ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

FUZZY LOGIC APPLIED IN NUCLEAR POWER REACTOR MONITORING

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Abstract. *Several tools and information processing techniques have been developed aiming at prioritizing information to the operator with the purpose to recognize faults and even actions to be taken to mitigate its effects. The Fuzzy Logic technique can be used in information processing, as a tool capable of capturing inaccurate information described in natural language and convert them to a numeric format. In this paper a fuzzy system will be developed to monitor nuclear power of IEA-R1 research reactor situated at IPEN in São Paulo. This system will make possible to show the nuclear power in a different way in order to identify faults in sensors and in the reactor control system.*

Keywords: *fuzzy logic, nuclear power reactor, sensors monitoring*

1. INTRODUCTION

Nuclear power reactors are in nature nonlinear systems with various components and are difficult to model due to their parameters vary with time as a function of power level. Many diverse models have been developed to model the dynamic response of such systems. Computer simulation of the behavior of complex systems and components, whose requires the solution of many equations and extensive use of closure relations, has become very important in modern design.

This way of proceeding is used particularly in the nuclear industry where safety rules are rather rigid and impose to closely examine any possible situation and mode of operation of the system. During the implementation of the physical-mathematical model, the discretization of the differential systems can be complicated by issues of stability and convergence.

Artificial Intelligence methodologies can be used in this context to overcome this problem due to their ability in perform functional mapping. The components of the experimental nuclear reactor IEA-R1 have been modeled using Artificial Neural Networks – ANN (Bueno, 2006), and using Group Method of Data Handling – GMDH (Gonçalves, 2006). Likewise, application of intelligent systems including Fuzzy Logic in the model of large-scale complex nonlinear systems as nuclear reactors is very promissory.

The experimental reactor IEA-R1 maximum nuclear power is 5 MW and it is normally determined by a combination of the following methods:

- Nuclear radiation detectors. The reactor nuclear power is proportional to the neutron core population. During the reactor operation, the neutron flux varies and therefore the nuclear power value follows this variation. The IEA-R1 instrumentation channel has 4 neutron detectors: one fission chamber, two ionization chambers compensated and two ionization chambers non-compensated.
- Period (T) monitoring. The rate of neutron flux variation is also monitored. The period – T– is the time the reactor spends to reach an increase power of a factor *e* ($e = 2.7182$).
- Thermal inventory. The thermal power (P) is calculated using the measured values of flow rate (M), specific heat (c_p) and the difference of outlet and inlet nuclear reactor core temperatures (T4-T3 = Δt) according to $P = M * Cp * \Delta t$.
- Monitoring of Nitrogen 16 activity. ^{16}N results from a reaction ^{16}O (n,p) ^{16}N, when water passes through reactor core. Due to the high level of reaction energy, the ^{16}N formation depends basically on the fission neutron flux and therefore on the reactor power.

The Thermal inventory measurement is used to calibrate the nuclear detectors. As shown in Cárdenas 2000 (ref 18) the uncertainty in thermal power measurement is about 4% when the reactor power is maximum, that is, 5.25 MW. For nuclear power values above this value, the uncertainty can be as great as 10%.

The objective of this work is to develop a Fuzzy System to model the nuclear Power of the IEA-R1 experimental Reactor in order to give best results, with uncertainties independent to the power value itself.

2. FUZZY LOGIC

Fuzzy logic was originally proposed by Lofti Zadeh in 1965 with the work "Fuzzy sets" (Zadeh, 1965) and then developed as a tool for manipulating and processing vague information in uncertain conditions. One of the main characteristics of this approach is the element partial membership which allows smooth transitions from one rule to another (Yager and Filev, 1994). In this context, the production of the membership functions, i.e., functions that define the membership degrees for each input and output of the system is called "fuzzyfication". All fuzzy set representing the crisp (physics) variables related by membership functions are the so called "knowledge basis".

The knowledge basis has uncertain information however significant for the system modeling. Although this uncertain is completely solved as the input and output fuzzy sets and the knowledge manipulation strategy are defined.

