2013 International Nuclear Atlantic Conference - INAC 2013
Recife, PE, Brazil, November 24-29, 2013
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
***ISBN:* 978-85-99141-05-2**

ñEXPERT SYSTEM FOR FAULT DIAGNOSIS IN PROCESS CONTROL VALVES USING FUZZYï LOGICò

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ABSTRACT

The models of asset maintenance of a process plant basically are classified in corrective maintenance, preventive, predictive and proactive ("online"). The corrective maintenance is the elementary and most obvious way of the maintenance models. The preventive maintenance consists in a fault prevention work, based on statistical studies that can lead to low efficiency or even an unexpected shutdown of the plant. Predictive maintenance aims to prevent equipment or systems failures through monitoring and tracking of parameters, allowing continuous operation as long as possible. The proactive maintenance usually includes predictive maintenance, emphasizing the root cause analysis of the failure. The maintenance predictive/proactive planning frequently uses software that integrates data from different systems, which facilitates a quick and effective decision- making. In nuclear plants this model has an important role regarding the reliability of equipment and systems. The main focus of this work is to study the development of a model of non-intrusive monitoring and diagnosis applied to process control valves using artificial intelligence by fuzzy logic technique, contributing in the development of predictive methodologies identifying faults in incipient state. The control valve analyzed belongs to a steam plant which simulates the secondary circuit of a PWR nuclear reactor ï Pressurized Water Reactor. This study makes use of MATLAB language through the "fuzzy logic toolbox" which uses the method of inference ñMamdaniò, acting by fuzzy conjunction, through Triangular Norms (t-norm) and Triangular Conorms (t-conorm). As input variables are used air pressure and displacement of the valve stem. Input data coming into the fuzzy system by graph of the automation system Delta VÊ available in the plant, which receives a signal of electric current from an ñintelligentò positioner installed on the valve. The output variable is the "status" of the valve. Through a rule base established by experts, it becomes possible to investigate failures establishing the operational status of the valve which constitutes the output of the expert system.

1. INTRODUCTION

Proactive maintenance allows a plant asset management, providing for the operation, the real condition of a device, in this case, the process control valves. It is possible to model the signals from a control valve of a PWR ï Power Water Reactor, using Artificial Intelligence Methodology through the *Fuzzy Logic Technique*, ensuring a high degree of reliability, operability and safety. Failures as stucked, excessive friction, valveôs misadjustment, load factor, course limit, etc., can be detected "online", allowing an intervention, thereby minimizing operational losses. The signature of the valve is the visual indication, clear and quick to operating conditions monitoring for possible failures. The issue of fault diagnosis in final control elements is a matter not yet treated in its entirety. The techniques about monitoring and diagnosis are divided into intrusive and non-intrusive that is more suitable for nuclear plants. Non-intrusive techniques applied to control valves are still a challenge for technicians and specialists [1]. The presented proposal is the monitoring and diagnosis of control valves with pneumatic actuator, through the analysis of valve displacement (*milimeters*) versus air pressure variation on the actuator (*pressure square inch)*. This work makes use of Artificial Intelligence Technique, using *Fuzzy Logic*, by the tool "*fuzzy-logic toolbox*-MATLABò, that is a powerful mathematical application software of problemôs solutions and graphic illustrations. This tool is based on fuzzy conjunction, through Triangular Norms and Conorms, via the Mandani inference system based on knowledge base established by rules provided by specialists in valves.

2. ARTIFICIAL INTELLIGENCE-FUZZY LOGIC

The foundations of Artificial Intelligence-AI is established in 1950, including mathematical logic and theory of recursive functions. In 1960, AI researchers tried to simulate the complex thinking process. Professor Lotfi Zadeh said in 1965 [2] that the vagueness set in classes denotes an important role in human thinking, particularly in pattern recognition, information communication and abstraction. Based on this, some *fuzzy* concepts in engineering can be defined. Conceptualizes the follow terms and its contextual usage: correlation (low, medium, high, perfect), stability (unstable, stable etc), errors (large, medium, small), frequency (high, low, ultra high etc), bandwidth (wide, narrow), sample (low, medium, high etc), resolution (high, low) etc.
Zadeh [3] states that this inaccuracy is that *fuzzy* logic differs from classical two-valued logic. In the classic system of two values, the classes have defined borders. In this way, the member of a class cannot be a member of another. A good example is the classes of type gender: male or female, living or dead. Thus, the *fuzzy* logic is a generalization of the classical two-valued logic. Figure 1 shows a block diagram of a FLS - Fuzzy Logic System. The FLS maps crisp inputs to crisp outputs. Mendel [4] names the variables from the classical logic as term crisp. Once established the rules, the diagram can be expressed by a relationship y = f (x). One of the greatest goals of FLS is to obtain explicit formulas for nonlinear mappings between x and y.

