA) technique, etc. and then apply those defuzzificated outputs to the new system with the final objective of establishing one or several maintenance procedures so that the process operator can make the best decisions. Finally, to be able to establish final conclusions, it will analyze a case study to validate the performance of the new system in the hydroelectric power plant of Balbina to be approximately to 220 km of the Manaus city.*

Keywords: Artificial Intelligence, Fuzzy Expert System, Predictive Maintenance.

1. INTRODUCTION

Over the past twenty years, maintenance has changed, perhaps more so than any other management discipline. The changes are due to huge increase in the number and variety of physical assets (plant, equipment and buildings) that must be maintained throughout the world, much more complex designs, new maintenance techniques and changing views on maintenance organization and responsibilities, due to this avalanche of changes, managers everywhere are looking for new approach to maintenance; they want to avoid the false starts and dead ends that always accompany major upheavals. Instead they seek a strategic framework that synthesizes the new developments into a coherent pattern, so that they can evaluate them sensibly and apply those likely to be of most value to them and their companies (Moubray, 1997).

In Brazil the ABNT (Technique Norms Brazilian Association) in the census NBR-5462 (1994) define Predictive Maintenance (MPd) as “Maintenance that allows guarantee a quality of desired service, with base to systematic applications of analysis techniques, using centralized supervision means or of sampling, to reduce to minimum the Preventive Maintenance (MP) and decrease a Corrective Maintenance (MC)”.

The specification OSA-CBM (Open System Architecture for Condition Based Maintenance) is defined by Mimosa (2009) as “A set of specifications of a standard architecture to manipulation of information in Condition Based Maintenance (CBM)”. These specifications propose to develop a CBM system established by seven functional layers/modules which have a well-known interface among them. Such layers are: Sensor Module, Signal Processing, Condition Monitor, Health Assessment (Diagnosis), Prognosis, Decision Making (Decision Support) and Presentation as depicted at Fig. 1.

In literature review there are many frameworks for CBM among which the specification OSA-CBM (Open System Architecture for Condition Based Maintenance) is used in this paper due to their very important features.

In the investigation works of Amaya, E. J. (2008), Souza, R. Q. (2008) and Tonaco, R. P. (2008) specify the major features of that specification and prove why they chose that framework to implement the SIMPBREBAL system. We are not going to concentrate giving more reasons of why was chosen this framework due to that this work is a continuation of the methodology of SIMPREBAL. It suggests previous readings for a better understanding about how

works and how SIMPREBAL system was implemented which can be found in (Álvares *et al.* 2007a, Álvares *et al.* 2007b, and Álvares *et al.* 2009).

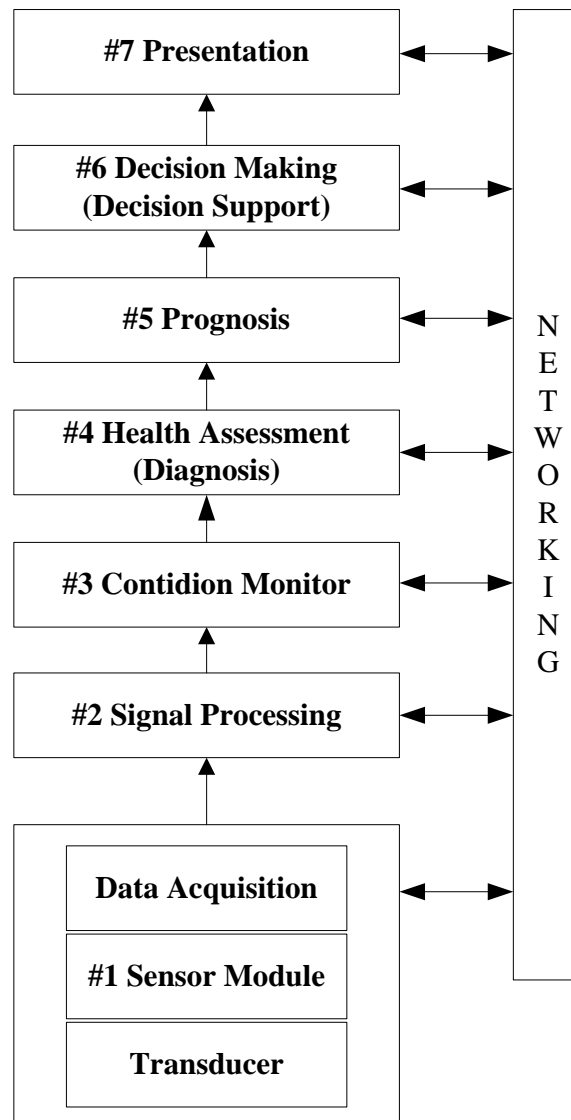


Figure 1. OSA-CBM layers (Holmberg *et al.* 2010, modified).