A fuzzy algorithm processes the membership functions for each one of the fuzzy sets and the results are aggregating through instructions or rules, producing the so called "rule basis".

There are basically two types of fuzzy system models differentiating in the ability of representing different kinds of information, i.e, in the form of representing the rule basis. The first include the linguistic models based in collections of IF-THEN rules with vague attributes and have fuzzy reasoning. In this type of model, fuzzy quantities are associating with linguistic labels and a fuzzy model is essentially a qualitative expression of the system. The second type of model is based in the Takagi-Sugeno-Kang reasoning method (Sugeno, 1985). These models are constructed by logic rules which are combination of fuzzy and crisp models (Yager and Filev, 1994).

A set of inference rules is adopted to manipulate the knowledge basis. The most used method to represent the human knowledge is through natural language expressions as: IF (antecedent) THEN (consequent).

Since decisions are based on the testing of all of the rules in the inference system, the rules must be combined in some manner in order to make a decision. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set.

One of the most used is the Mamdani implication method for inference in which the aggregated output is:

$$\mu_{B_n^k}(\alpha(i),\alpha(j)) = \max[\min[\mu_{A_{n1}^k}(\alpha(i)),\mu_{A_{n2}^k}(\alpha(j))]], \qquad \text{for } k = 1,...,r \tag{1}$$

where A_{n1}^k and A_{n2}^k represent antecedent fuzzy sets, μ represent membership functions, B_n^k represent the consequent fuzzy set for inputs $\alpha(i)$ and $\alpha(j)$.

Often fuzzy process output must be a scalar quantity and not fuzzy sets. A crisp value for the system output is obtained by the defuzzyfication of the fuzzy output set. In the literature there are some defuzzyfication methods as, for instance, centroid, bisector, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum. Perhaps the most popular defuzzification method is the centroid calculation, which returns the center of area under the curve. In this method the crisp value is obtained by the center of area given by the gather of the output membership functions as

$$y^* = \frac{\int \mu_{B_n^k}(y)\,y\,dy}{\int \mu_{B_n^k}(y)\,dy} \tag{2}$$

being y^* the value obtained by the defuzzyfication and e B_n^k consequent fuzzy sets.

3. IEA-R1 RESEARCH REACTOR

The Ipen nuclear research reactor IEA-R1 is a pool type reactor using water for the cooling and moderation functions and graphite and beryllium as reflector. Its first criticality was in September 16th, 1957. Since then, its nominal operation power was 2 MW. In 1997 a modernization process was performed to increase the power to 5 MW, in a full cycle operation time of 120 hours, in order to improve its radioisotope production capacity. Figure 1 shows a flowchart diagram of the Ipen nuclear research reactor IEA-R1.

