IMPLEMENTATION OF A FUZZY CONTROLLER FOR pH REGULATION IN OIL PROCESS

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Abstract. *This work proposes the design, implementation and performance evaluation of a fuzzy controller for pH regulation in a stirred-tank reactor. The controller is designed to perform pH neutralization of industrial plants, mainly in units found in oil refineries where is strongly required to mitigate uncertainties and nonlinearities. Classic PID (proportional-integral-derivative) controllers are the most popular control system present in industrial plants although they are not suitable for applications in non-linear systems. On the other hand, fuzzy logic properly deals with system non-linearities and uncertainties where occur frequent changes at the operation point and disturbances. On account of their low complexity, the fuzzy controller requires little computational effort and may be applied to commercial solutions based on microprocessors, microcontrollers and PLC with good performance. In addition, it adjusts the changes in pH regulating process, avoiding or reducing the need for re-tuning to maintain the desired performance. The system is developed in Simulink/MatLab® software. It emulates a real plant through the use of the fuzzy inference toolbox of this software. The results are presented and lead to conclude that the fuzzy system is apropriated to systems with non-linear characteristics like pH regulation in oil process.*

Keywords*: fuzzy control, nonlinearity, pH process control, Hammerstein model*

1. INTRODUCTION

Control systems are fundamental for satisfactory performance of industrial processes. For instance, regulation of **pH** has an important role in the chemical industry, particularly in the petrochemical one. Its main concern is to increase the efficiency of chemical reactions while reducing environmental impact (Wan *et al.*, 2006).

However, **pH** control is challenging due to its nonlinearities which interfere with gain adjustment of the process (Vale *et al.*, 2008). Besides, sensors and actuators applied in industrial plants are devices which contribute with nonlinearities such as dead-zones, hysteresis and backlash.

In order to overcome this issue, several linear control techniques have been used in nonlinear plants (Goder and Pelletier, 1996; Maia and Resende, 1998; Araújo, 2002; Barrado *et al.*, 2003; Fonseca, 2005; Soto, 2006; Cavalcanti, 2008). PID controllers are the most popular commercial solution applied in the industry (Wang, 2001; Piazzi and Visioli, 2002; Chen and Seborg, 2003; Åström and Hägglund, 2004). Nevertheless, its use is more adequate to a specific operation range of a plant linearized model. Whenever changes or perturbations lead the process to work out of its operating point, manual adjustment of PID controller parameters is required. Several approaches have been proposed to treat this issue such as adaptive linear, scheduling predictive, scheduling PI, automatic tuning and scheduling gain, neural networks, among others (Gustafsson, 1995; Loh *et al.,* 1995; Palancar *et al.,* 1996; Klatt and Engell, 1996; Fontes *et al.*, 2008). Despite this, such control structures may present considerable overshoot or response time and do not achieve system specifications. This matter is also present in **pH** control.

Reznik (2000) has suggested the utilization of fuzzy logic for online tuning of PID gain. Fuzzy control deals properly with nonlinearities and uncertainties present in plant dynamics (Michael *et al.*, 1994). Moreover, fuzzy systems are able to regulate controller parameters not only around operating point but also in the transition state. Fuzzy-in-line (Parekh *et al.*, 1994), model based fuzzy (Kelkar and Postlethwait, 1994), predictive fuzzy (Cho *et al.,* 1999), fuzzy-PI control (Fuente *et al.*, 2002) and fuzzy-PID (Ghee *et al.*, 2002) are some of the techniques proposed.

This paper will present a fuzzy-PI with a wide operating range to control a **pH** neutralization plant of the oil industry. Simulations were held using Simulink/Matlab® programming language. The utilized simulation model was the simplified model by Hammerstein. Comparisons and validations with previously used PI and scheduling PI controllers will be presented.