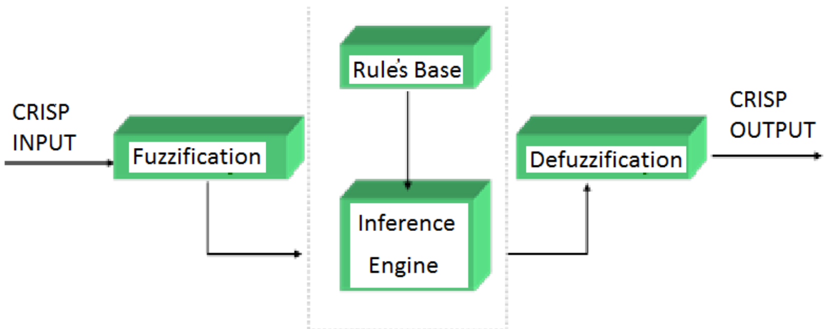

Figure 1: Block diagram of a FLS[5].

The FLS is divided: Fuzification, Rulesôbase, Inference Engine and Defuzification.

ã ***Fuzzification****: is based* on the concept of fuzzy set. Unlike the classical theory of sets and its mathematical logic rigidity, the *Fuzzy Logic* presents the term membership as a degree with gradual variations. In the *Fuzzy Logic Toolbox*, the input is always a crisp numerical value limited to the universe of discourse of the input variable and the output is a fuzzy degree of membership in the qualifying linguistic set (always the interval between 0 and 1).

Classic set *A = {0.1}* discrete values *0* and *1; and Fuzzy Set B = [0.1].*

The degree of membership can assume continuous values from *0* to *1*, then the membership *"x"* of a subset *fuzzy* "*B"* of "X" can be described as: ***ε*** *B: x* → *[0.1];*where µA is the degree of membership. Therefore, the fuzzification that is the first step, consists to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. The membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between o and 1. The membership function can assume various geometric shapes (trapezoidal, triangular, Gaussian, etc). The *fuzzy* set can be described as:

B = {(x, ***ε*** *(B) (x))/x ‘ X}*. Each pair (x, µA (X)), (1)

that is called a *singleton* with a degree of membership µA (x) in a universe of discourse. Figure 2 presents the fuzzification step considering an input variable and a triangular membership function.

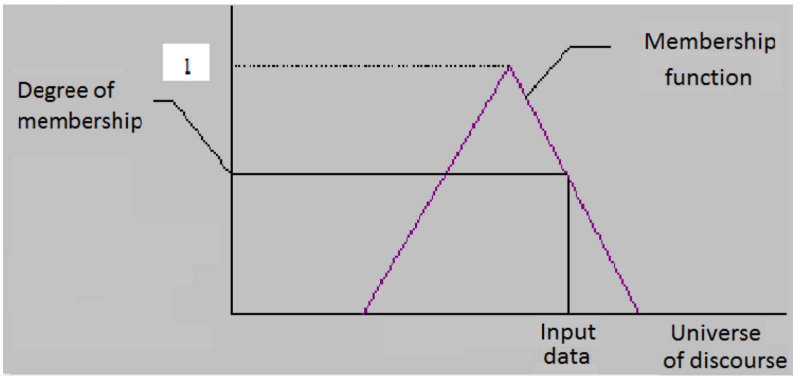

Figure 2: Fuzzification of an input variable [5].

The main operations between fuzzy sets are union, intersection, and complement. The *fuzzy* set *G* can be written as:

G =µ G (x1)/x1v.....v µ G (x 8)/x8 = × *µ G (xi)/xi* for *xi ‘ X.* (2)

Note: the symbol "v" means Union.