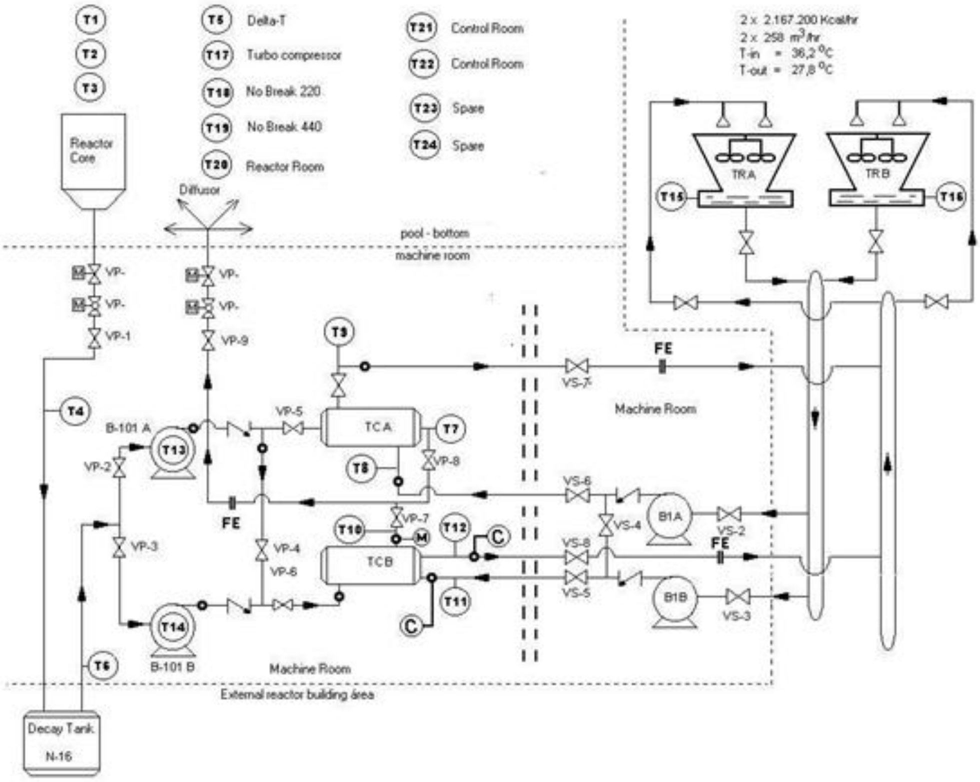

Figure 1. IEA-R1 experimental reactor schematic diagram

3.1 IEA-R1 Data Acquisition System (DAS)

The Ipen reactor Data Acquisition System monitors 58 operational variables, including temperature, flow, level, pressure, nuclear radiation, nuclear power and rod position (Table 1). The DAS performs the storage the temporal history of all process variables monitored and does not interfere with the reactor control.

Table 1. IEA-R1 DAS variables.

Z1	Control rod position [0 a 1000 mm]
Z2-Z4	Safety rod position 1, 2 and 3[0 a 999 mm]
N2-N4	% power (safety channel 1, 2 and 3) [%]
N5	Logarithm Power (log channel) [%]
N6-N8	% power [%]
F1M3	Primary loop flowrate [gpm]
F2M3	Secondary loop flowrate [gpm]
C1-C2	Pool water conductivity [µmho]
L1	Pool water level [%]
R1M3-R14M3	Nuclear dose rate [mR/h]
T1-T3	Pool water temperature [º C]
T4 and T6	Decay tank inlet and outlet temperature [º C]
T5	(T4-T3) [º C]
T7	Primary loop outlet temperature (heat exchanger A) [º C]
T8-T9	Secondary loop inlet and outlet temperature (heat exchanger A) [º C]
T10	Primary loop outlet temperature (heat exchanger B) [º C]
T11-T12	Secondary loop inlet and outlet temperature (heat exchanger B) [º C]
T13-T14	Housing pump B101-A and B102-A temperature [º C]
T15-T16	Cooling tower A and B temperature [º C]
T17	Housing turbo compressor temperature [º C]
T18-T19	NO-BREAK temperature –220V and 440V [º C]
T20-T24	Room temperature [º C]

4. FUZZY MONITORING SYSTEM

This section describes the fuzzy model developed at Matlab software using the Fuzzy Logic Toolbox to monitoring the nuclear power reactor. The experimental data was obtained from IEA-R1 data acquisition system. Three variables were defined as system inputs, they are: T3, T4 and F1M3. Each one of the system inputs were constructed with 3 Gaussian membership functions called: Low, Medium and High. An example of the input fuzzy set is shown in Fig. 2.

