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Development of an Integrated Condition Monitoring and Diagnostic System for Process Control Valves Used in Nuclear Power Plant

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The reliability question of the components, specifically the process control valves, became an important point to be investigated in nuclear power plants and others areas such as oil refinery or offshore oil platform, considering security and extension life of the plant. Therefore, the necessity of improvements in monitoring and diagnosis methods started to be the extreme relevance in the maintenance predictive field, as mentioned by Guimarães Carneiro (2007), establishing as main goal the reliability and readiness of the components systems. The development of nonintrusive monitoring and diagnostics method makes it possible to identify malfunctions in plant components during normal plant operation. The purpose is to present an analysis and diagnostic of a water flow control valve that charges a steam generator, simulating part of the secondary circuit of a power water reactor. This facility is part of the laboratory of tests of propulsion equipment of the Brazilian Navy, in São Paulo – Brazil (2007). The methodology of this project is based on the graphic analysis of two parameters; the valve actuator air pressure and the valve plug displacement. The data come from intelligent positioner; it is a kit of Delta V™ Automation System (2010). The analysis is implemented on detection of anomalies approach using Expert Systems by Fuzzy Logic technique based on rules and knowledge base. A distinct approach as mentioned by Choudhury (2005), Desborough (2001), Gerry (2001) or Camila Pinto (2010). Once the baseline measurements of control valves are taken, it is possible to detect fault symptoms, leaking, attrition, clamping, damage, etc. The system of monitoring and diagnostic was designed at the MATLAB™ platform “FUZZY LOGIC TOOLBOX”.

1. Introduction

Monitoring, maintenance and reliability of plant equipment are important operational issues and the identification of malfunctions in plant components are crucial points. The early detection allows to avoid catastrophic failures and the associated costs, besides to prevent interference with normal operation of plant. This paper presents a nonintrusive diagnostic technique to identify operational malfunctions in control valves, used in nuclear power plant. The diagnostic is based on the analysis of the parameters, such as, electrical current signals, related to the valve actuator air pressure and the valve plug displacement. These signals come from an intelligent positioner installed aside of the control valve and are presented in graphic format by the software VALVELINK®, developed by de EMERSON Management (figure1, acquired by the Delta V manual - 2010). The parameters extracted from the electronic signature of the valve constitute the set of input variables of the fuzzy logic and expert system.

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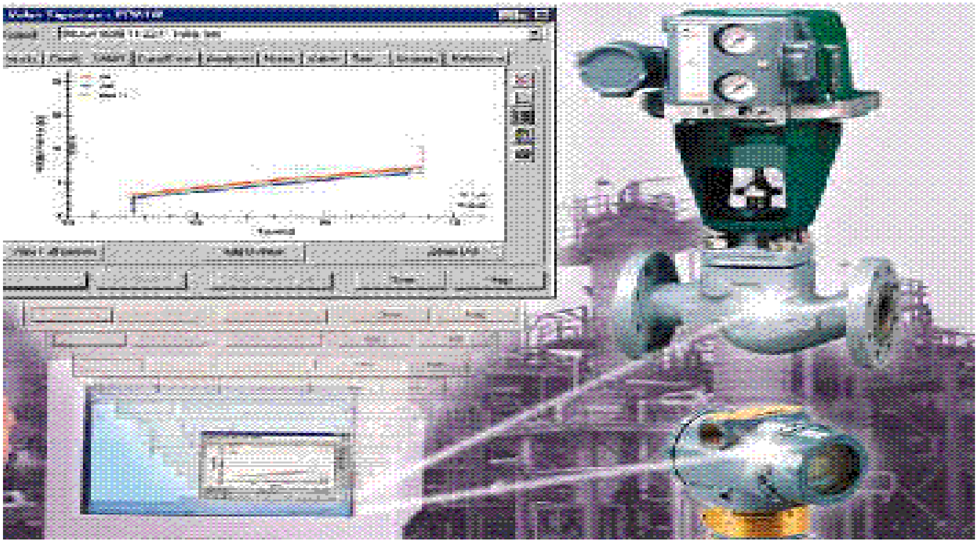

Figure 1: Ilustration of the valve, intelligent positioner and the electronic signature.

2. Fuzzy logic and Expert system

Fuzzy Logic is a formal approach to map a set of input data to a set of output data, providing a systematic approach for making decisions which can be quantified in the form of a crisp values. The difference between classical logic and fuzzy logic is that if/then rules are supposed to be true or false, and in fuzzy logic they can be true to a certain degree, through a fuzzy linguistic description. Data input and output of the expert system are linguistic variables. The linguistic variable is a variable whose arguments are referred to as fuzzy values. Fuzzy logic has advantages due its approximation with the human thought. The Fuzzy Logic System (FLS) maps *CRISP* (classical) inputs. Mendel (1995) developed the figure 2 that shows the FLS diagram with 4 boxes: RULES, FUZZIFIER, DEFUZZIFIER and INFERENCE MECHANISM.