Defining three *fuzzy* sets *A*, *B and C* in the universe of *X*. For a given element *x* of the universe the following theoretical function for sets of operations of union, intersection and complement are defined by *A*, *B* and *C* in *X* [6]*:*

$$\text{Union } \boldsymbol{\varepsilon}_{(A \cup B)}(x) = \boldsymbol{\varepsilon}_A(x) \vee \boldsymbol{\varepsilon}_B(x); \qquad (3)$$
$$\text{Intersection } \boldsymbol{\varepsilon}_{(A \cap B)}(x) = \boldsymbol{\varepsilon}_A(x) \wedge \boldsymbol{\varepsilon}_B(x); \text{ and} \qquad (4)$$
$$\text{Complement } \boldsymbol{\varepsilon}_{A\sim}(x) = 1 - \boldsymbol{\varepsilon}_A(x). \qquad (5)$$

The diagrams for these operations are shown in figure 3.

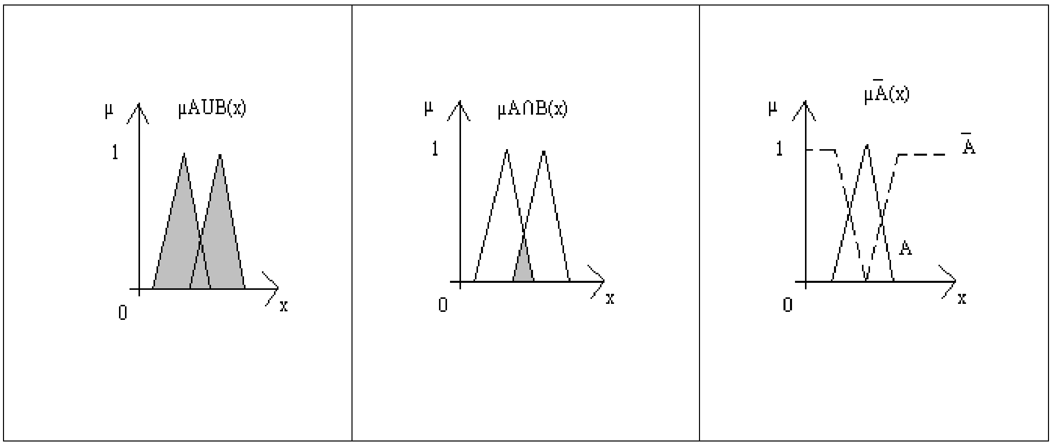

Figure 3: Union, intersection and complement of fuzzy sets.

ã ***Ruleôs Base***:

In artificial intelligence, there are several ways to represent knowledge. However, one of the most common ways of representing human knowledge is through natural language expressions. Hence we have expressions like:

IF premise (antecedent), THEN conclusion (consequent). (6)

Timothy [6] states that this representation is generally referred to as deductive way. Typically expressed an inference that is known (premise, antecedent, hypothesis), which can be inferred, or derive from, the other fact called completion (consequent). This knowledge representation called superficial knowledge is appropriate in linguistic context, because it expresses the empirical knowledge and heuristics of own communication language of the human being, capturing, so a deep form of knowledge.

The rules are provided by experts or can be extracted from numerical data (where will the *expertise* of specialist in valves and the mass of data to be reported by the instrumentation team process plant). What is described by the human being (specialist) is taken as the basis for developing the rules. Each rule is part of a conditional structure with one or more clauses, such as "If A then B else C".

The rules can be classified as multi-antecedent or multi-consequent, incomplete, mixed, sentence, quantifier phrases, comparative, etc, [7].

ã ***Inference Engine*** is an algorithm that deals with the rules that represent the knowledge of an expert, that is a procedure used to assess the *fuzzy* linguistic descriptions. These procedures can be implemented on a computer when itôs necessary quick processing. However, sometimes, it is useful to make an inference manually, with few rules, to check computer programs and/or to check the perfect functioning of the own inference. Several methods of inference could be cited. The most known are *Systems of Mamdani and Sugeno.*

Considering a simple system of two rules, where each rule has two antecedents and a consequent, and that can be easily extended to *fuzzy* rule base or *fuzzy* systems with any number of antecedents and consequents. A *fuzzy* system with two non-interactive entries $x1$ and $x2$ (antecedents) and a simple output y (consequent) is described by a collection of linguistic expressions "*IF-THEN" proposition* in the form of *Mamdani*:

$$\text{IF } x1 \text{ is } (A_1)^k \text{ and } x2 \text{ is } (A_2)^k \text{ THEN } y^k \textit{ is } B^k \text{ for } k = 1, 2, ..., r \quad (7)$$

where $(A_1)^k$ and $(A_2)^k$ are *fuzzy* sets representing the k^{th} antecedent pair and B^k is the *fuzzy* set representing the k^{th} consequent.