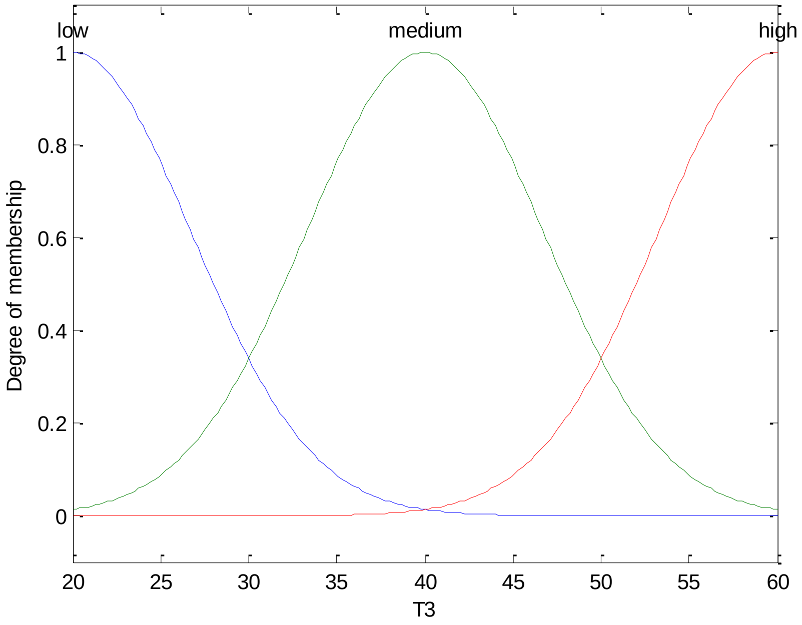

Figure 2. Membership function for the input variable T3

The model has only one output variable, called N2 (Fig. 3). This variable was also composed by three Gaussian membership functions with the same labels as the input variables.

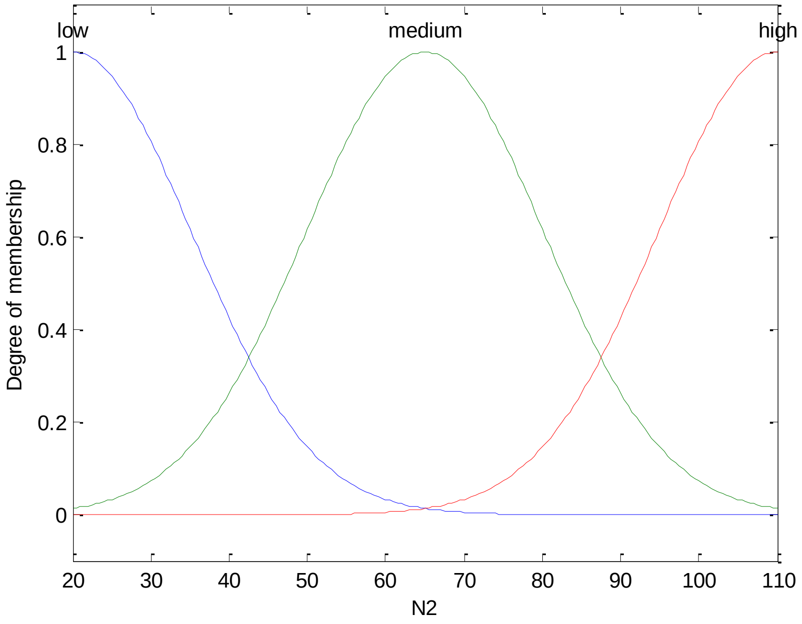

Figure 3. Membership function for the output variable N2

The rule base was composed by only 3 rules. All rules were design with the same weight.

The Mamdani type model developed used the centroid calculation as defuzzification method. (Section 2).

The fuzzy monitoring system developed is shown in Figure 4.