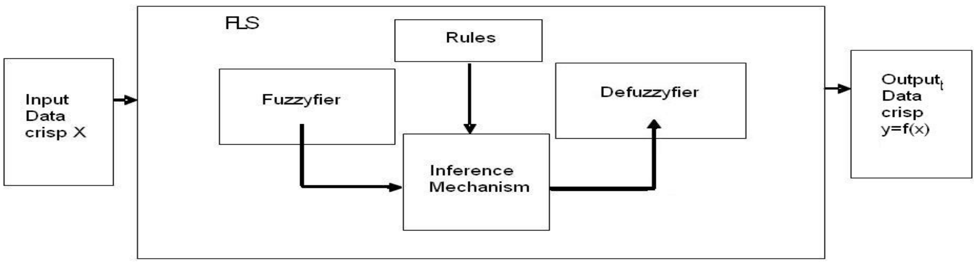

Figure 2 – FLS diagram

After the rules established, the diagram could be represent by a relation y=f(x). The purpose of the FLS is to explicit formulas to nonlinear map between x and y. The rules are provided by the experts or extracted from numeric data.

The INPUT DATA will be fuzzified, that means, data transformation by a membership function with a grade between 0 to 1 and processed by the INFERENCE MECHANISM, comparing with information about a "healthy" valve according to the RULES loaded by the experts (tacit knowledge about the several valves during its operation). The last box defuzzifies the signal and sends to OUTPUT with its owing diagnostic in *crisp* form. Klir (1995) and Navarro (2011) state the fuzzy set's concept .

Classic set $A=\{0,1\}$ discrete values *0* and *1;* Fuzzy set $B=[0,1]$

Professor Zadeh (1987) states that the membership function could be assumed continuous values between *0* and *1,* so the relevance *"x"* of a fuzzy subset "*B"* of "X" could be denoted by $\mu B: x \in [0,1]$; where μA is the relevance grade. The membership function could assume several geometric shapes (trapezoidal, triangular, sine, Gaussian, etc). The fuzzy set could be denoted as equation 1:

$$B=\{(x, \mu B(x)) / x \in X\} \quad (1)$$

Each pair (x, μA(X)) is named *singleton* with a relevance μA(x) in a universe of discourse *X.* The INFERENCE MECHANISM is an algorithm that treats the RULES representing the expert knowledge. Each rule has part of a conditional structure with one or more terms with its fuzzy propositions and connectives, as If A then B else C". The RULES are classified as multi-antecedent or multi-consequent, incomplete, mixed, comparative, quantified, etc. The output of INFERENCE MECHANISM generates a numeric value that is the input of the DEFUZZIFIER. There are several methods to make the defuzzification as height, modified height, maximum, average of maximum and center of gravity called also centroid method, which was implemented in this project.

3. Case Study

The case was obtained from a control valve (Figure 3) that charges combustible to the steam generator of the laboratory of tests of propulsion equipment in the Brazilian Navy, that simulates a secondary circuit of Power Water Reactor (PWR). The data was acquired by the valvelink® software through the electronic positioner.