Itôs possible to illustrate the above equation, whereas two inputs $x1$ and $x2$ with scalar values (crisp), with delta functions and using the max-min inference method. The member function for the inputs $x1$ and $x2$ are described as:

$$\boldsymbol{\varepsilon}\ (x1) = \check{u}(x1\ \bar{\imath}\ \ input\ (i)) = 1,\ x1 = input\ (i);\ 0, \quad (8)$$

$$\boldsymbol{\varepsilon}\ (x2) = \check{u}(x2\ \bar{\imath}\ \ input\ (j)) = 1,\ x2 = input\ (j);\ 0, \quad (9)$$

Based on inference method of Mamdani implication, the output produced for r rules will be as below and in Figure 4, which in this case is used the method of minimum maximum:

$$\boldsymbol{\varepsilon}\ (B)^k(y) = Max^k[min\ [\boldsymbol{\varepsilon}\ (A_1)^k(input\ (i)),\ \boldsymbol{\varepsilon}\ (A_2)^k\ (input\ (j))]],\ k = 1, 2, ..., r. \quad (10)$$

Itôs still possible to get the MAMDANI inference through intersection operators:

$$R_c = A\ X\ B = \acute{U}\ U\ X\ V\ (\mu A\ (u) \wedge \boldsymbol{\varepsilon}\ (B)\ (v))/(u, v) \quad (11)$$

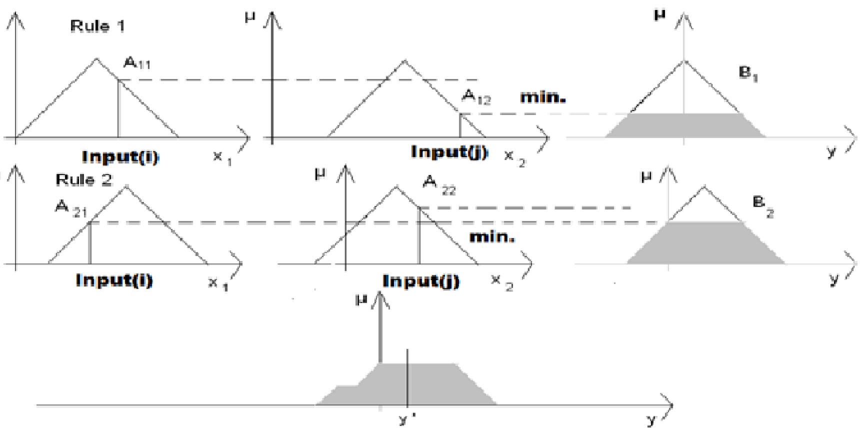

Figura 4: Mamdani inference graphics.

ã ***Defuzzification**:* this is the conversion of a *fuzzy* quantity for a precise amount (crisp), while fuzzification is the reverse process. As much as fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variable is generally a single number. The output of a *fuzzy* process can be a logical union of two or more functions defined in the universe of discourse of an output variable. For example, a fuzzy output consists of two parts, a triangular and trapezoidal shape.

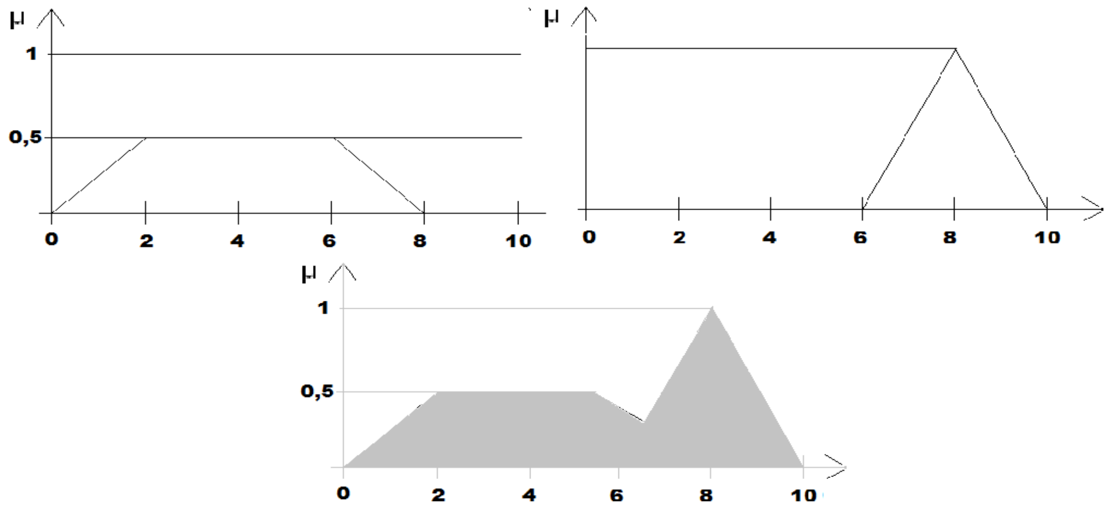

Figura 5: Typical fuzzy process output.