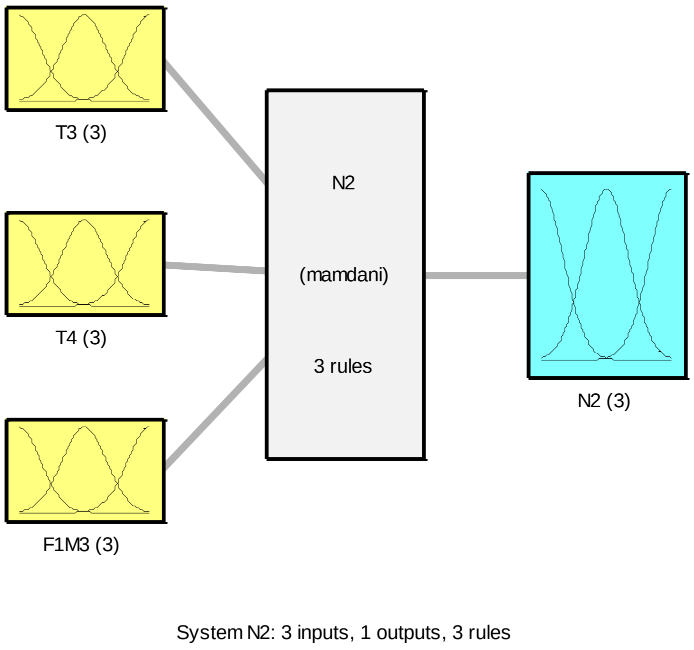

Figure 4. Fuzzy Monitoring System

5. RESULTS

The Fuzzy Monitoring System developed was used to estimate the IEA-R1 nuclear power (N2). Data from a typical operation cycle (about 60 hours) was used. The Data Acquisition System collects data at every 30 seconds, performing 7197 data samples for each all the 54 variables.

Figure 5 shows the result of Nuclear Power obtained from the Fuzzy Monitoring System and the comparison with the actual N2 value measured by the nuclear detector.

In order to compare these values, it was calculated the residual according to equation 3:

$$res = ((N2 fuzzy - N2) / N2) * 100 \qquad (3)$$

and the mean value of the residuals obtained is 1.58% (Fig. 6).

The residual value is compared with the uncertainties of the different nuclear power measurements methods.

Table 2. Uncertainty % for different Nuclear Power measurement

Nuclear Power measurement method	uncertainty
Nuclear Detector	4 %
Thermal Inventory	4 % to10 %
-----------------------------	residual
Fuzzy System	1.58 %