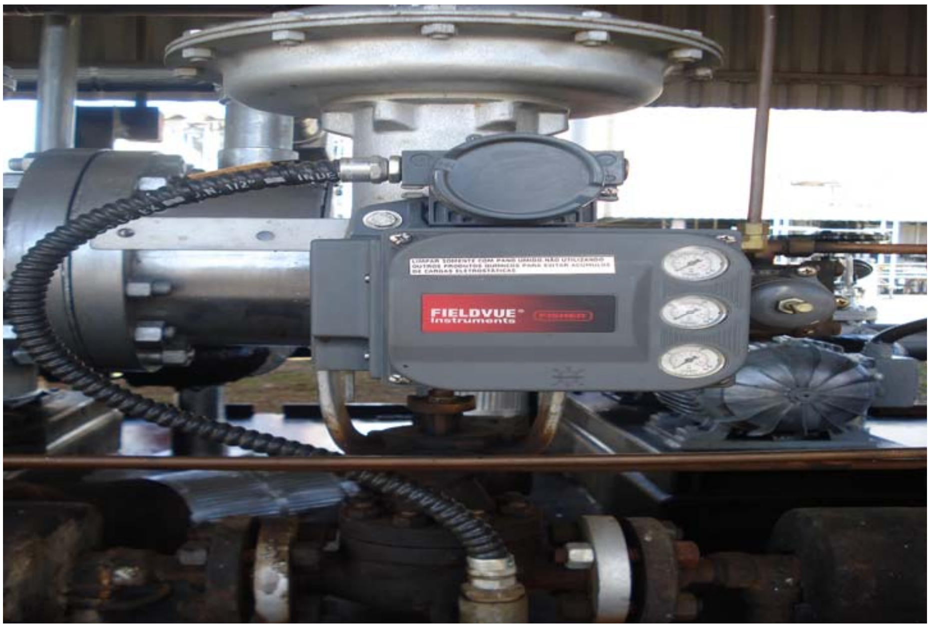

Figura 3 – Flow control valve and its intelligent positioner

The figure 4 shows the signature of the control valve, in both cycles working properly, used as a baseline. The graph is given by the coordinates: **displacement (mm)** x **actuator pressure (psi).** The Table 1 shows the "valve status" – range of the input pairs. The valve will be opened with the pair (0,0), (zero displacement in millimeters – zero air pressure actuator in pressure square inch); "1/4" (meaning 25% of the total displacement) with the pair (5,4); "1/2" with the pair (10,6); "3/4"with the pair (15,8) and will be closed with the pair (20,10) representing that the plug touched the base and the last status "strongly closed" will be an interval from (20,11) to (20,46) representing the excess of the air pressure to guarantee that the valve will be sealed, avoid leaking.

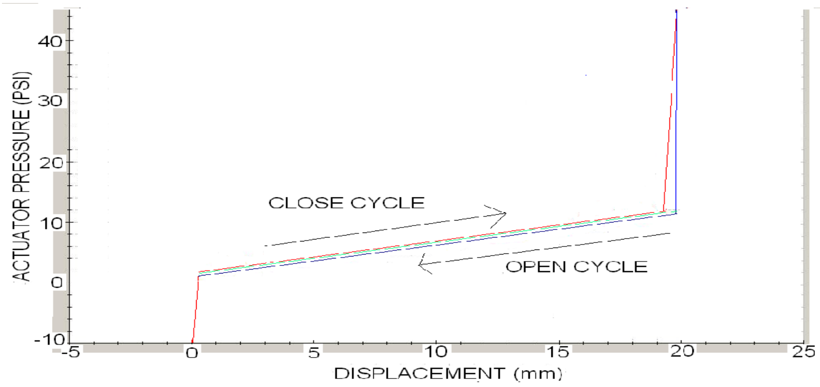

Figure 4: Signature of the valve – baseline.

Table 1: Valve status-input ranges.

Valve Status	Open	¼	½	¾	Closed	Strongly Closed
Pairs	(0,0)	(5,4)	(10,6)	(15,8)	(20,10)	from(20,11)to(20,46)

The Figure 5 shows the valve´s signature after a period of time in operation presenting anomalies such as, problem during the stem motion (ripples - close cycle), stiction and the bottom line (open cycle) stuck problem.

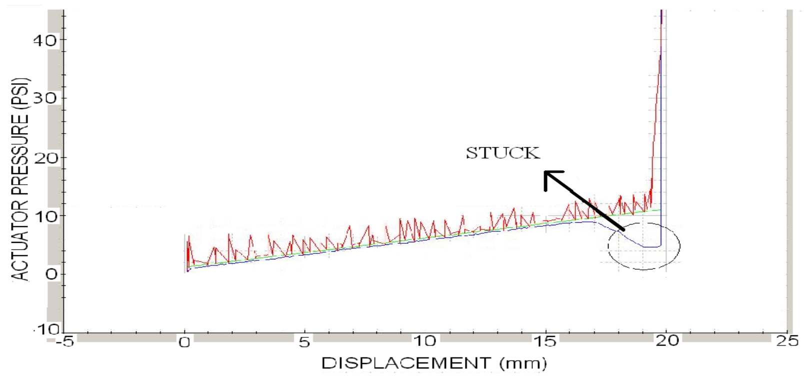

Figure 5: Valve´s signature with anomalies.

The air pressure goes down from 46 PSI starting the stem motion in 5 PSI instead of 11 PSI.
For instance, these information are the input of the fuzzy logic expert system, being processed by the inference mechanism through the rules base developed by the expertise of the instrumentation team.

Table 2: Rules base of the diagnostic system.