It is very important be aware of the advantages and disadvantages to pose each framework for an implementation and study more deep. The framework or specification OSA-CBM is not specific the way how it must implement each module, besides it is not define which technologies use and either which algorithms to develop and finally it does not speak about treatment of the information in each layer. Just define the kind of dates received into the input and produced in the output from each module, also their transmission way among modules and therefore as feature giving independence among the layers.

In spite of those difficulties to present this framework, the SIMPREBAL methodology covered some of these important issues and it is due to that the SIMPREBAL methodology raised, in the project of investigation ANEEL-ELETRONORTE, entitled “Modernization of the Process Automation Areas of the Power Plants of Balbina and Samuel” (Contract number 4500052325 and project number 128), as a predictive maintenance system capable to generate diagnosis and prognosis of faults aiming to help to the process operators of the Balbina’s hydroelectric power plant on the decision making with relation to the actions of maintenance and the running states of the devices (Álvares *et al.* 2009).

Well, without further preliminaries, the methodological proposal poses well-known characteristics and could be write here directly, but it would be even better make a comparative table between the new and old system highlighting and overlapping their characteristics commons and owns more relevant of each system giving emphasis to the new contributions as shown in the Tab. 1.

Table 1. Comparative table between new and old features more significant of SIMPREBAL system aiming to a better understanding for the building of the basis of fuzzy expert system

| FEATURES | OLD SYSTEM | NEW SYSTEM |
|--|---|---|
| Integrate to the specification OSA-CBM (Open System Architecture for Condition Based Maintenance) artificial intelligence techniques for the knowledge representation – specialist system based on production rules – warranting a high performance of the obtained dates. | In this point is important mention that, the knowledge base of SIMPREBAL poses only production rules in format JESS without any kind of fuzzy rule implemented to give a better flexibility to the rules processing. | Besides comply with this feature to be an expert system based on production rules in format JESS, here it was implemented fuzzy rules with the NRC FuzzyJ Toolkit for the Java Platform Version 1.8 and therefore, giving more flexibility to rules processing of the SIMPREBAL's inference engine. |
| Use the FMEA ⁽¹⁾ (Failure Mode and Effect Analysis) tool for the building of the knowledge base of SIMPREBAL system according to previous interviews made to the process operators. | The FMEA built is based on interviews with the operators of Balbina's power plant. | The new system pose the same knowledge base built through FMEA. If it is necessary will increase more knowledge in this point aiming to a better decision making of process when occur a fault in any device or system. |
| Add to the system the KPI (Key Performance Indicators) related to policy of RCM (Reliability Centered Maintenance) and thus, increasing the availability and reliability of the production assets. | It was implemented successfully and evaluated the performance of SIMPREBAL system, increasing the availability of the devices of the BALBINA's power plant. | In this point are not necessary make modifications because the strong point of this methodology is centered in building fuzzy production rules, therefore it will keep the same concepts. |
| Adapt the OSA-CBM model to an architecture server/client so that monitored parameters, diagnosis, prognosis and decision making can be accessed remotely from any web browser. | This feature is necessary because principally the process operators must have access to any monitored physic variable in the SIMPREBAL's screen so that they can see their trends and thus establishing some appropriate maintenance actions about the items, sub-systems, systems among others. | This methodology will keep this feature since the SIMPREBAL system must be monitored from any computer inside of the plant, even out of her if needed. In this point, it may be interesting add some graphics about the trends of the output fuzzy sets. |
| Present issues about the maintenance techniques such as condition based maintenance (CBM), Failure Tree Analysis (FTA) among others relevant concepts that form the state of art of this subject. | This methodology is based on such concepts that are acknowledged for the maintenance engineering. | In this point follow the same concepts because they are one of the strong points of the new and old methodology. Besides such concepts, this study has concepts related to fuzzy logic, fuzzy sets, fuzzy system engineering and fuzzy rules among others. |
| Present the principal technologies in industrial environments. | Here, intelligent sensors, actuators, devices of acquisition and transmission of dates in industrial automation are used because they belong to any automated factory. In this study, the Balbina's plant has implemented the Fieldbus technology, Networks of communication H1, HSE and the specification OPC (Ole for Process Control). | As it is working in the same environment, it will follow using the same technologies and specifications. In this point, there is no a lot of to say. |