The two top graphs in Figure 5 with member functions of trapezoidal and triangular shape, represent the two parts of fuzzy output that enveloped, involves, in this case, the union of the previous areas.

$$C_k \;=\; U^{k}{}_{i=1} C_i \;=\; C \qquad (12)$$

This method presents the characteristic to involve all members through the union of their areas, as can be seen in the relation above. The centroid method or center of gravity is

$$Y^* = \left(\int \mu C\,(y)\; y\; dy \right) / \left(\int \mu C\,(y)\; dy \right), \qquad (13)$$

where $\int$ denotes a algebraic integration. The output of the FLS or specialist system is not fuzzy anymore, it is a numeric value. There are several methods used to perform *defuzzification*: height, height modified, maximum average, maximum, and centroid. The centroid method has been used on this project and consists of the control action calculated by obtaining of the gravity center of the distribution possibilities of global control action. According Sugeno 1985[8] and Lee 1990[9], this procedure is also called central area or center of gravity, it is the most usual and has great physical appeal.

Figure 6 shows the graphical representation of *defuzzification* method centroid or center of gravity method.

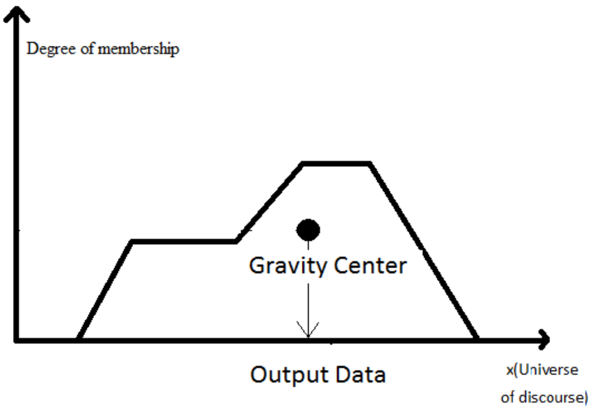

Figure 6: Center of gravity method.

3. CASE STUDY

The case study presented deals with the analysis and diagnosis of the temperature control valve TV- 462B that performs the cooling of lubricating oil of the main propulsion turbine of the secondary circuit of a PWR. It is installed in a plant testing propulsion in the laboratory ï LATEP ï of the Brazilian's Navy.

There were used as input variables of the Fuzzy System, the compressed air pressure from valveôs actuator, in PSI (Pressure Square Inch) and the displacement of the valve stem in mm (milimeters). The system output variable has the "status" of the valve, by percentage (0 to 100%) of opening/closing, with indications that the valve is stuck open, stuck closed, with friction, with difficulty to open, or needing to schedule maintenance. The data (signature of the valve) acquired by the DeltaV Ê automation system installed in the laboratory consist of input data of the Fuzzy Logic System - FLS.
The valve has the following features:

Input variable	Output variable
excvalv Ÿ 4 to 23 mm	statvalv Ÿ 0 to 100% (from opening to closing)
pressat Ÿ 0 to 28 PSI	

The figure 7 shows the correct signature (no failures) of the valve "baseline", where at the top there is the closing cycle and at the bottom the opening cycle, which represents the tour of the valve stem 4 - 23 mm and 0 to 28 PSI the pressure on its diaphragm.

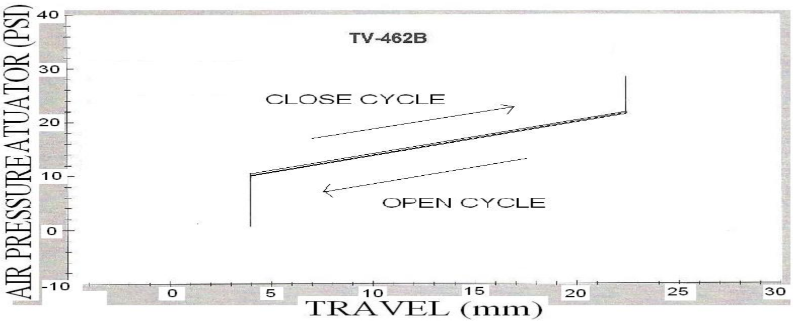

Figure 7: Valveôs baseline TV-462B.