RULES
1. If (excvalv is open) and (pressat is open) then (statvalv is open)
2. If (excvalv is a quarter) and (pressat is a quarter) then (statvalv is a quarter)
3. If (excvalv is a half) and (pressat is a half) then (statvalv is a half)
4. If (excvalv is three quarter) and (pressat is three quarter) then (statvalv is three quarter)
5. If (excvalv is close) and (pressat is close) then (statvalv is close)
6. If (excvalv is open) and (pressat is strongly_close) then (statvalv is stuck-open)
7. If (excvalv is a quarter) and (pressat is three quarter) then (statvalv is stuck-close)
8. If (excvalv is three quarter) and (pressat is a quarter) then (statvalv is hard to close)
9. If (excvalv is a quarter) and (pressat is a half) then (statvalv is hard to close)
10. If (excvalv is close) and (pressat is three quarter) then (statvalv is hard to open)
11. If (excvalv is close) and (pressat is a half) then (statvalv is stuck-open)
12. If (excvalv is close) and (pressat is a quarter) then (statvalv is stuck close)
13. If (excvalv is three quarter) and (pressat is a half) then (statvalv is hard to open)
14. If (excvalv is close) and (pressat is strongly_close) then (statvalv is strongly_close)
15. If (excvalv is close) and (pressat is open) then (statvalv is stuck-close)

The figure 6 shows the rule viewer - MATLAB® fuzzy logic toolbox – an implementation of the 15 rules of the table 2. Considering the case study, the rule 15 demonstrates the performance of the system. The output of the rule 15 is the diagnostic of the valve: "stuck closed", checking, the inputs (excvalv=close) and (pressat=open) the output (statvalv=stuck close), where ***Excvalv*** *means - the plug displacement;* ***Pressat*** *- actuator air pressure;* ***Statvalv*** *- diagnostic.*

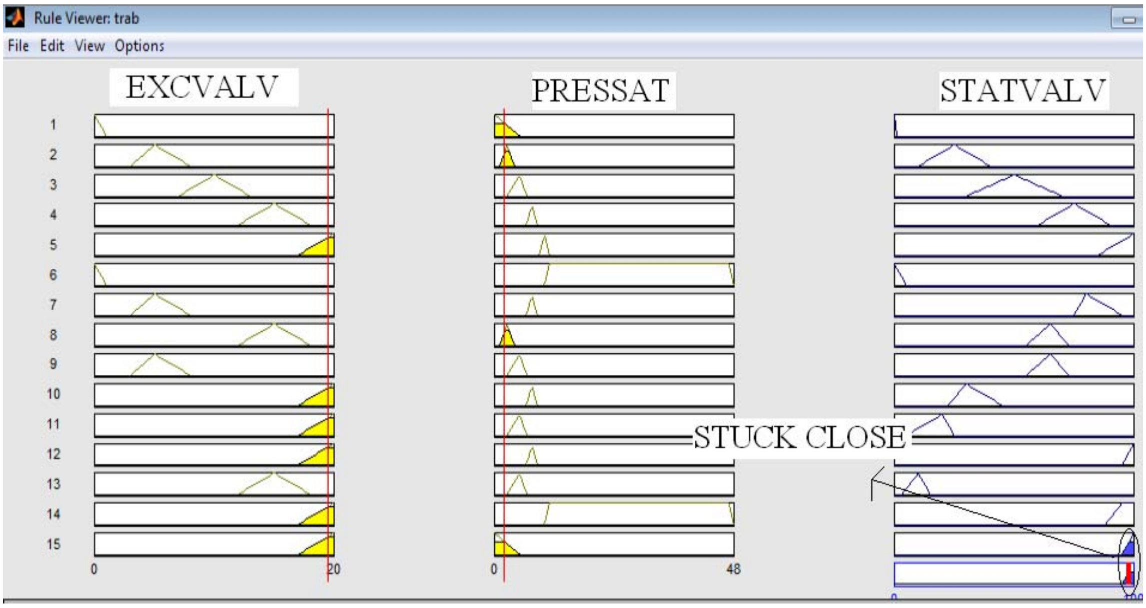

Figure 6: Rule viewer.

4. Conclusion

Fuzzy Logic has been proved a powerful tool in monitoring and diagnostics systems for sensors in nuclear power plants, this paper shows that is possible to diagnostic and monitoring integrated condition in control process valves. Several tests have been made demonstrating a good performance of the technique. The knowledge base given by the expertise of the instrumentation's staff has been implemented in a satisfactory way, proving that right rules and correct inferences with the input data produce a coherent output, indicating the real valve's situation. The failures could be classified as aggressive, moderate or incipient, depends on the current stage, of course the monitoring system should detect faults in advance avoiding unexpected consequences and the associated costs. Each valve has its own characteristics and specifics failures could happen, but all of them can be modeled by the system considering such specific rules. This methodology is a good insight in the area of the prognostic healthy machine – the use of a friendly tool of AI (Fuzzy Logic toolbox of MATLAB®) combined with industrial software used in control process valves (VALVELINK®). Certainly, valves and monitoring technologies have played a key role in both cost reduction measures and improved monitoring activities. Therefore, the development of non-intrusive techniques applied for predictive maintenance have proven substantially to improve the overall operation of process contributing for reliability of plants particularly those that run nonstop.

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