⁽¹⁾ : (Álvares *et al.* 2007c)

Well, as it was described lines above in the Tab. 1, the enhanced system have their initial features previously built in the first version of SIMPREBAL that will be the basis of our methodology and thus, accomplish a system more robust to comply with the demand of the industry of the Predictive Maintenance (MPd) of the automated system machines. It is important to keep this table in mind because they are features more relevant that will give begin to the building of the fuzzy expert system.

Now after an overview of the SIMPREBAL system and their features, it is possible giving begin to the steps for the building of the fuzzy expert system. To accomplish such target it will sketch how is structured the fuzzy expert system in the specification OSA-CBM as shown at Fig. 2. This is another very important point, because, it will specific each module of the fuzzy expert system adapted to the specification OSA-CBM.

To continue with this subject, it will mention the general objectives and the specific objectives as follow:

1.1. General objectives

The major objective of this methodology is giving continuity to the SIMPREBAL methodology being aware of all the reaches of the first version for the new version and keeping this in mind, the principal contribution lead to the building of a fuzzy expert system adapted to the framework OSA-CBM for predictive maintenance of hydroelectric power plants, with the target of establishing appropriate maintenance actions about the running states of the monitored machines in all the plant, in specific, hydraulic generator units.

1.2. Specific objectives

Considering the features that already were implemented in the first version of the system as depicted in the Table. 1. It will mention the following reaches or new contributions to the SIMPREBAL system such as:

- Present the issues related to state of the art of this subject as fuzzy logic, fuzzy sets theory, fuzzy control and fuzzy system engineering, fuzzy inference process such as Mandani-Style, Sugeno-Style among others, fuzziness according to the properties of the devices, techniques of defuzzification such as Center of gravity (COG), Center of Area (COA) among others, JESS (Java Expert System Shell), NRC FuzzyJ Toolkit for the Java Platform version 1.8 for the building of the overall fuzzy knowledge base. All those methodologies and foundations mentioned adapted to Reliability Centered Maintenance (CRM) policy implemented in the SIMPREBAL system.
- Adapting the framework of the fuzzy sets theory to the methodology OSA-CBM. Here is important mention that, this study/implementation, it will carry out in each layer of the specification OSA-CBM to find out if it is needed make such approach or not.
- Carry out a case study applied to Balbina's hydroelectric power plant again to be able to assess the performance of the new methodology and therefore establishing final quantitative and qualitative results according to the methods and techniques used and the assessment of the diagnosis and decision making given by the system and finally in this point a comparative study along with the old system is advisable.

2. PRELIMINARY FOUNDATIONS

The next definitions, formulas, concepts, and methodologies are defined with the purpose of establishing a solid basis of the suitable foundations for the building of the methodology based on fuzzy concepts adapted to specification OSA-CBM (Open System Architecture for Condition Based Maintenance).