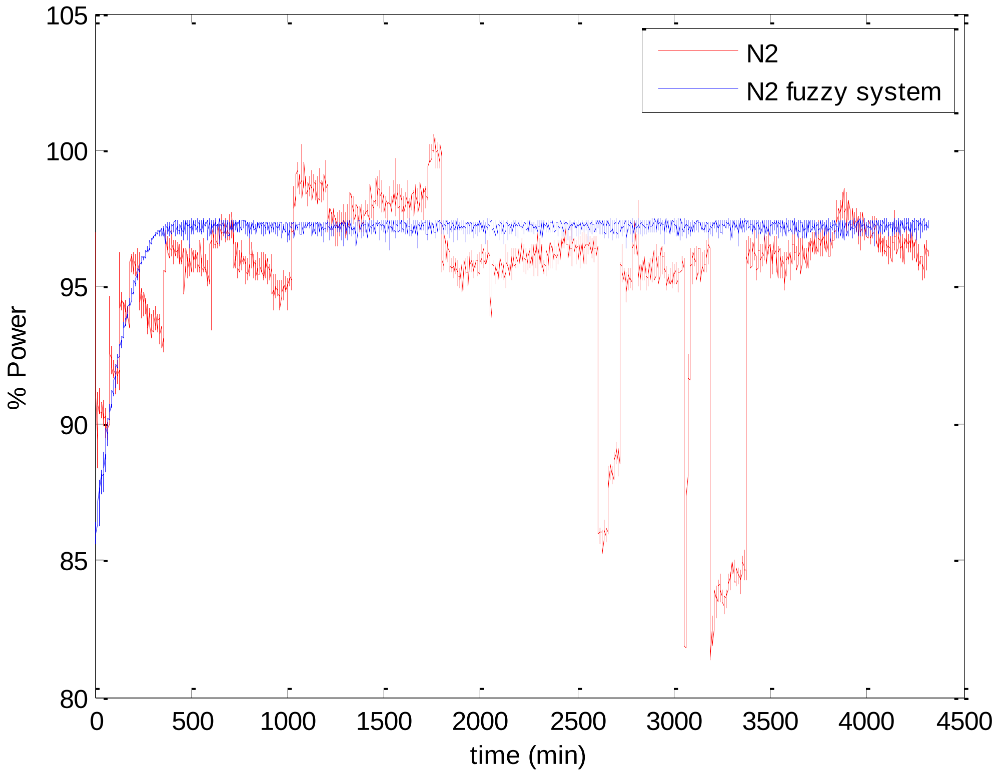

Figure 5. Comparison between N2 fuzzy system and N2

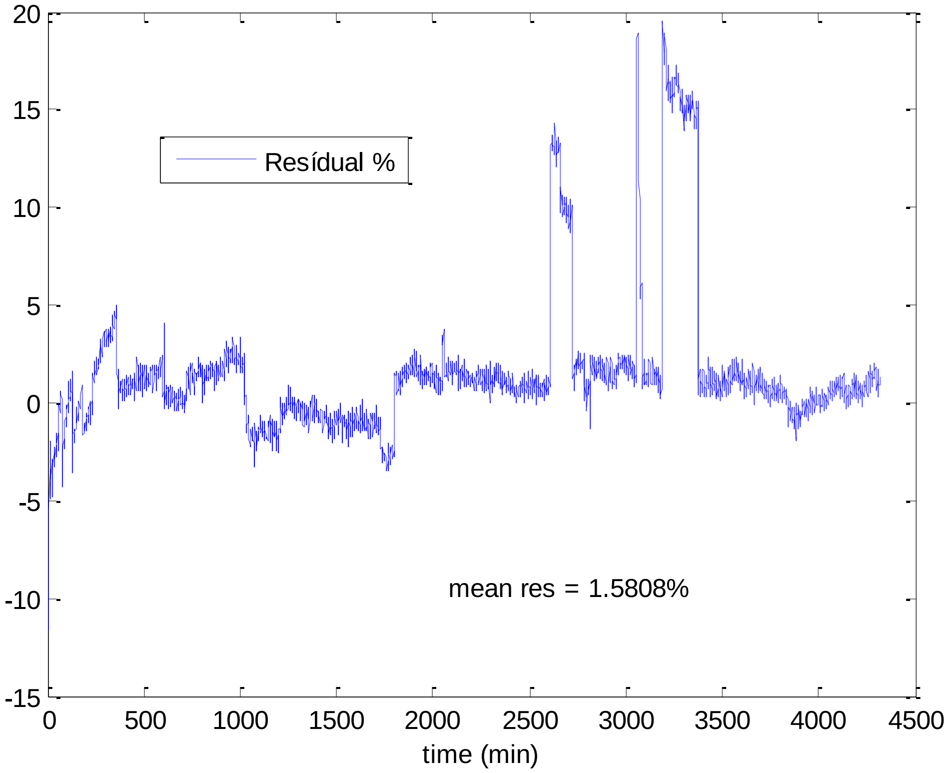

Figure 6. Difference % between N2 calculated by fuzzy system and N2 measured.

6. CONCLUSION

A Fuzzy System was developed in this work using the Matlab software aiming the nuclear power monitoring. The model uses as input the measured values obtained from a typical IEA-R1 reactor operation. These measured values are: T3, T4 and F1M3. The main objective was to use all the cited input variables to monitoring nuclear power reactor and to compare the obtained results with the IEA-R1 database.

The fuzzy system developed has some advantages which are it uses only 3 rules to esteem the output, easy implementation and the mean residual was around 1.58%.

Hence the proposal methodology suggests a fuzzy monitoring system which was able to reproduce the IEA-R1 database in most simulated situations and has a great flexibility once it is possible to give different weights to one determined rule, for example. These elements amplify the model sensitivity significantly to nuclear power monitoring and make the proposed methodology very adaptable to any new standards.

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8. RESPONSIBILITY NOTICE