The table 1 shows the values of the variables and the respective valve status as output variable. The "status" closed represents that the stem touched the base. And closed strongly represents the excess air pressure to ensure that the valve is sealed to avoid leakage. The diagnosis due to the status of the valve is represented by the table 2. It shows when the stem is working normally, or is locked, or with motion difficulties or need maintenance.

Table 1: Valveôs range

Valve Status	*Open*	*¼*	*½*	*¾*	*Closed*	*Strongly closed*
TV462B	(4; 0)	(9; 12.5)	(14; 15)	(19; 17.5)	(23;20)	(23;20) (23;28)

Table 2: Diagnosis by "Status" of the valve

Valve Status	*Stuck open*	*Closing normally*	*Opening normally*	*Difficulty to close*	*Requiring maintenance*	*Stuck closed*
TV462B	(4.28)	(4.0) (23.28)	(23.28) (23.20)	(4.12) (5.12)	(20.17) (20.1)	(20.0)

The table 3 shows the membership functions and input/output variables.

Table 3: Membership functions and their values

TV462B	*Values (excvalv)*	*Values (pressat)*	*Values (statvalv)*	*Membership Function*
Open	[3 4 7]	[0 12 10]	[-1 15 0]	Trimf
¼	[12 9 6]	[11 12.75 14.5]	[10 25 40]	Trimf
Half open	[11 14 17]	[15.5 14 17]	[30 50 70]	Trimf
¾	[16 19 22]	[15.75 17 19]	[60 75 90]	Trimf
Closed	[21 23 26]	[18 21 24]	[85100105]	Trimf
Strongly closed	Not applicable	[21 30 19 32]	[95120125 88]	Tramf
Stuck open			[-3 0 5]	Trimf
Difficulty to close			[3 10 15]	Trimf
Requiring maintenance			[75 80 85]	Trimf
Stuck closed			[95100120]	Trimf

The figure 8 shows an anomaly on the left in the upper cycle (close). This anomaly indicates difficulty in movement, and is transferred to the inputs of the FLS through Valvelink®, module of Delta V® automation system. The data are treated according to the rule base and will provide an output, which in this case will then automatically diagnose as an incipient failure.

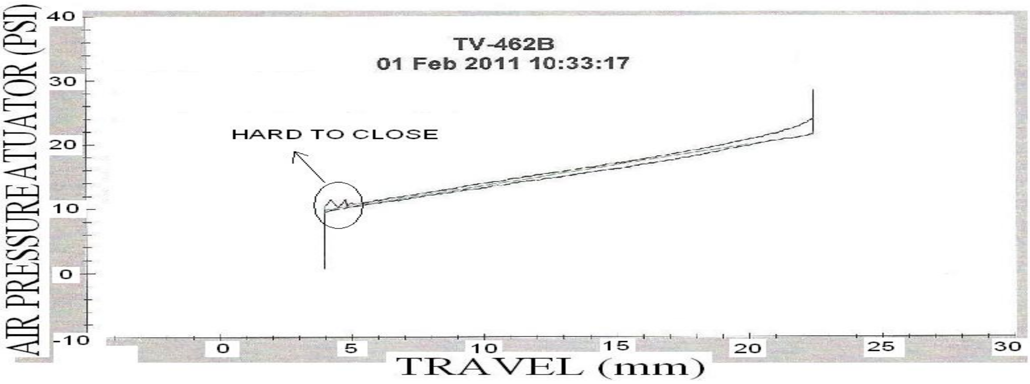

Figure 8: Valveôs Signature TV-462B.

The table 4 shows the rules provided by the specialists in instrumentation and control.

Table 4: Valveôs rules base.