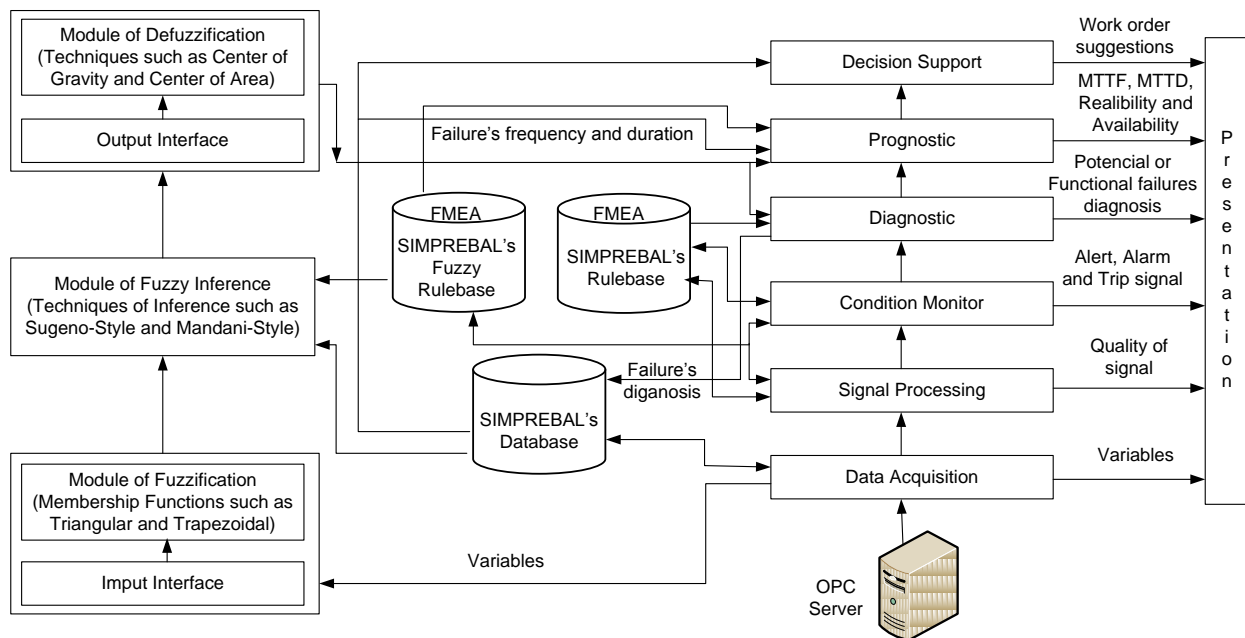


Figure 2. Structured Architecture of the enhanced system adapted to the specification OSA-CBM (Álvares and Amaya 2010, modified).

2.1 Encoding mechanisms

In the encoding phase (Fuzziness/Fuzzification), it accept any numeric input information from the external world and transform it into a format acceptable to the processing carried out within the framework of the formalism of fuzzy sets. It can look at the encoding process as a certain nonlinear normalization that converts any real number into its normalized version, usually with the values confined to the unit interval $[0,1]$ (Pedrycz y Gomide, 2007).

When it is going to analyze the encoding process in any industrial process (For instance, a hydroelectric power plant), it must be aware of the features and electric properties of the measurement instruments involved on the industrial process. For instance, sensors, actuators, programmable logic controllers and pumps to be operating in some plant industrial segment to maintain some pre-established performance.

After indentifying such electromechanical properties, the next step is, identifying the physic variables involved in each device, for instance, the temperature variable measured in some sensor and after to assign a appropriate membership function (for instance, such as Triangular or Trapezoidal Membership Functions) to the monitored physic variable (for example, add Membership Functions to the terms COLD, OK and WARM of the monitored temperature physic variable).

In the process to assign a suitable membership function to each monitored physic variable inside some industrial process, means in other words that, it must to assign a membership function to each range pre-defined for the fabricant of the device to sample that physic variable, or give such membership functions according to pre-established objectives by the system (running conditions).

According to Orchard (2001), the process to assign a appropriate membership function to each process variable, and thus, encode (Fuzzificate) the measures from them, it would be as represent the “uncertainty” of the measurements or the skill of operator to read the values of the instruments involved in some process.

2.2. Decoding mechanisms

According to Pedrycz and Gomide (2007) define the decoding process (Defuzzification) as, the process complementary to the one realized through the encoding. Given are some fuzzy sets, and the goal would be to develop its numeric representative. This transformation is referred to as decoding mechanism.

There are two main directions that are pursued (Pedrycz and Gomide, 2007):

- (a) Decoding complete on a basis of a single fuzzy set; this avenue seems to be more vigorously discussed with various techniques being developed in several papers.
- (b) Decoding realized on a basis of certain finite family of fuzzy sets and levels of their activations.

One has to be fully aware that the way for the decoding could be realized is by no means unique. This is not surprising at all as membership functions are just continuous functions with infinite number of membership values or when dealing with finite spaces vectors of grades of membership, say $[0,1]^n$. Associating a single numeric value with the vector of numbers cannot be done in a unique manner (Pedrycz and Gomide, 2007).

In the next lines, it is going to give some equations adapted by, Pedrycz and Gomide (2007) of (Runkler and Glesner, 1993) and of Wierman (1997).

Consider a certain fuzzy set with its membership function $B(x)$. Denote the transformation of B into some numeric representative by $\hat{x} = D(B)$. The most commonly encountered methods include the following:

2.2.1. Centre of area

It finds a position of \hat{x} such that it results in the equal areas below the membership function positioned on the left and on the right from this representative. In order words we have:

$$\int_{-\infty}^{\hat{x}} B(x)dx = \int_{\hat{x}}^{\infty} B(x)dx \quad (1)$$

It assumes that the membership function can be integrated.