RULES
1. If (excvalv is open) and (pressat is open) then (statvalv is open)
2. If (excvalv is a room) and (pressat is a room) then (statvalv is a room)
3. If (excvalv is in the middle) and (pressat is in the middle) then (statvalv is in the middle)
4. If (excvalv is three quarters) and (pressat is three quarters) then (statvalv is three rooms)
5. If (excvalv is closed) and (pressat is closed) then (statvalv is closed)
6. If (excvalv is open) and (pressat is strongly closed) then (statvalv is stuck open)
7. If (excvalv is open) and (pressat is three quarters) then (statvalv is set)
8. If (excvalv is open) and (pressat is a room) then (statvalv is difficult to close)
9. If (excvalv is a room) and (pressat is in the middle) then (statvalv is difficult to close)
10. If (excvalv is a room) and (pressat is three quarters) then (statvalv is necessary.)
11. If (excvalv is in the middle) and (pressat is three quarters) then (statvalv is difficult to close)
12. If (excvalv is in the middle) and (pressat is closed) then (statvalv is in need of maintenance)
13. If (excvalv is three quarters) and (pressat is closed) then (statvalv is needed.)
14. If (excvalv is closed) and (pressat is strongly closed) then (statvalv is fort.)
15. If (excvalv is closed) and (pressat is open) then (statvalv is stuck closed)

The figures 9, 10, 11 present the MATLAB® chart of membership functions of inputs "excvalv" and "pressat", and the output ñstatvalvò respectively.

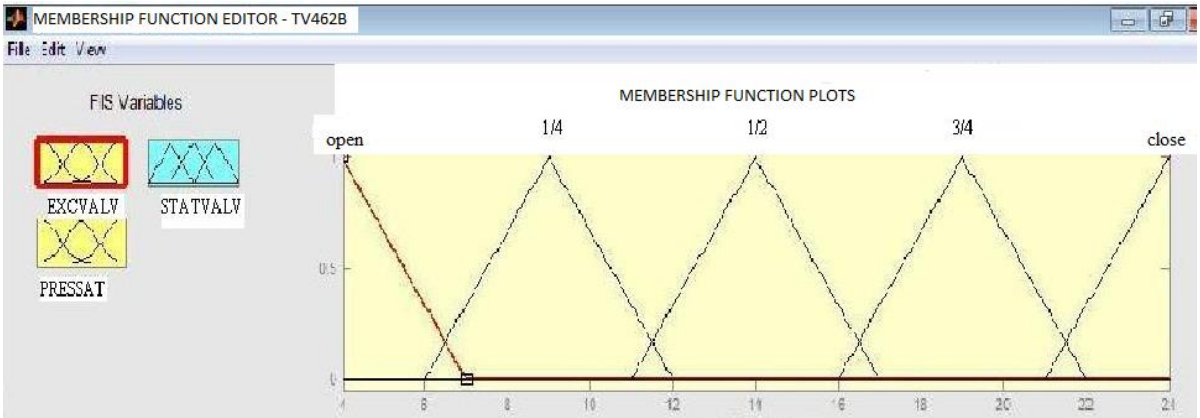

Figure 9 : The input variable ñexcvalvò.