2.2.2. Centre of gravity

Here the technique of centre of gravity decodes, the final fuzzy set, returning a decimal number to represent the fuzzy set. In others words, it assess the first moment of area, of a resultant fuzzy set, with respect to the axis of membership (Orchard, 2001). Here the result of decoding (Defuzzification) is obtained as follow:

$$\hat{x} = \frac{\int_x B(x)x dx}{\int_x B(x) dx} \quad (2)$$

It assumes that the above integrals do exit.

Given the larger number of decoding alternatives, it could be helpful to establish some systematic criteria that can be accepted and any decoding scheme could satisfy (Pedrycz and Gomide, 2007). The example of some axiomatic frameworks has been offered by Runkler and Glesner (1993). The authors proposed a series of requirements that are organized into several groups, namely (a) basic constraints in which issues of specific forms of membership functions (constant and singletons) and monotonicity, (b) graphically motivated requirements including symmetry, translation, scaling, offset, (c) constraints motivated by the use of logic operations and linguistic modifiers (dilation and concentration), and (d) requirements specific to some application domains are discussed (Pedrycz and Gomide, 2007).

2.2.3. Mamdani-style inference

The most commonly used fuzzy inference technique is the so-called Mamdani method. In 1975, Professor Ebrahim Mamdani of London University built one of the first fuzzy systems to control a steam engine and boiler combination. He applied a set of fuzzy rules supplied by experienced human operators (Negnevitsky, 2005).

The Mamdani-style fuzzy inference process is performed in four steps: fuzzification of the input variables, rule evaluation, aggregation of the rule outputs, and finally defuzzification (Negnevitsky, 2005). Due to the structure of the rules previously implemented of the first version of SIMPREBAL system, for this reason, it was implemented fuzzy rules with Mamdani-style fuzzy inference for the processing of the SIMPREBAL's rules.

2.2.4. Sugeno-style inference

Mamdani-style inference requires finding the centroid of a two-dimensional shape by integrating across a continuously varying function. In general, this process is not computationally efficient (Negnevitsky, 2005). But this Mamdani-style inefficient computational feature can be overcome through using triangular and trapezoidal membership function (Pedrycz and Gomide, 2007), and it is by this reason that it applied Mamdani-style inference into SIMPREBAL's fuzzy rules base.

It can use a single spike, a singleton, as the membership function of the rule consequent. This method was first introduced by Michio Sugeno in 1985. A singleton, or more precisely a fuzzy singleton, is a fuzzy set with a membership function that is unity at a single particular point on the universe of discourse (UOD) and zero everywhere else. Sugeno-style fuzzy inference is very similar to the Mamdani method, Sugeno changed only a rule consequent, instead of a fuzzy set, Sugeno used a mathematical function of the input variable (Negnevitsky, 2005).

3. CASE OF STUDY

For the case of study of SIMPREBAL system (Álvares *et al.* 2007b, Amaya. 2008, Souza. 2008, Tonaco. 2008), specify study about maintenance of hydraulic generators units of the Balbina's hydroelectric power plant, it already has a structure well-defined about all the plant, sensors, OPC servers, industrial segments, Data base through storage variables' historic event, work orders among others, Rule base through the application of FMEA table (Álvares *et al.* 2007c), actuators, concentrators, etc. Besides it have all the physics variables entirely labeled (Stored in their own Data base) and measurements through intelligent sensors using technology Fieldbus Foundation through of all five hydraulic generator units to pose Balbina (Smar 2001, Smar 2005).

An alternative methodological approach is being presented in the same congress by Alape *et al.* (2011), in which it built a knowledge-base based on the CBR (Case-Base Reasoning) algorithm for the new SIMPREBAL system.

In the next lines, it going to approach the methodology itself covering the case of study for a better understanding, specifying each step/phase of the methodology of the fuzzy rules based expert system adapted to the specification OSA-CBM according to the Figure 2.

4. APPROACH OF THE METHODOLOGICAL PROPOSAL

The building of our fuzzy expert system adapted to the specification OSA-CBM incorporates the following steps according to Fig. 2. (Negnevitsky. 2005, Pedrycz and Gomide. 2007, Orchard. 2001):

4.1. Fuzzification of the system's inputs and determination of their fuzzy sets

In this stage, it must be aware of all physic variables involved in the industrial process; it must define all fuzzy variables (linguistic variables) of the system (i.e. Define all the terms of each fuzzy variable). To define appropriate linguistic terms it must have in consideration the following: (a) Define the type of membership function (Determine a adequate fuzzy set) that must be used for that monitored physic variable (In general, using an aggregation/combination of triangular and/or trapezoidal membership functions is enough for a fast computational processing), (b) How many terms should be used to define completely that physic variable (In many cases, using a number of odd terms is adequate to avoid complex processing of the system's rules, for example, 3 or 5 terms would be enough).

For instance, for the study case in the Balbina's Hydroelectric Power Plant, it is going to fuzzificate (encode) some temperature physic variable considering the following statements (Álvares and Amaya, 2010):

I. In the Condition Monitor Layer of the specification OSA-CBM (See Figure 2), in the first version of SIMPREBAL system, it was defined four level of operation for each monitored physic variable (i.e. NORMAL, ALERT, ALARM and TRIP).

- II. Such levels are defined as: NORMAL ($< 85^{\circ}\text{C}$), ALERT ($100 - 130^{\circ}\text{C}$), ALARM ($130 - 155^{\circ}\text{C}$) and TRIP ($> 155^{\circ}\text{C}$).
- III. The temperature physic variable (For instance, the Coil Stator Temperature variable, with code/label 49G1A) and units of $^{\circ}\text{C}$) to fuzzificate is belonging to the Electric Generator System of Balbina.

Now, it is going to fuzzificate that temperature (Coil stator) with their respective membership functions (Triangular and Trapezoidal for a fast processing of the rules) and their appropriate fuzzy terms according to the considerations above quoted:

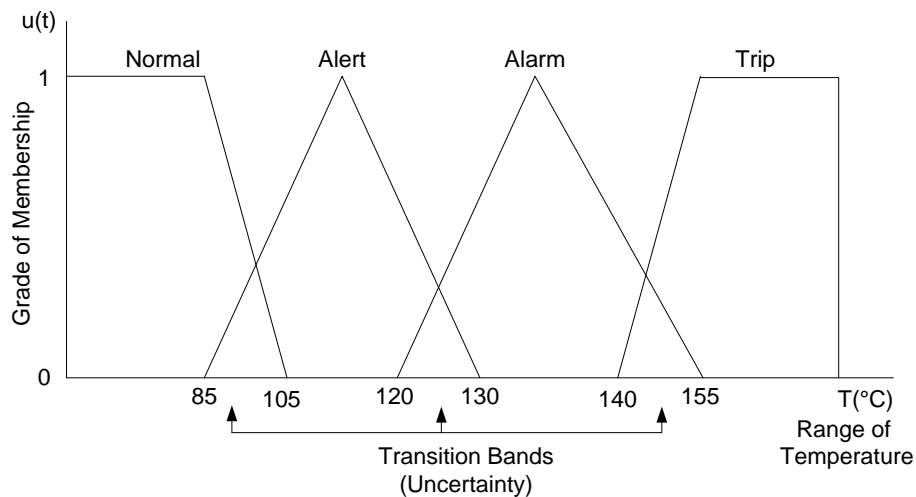


Figure 3. Fuzzification (Encoding) of the Coil Stator Temperature Variable with Fuzzy Terms NORMAL, ALERT, ALARM and TRIP.

In the Figure 3, it is clear note that, the ranges were fuzzificated with their respective fuzzy sets (Triangular and Trapezoidal). It is important mentioned that, those Transition Bands or Uncertainty Bands were choice according to specification of temperature measurement in the device, system or sub-system, level of spam, imprecision of measurement of the operators among others features of the device's operation .

Following the same reasoning, it could apply the same concepts into the other variables of process such as level, pressure, flow and among others that are belonging to SIMPREBAL's system. Fuzzificating (Encoding) the system's input variables avoid problems related to unnecessary work orders due to the lack of a appropriate range, range of uncertainty that the first version of SIMPREBAL had not implemented (Souza, 2008), more flexibility and speed into the processing of the rule since, the membership function are triangular and trapezoidal functions (Pedrycz and Gomide, 2007).

4.2. Elicit and construct fuzzy rules and perform fuzzy inference into the system

The JESS (Java Expert System Shell) language is an interpreter, to specify the grammar for the building of Production Rules Based Expert System in a Java programming environment (Friedman, 2003). This language was used for the building of the fuzzy capabilities less production rules for the first version of the knowledge base of SIMPREBAL system.