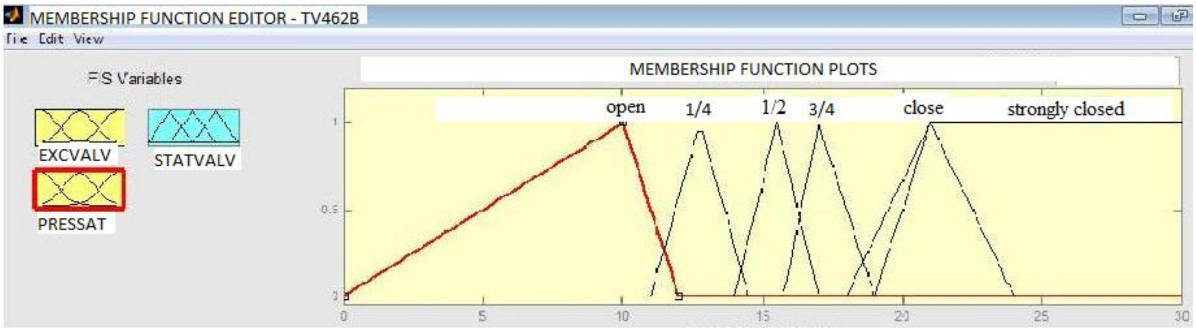

Figure 10 : The input variable ñpressatò

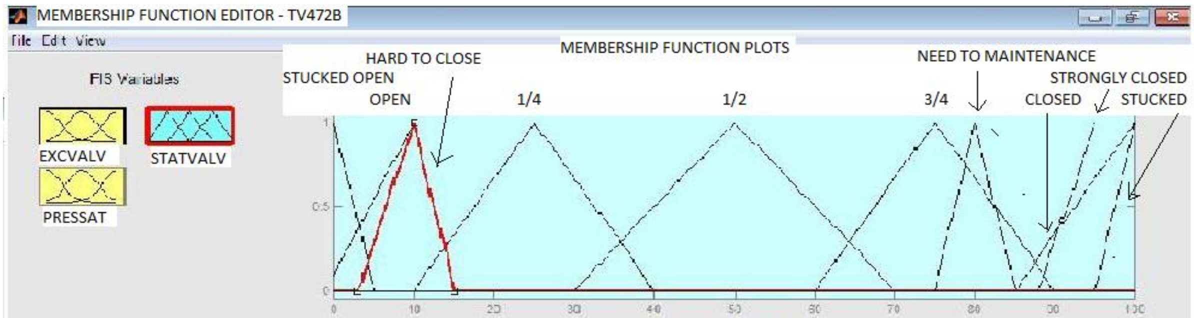

Figure 11 : The output variable ñstatvalvò

The figure 12 shows the rulesô viewer with emphasis on the 8, which the intensity of the two inputs generates a diagnosis, showing a type of failure. Due the entries "excvalv" and "pressat" present as "open" and "a quarter", the output variable "statvalv" present itself with the diagnosis "difficult to close", demonstrating an incipient failure, at the beginning of the closing valve.

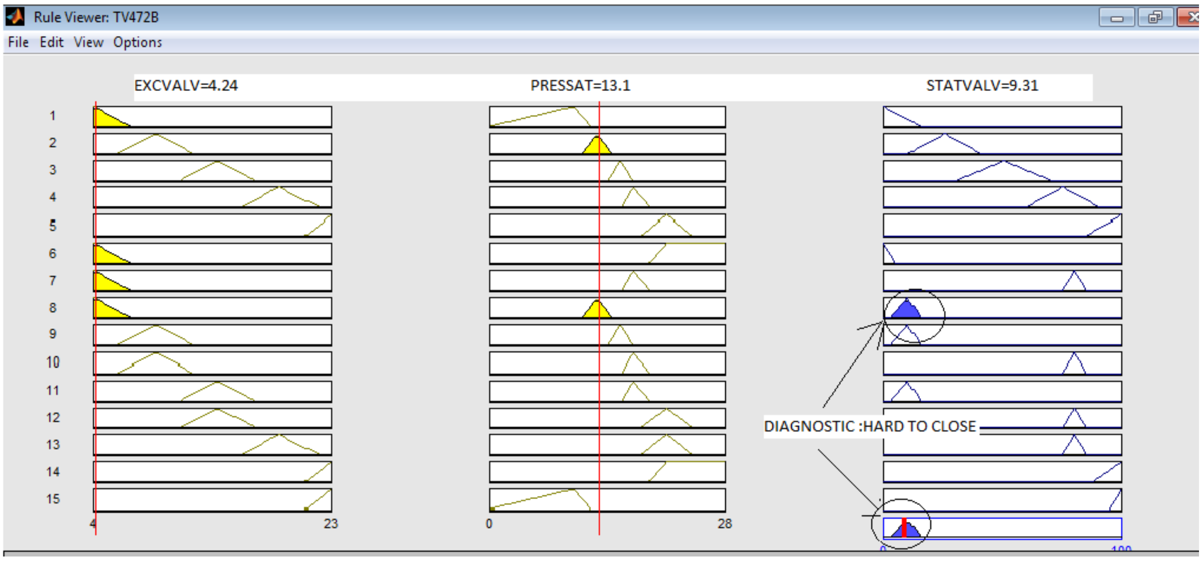

Figure12 : Rules viewer

3. CONCLUSIONS

The paper shows that expert system technology has brought significant improvements on predictive/proactive maintenance, considering the specific case, using Artificial Intelligence by the Fuzzy Logic Technique, detecting failures in advance which is a relevant contribution for condition monitoring and diagnose system.

The use of the MATLAB® platform aggregated to the *Fuzzylogic toolbox* has proved to be a powerful tool, using the tacit knowledge of the experts allowing the expert systems create a favorable scenario, becoming possible to learn about the correct diagnosis of a final control element (valves) of great importance to control in industrial plant, and particularly in nuclear plant, where the availability of the equipment should be high and unexpected intervention should be avoided.

However, this technique should be improved, testing different situations of failures in order to check the performance of the expert system mainly for failures on incipient stage. Furthermore the system must also be able to analyze different types of valves.

ACKNOWLEDGMENTS

Acknowledge the help of the engineers and technicians of CTMSP who helped us with data of valve.

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