Here, it will follow using the same programming environment, but now it will introduce fuzzy capabilities into the JESS rules using the NRC FuzzyJ Toolkit (FuzzyJESS) built by Orchard (2011).

In this phase, basically it will work in the Condition Monitor Layer and Signal Processing of the specification OSA-CBM (As a feedback) as shown in the Figure 2. The SIMPREBAL system use FMEA (Failure Mode and Effect Analysis) table to generate their Knowledge Base which help to establish the rules of system and therefore, help to create new fuzzy rules too (Álvares *et al.* 2007c).

To continuation it will build, as an example, a FuzzyJESS rule beginning with the JESS rule of the first version of SIMPREBAL system as depicted in the Figure 4.

Now, it will build the FuzzyJESS rule equivalent to the rule below depicted as shown in the Figure 5.

As shown in the Fig. 5, it is clear that the new rule (FuzzyJESS rule) compared with the old rule has more code, but it is more flexible than simple JESS rule. It can see that, the new rule use appropriates membership function (Triangular and Trapezoidal) according to the interviews with the process operators, electric properties of the instruments among others important features.

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;This a very simple example about the building of a fuzzy capabilities less jess rule
;in the didactic plant (PD3) that pose Fieldbus technology implemented in their
;devices of measurement of the monitored physic variables such as tempretature,
;flow, level among others. For the case of the SIMPREBAL sytem, it must follow
;the same reasoning considering the features own of each instrument involved in
;the process. The PD3 is a micro industrial process that serve as training to the
;operators of the Balbina's hydroelectric power plant (Álvares and Amaya, 2007).

;***** WARMING OF WATER (TANK 1) MIX OF Water (TANK 2) *****

;***** TANK TEMPERATURE *****

(defrule PD3-TANQ-A-M-MonitoracaoCondicao-21
(Tag {label == "pd3.tanq_a_m.t.tanq1" && value != "" && value <= "15"})
=>
(assert (condition-NORMAL ?label))
)
    
```

Figure 4. Old version of the JESS rules implemented in the first version of SIMPREBAL system.

```

;*****FUZZY VERSION OF THE RULE: PD3-TANQ-A-M-MonitoracaoCondicao-21*****
;
;;We define a global variable for the TEMPERATURE
(defglobal ?*tempFvar* = (new FuzzyVariable "temperature" 0.0 105.0 "C"))

;;A initial rule to add terms into the TEMPERATURE variable
;;fuzzy TEMPERATURA (Creating fuzzy terms)
(defrule init
=>
(load-package nrc.fuzzy.jess.FuzzyFunctions)
(bind ?xTrip (create$ 55 58))
(bind ?yTrip (create$ 0.0 1.0))
(*tempFvar* addTerm "NORMAL" (new TriangleFuzzySet 9 18))
(*tempFvar* addTerm "ALERT" (new TriangleFuzzySet 31.5 33))
(*tempFvar* addTerm "ALARM" (new TriangleFuzzySet 51.5 13))
(*tempFvar* addTerm "TRIP" ?xTrip ?yTrip 2)

;;Fuzzificating the measurement of the reading of TEMPERATURE sensor (Thermoresistence-
;;RTD) - A Value according to the precision of instrument (for example 0.015 of spam)

(assert (imputTempFuzzy (new FuzzyValue ?*tempFvar* (new TriangleFuzzySet(value - 0.015
value value + 0.015))))))
)

;;Performing the rule (Executing/Firing Applying Mandani-style inference by default)

(defrule PD3-TANQ-A-M-MonitoracaoCondicao-21

(Tag {label == "pd3.tanq_a_m.t.tanq1"})
(imputTempFuzzy ?t&:(fuzzy-match ?t "NORMAL"))
=>
(assert (condition-NORMAL ?label))
)
    
```

Figure 5. New version of the FuzzyJESS rules implemented in the last version of SIMPREBAL system.

In this case of study, it is going to use the Mandani-Style fuzzy inference method (By default implemented in the package FuzzyJESS), because it more adapt to the kind of rules of SIMPREBAL system and it is easily implemented with the package FuzzyJESS. It is important mentioned that according to the format of the rules of the first version of SIMPREBAL system, it was made a previous comparative study among the Sugeno and Mandani techniques and thus, it arrived to the conclusion that, the kind of Mandani-style rules adapt better into the JESS rules of the SIMPREBAL system, since, as it was defined in the items 2.2.3 and 2.2.4, is clear that, the great difference among both methods is that, the Mandani technique use fuzzy sets in their consequents and antecedents, unlike the Sugeno-style technique that use in the consequents mathematics functions. Therefore with this characteristic the SIMPREBAL system fuzzy rule base, as shown in the Figure 2, use Mandani fuzzy inference for the processing among the fuzzy inputs and fuzzy rules originating fuzzy outputs (Resultant Fuzzy Sets) and not fuzzy singletons (Fuzzy Sets with a only element in the Universe of Discourse).

For more complex systems, it must follow the same steps as depicted in the Figure 5 and then store them into a Fuzzy Rule Base (Fuzzy Knowledge Base) in a format modifiable, for this case, this format is a file with extension (.txt). This is a pre-requisite of the initial basis of the first version of SIMPREBAL system (Álvares and Amaya, 2010).

4.3. Defuzzificate the system's final outputs

Here, it are going to use Centre of Gravity (COG) technique (By default implemented in the package FuzzyJESS), since this method is the most appropriate for our application due to that, the resultant output are fuzzy sets and not fuzzy singletons. If the SIMPREBAL's outputs were fuzzy singletons then, the most appropriate would be use the Centre of Area (COA) technique (Negnevitsky. 2005, Pedrycz and Gomide. 2007, Orchard. 2001).

For instance, for this study of case, a fuzzy final output of Coil Stator Temperature could be something as depicted in the Figure 6:

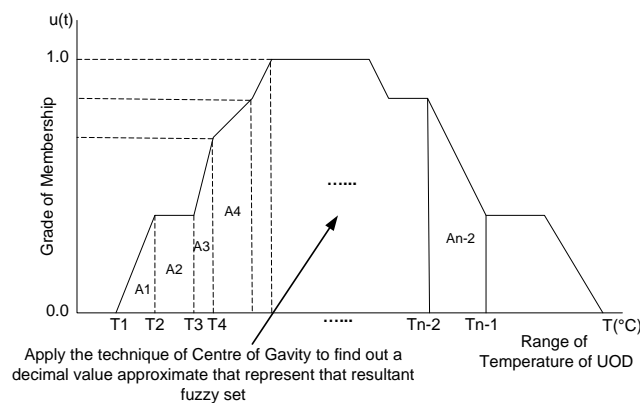


Figure 6. A resultant Fuzzy Set as result of the fuzzy inference process among Coil Stator Temperature and Fuzzy Rule Base in which it expect to find a decimal value.

In the Fig. 6. It can see that the defuzzification process imply as result a decimal value to substitute all the resultant fuzzy set. It be able to get this value and give certain meaning to use for the system, it must apply the Eq. (2). This value could be used to feedback of the layers of Diagnostic and Prognostic of the specification OSA-CBM and with help of a neural network (i.e. Through applying the backpropagation or Radial Base function algorithms) for learning and thus, to predict the future behavior of the devices in the Balbina's generator units with the objective of establishing appropriate predictive maintenance actions to avoid unnecessary stopped of the machines.

5. CONCLUSIONS

With these contributions, it could to say that, the rules that were implemented in the last version of SIMPREBAL presented more flexibility in terms of processing, speed (Due to their membership function that are Triangular and Trapezoidal functions).

The version of the SIMPREBAL system's fuzzy rules dealing with the aspect of uncertainty that is generated due to physic features such spam, mistake of the operators with relation to the interpretation of the reading of the devices that belonging to the Balbina's hydroelectric power plant (Hydraulic generator units) among others.

Another important thing to mention is that, the outputs of the fuzzy processing (Processing of the fuzzy rules and fuzzy inputs through applying Mandani-style fuzzy inference), it should help to decide about decision making, prognosis and diagnosis layer (i.e. a feedback into those layers). This subject should be carried out along with an appropriate neural network for learning (i.e. Learning of their membership functions, fuzzy rules, among others).

With the FuzzyJESS rules along with other technique of artificial intelligence such as Neural Networks, it expects that the system learn to find out appropriate membership functions, fuzzy rules and thus, giving yet more flexibility into our Fuzzy Knowledge Base, this could be carried out as a future work.

Probably in a future version of system it could implement fuzzy rules as a combination of inference Sugeno and Mandani-style to gain a better performance of the system.

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