2.THE pH NEUTRALIZATION PROCESS

The **pH** neutralization process is performed by controlling the addition of acid and base flows in a continuous stirred-tank reactor (CSTR). The mixture of these two elements is done by the stirrer and the valve aperture determines the amount of acid to be added the tank. A sensor, installed in the process tank, is responsible to detect **pH** level (Fontes *et al.*, 2008). Figure 1 shows the **pH** plant structure.

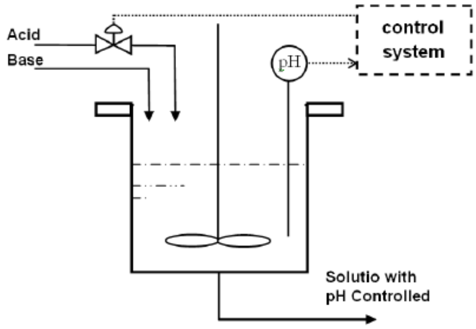

Figure 1. **pH** process structure in Vale *et al.* (2010)

2.1. Modeling of pH process

The **pH** process simulation was based on the Hammerstein model, where the static non-linearity precedes the system dynamic. The tank level control was disregarded. To have a greater similarity with a real process, essential tools in industrial processes were added to the simulated process, besides the Hammerstein model: the actuator, the sensor and a Fuzzy-PI controller. Figure 2 shows the block diagram of simulated process.

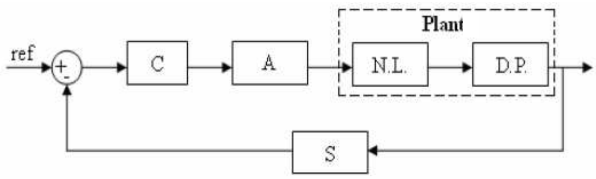

Figure 2. Block diagram of simulated process Vale *et al.* (2010)

- Fuzzy-PI controller (“C”): responsible for the plant control signal generation, which has the task to open or to close the valve;
- Actuator (“A”): the valve is composed by a dead-zone non-linearity, and a transfer function to represent the valve dynamic;
- Static nonlinearity (“N.L.”): detailed in the Equation (1);
- Dynamics Plant (“D.P.”): Represented by a first order transfer function showed in Equation (2);
- Sensor (“S”): Represented by a first order transfer function (Equation4) and a normalization in the output. This normalization makes the value process output to be between 0 and 100% (equivalent to the range of 0 to 14 **pH**).

The Static nonlinearity has a nonlinear static gain in series with a linear function which represents the overall system dynamics. Equation (1) shows the static nonlinearity which represents an industrial process (Vale *et al.*, 2010). The variable *u* ranges from 0 to 100%.

$$y = 7\left(\frac{0.02u-1}{\sqrt{0.1+0.9(0.02u-1)^2}}+1\right) \tag{1}$$

The linear transfer function in for the **pH** plant dynamics is showed in Eq. (2).

$$G_p(s)=\frac{1}{200s+1} \tag{2}$$

In addition, modeling of the system sensor and actuator was provided in order to have a faithful description of the **pH** plant. The elements adopted were according to the model developed by Vale *et al.* (2010). Equation (3) is the transfer function (TF) of the actuator/valve with a dead-zone to simulate its nonlinearity.

$$G_A(s) = \frac{1}{30s+1} \tag{3}$$

A first order transfer function represents the sensor dynamics whose output is the **pH** value, as in Eq. (4). Its time constant is 10 s and the gain is 1.

$$G_s(s) = \frac{1}{10s+1} \tag{4}$$

In order to have a visual identification of **pH** level, the sensor output was normalized to display values from 0% to 100%. This maximum value is reached when **pH** is equal to 14 (Vale *et al.*, 2010).

With the intention to replicate the plant dynamics in a more accurate model, a block representing the dynamics of a disturbance was added to the system output. Its time constant is higher than the plant one. The transfer function used to characterize it is in Eq. 5.

$$G_d(s) = \frac{1}{1200s+1} \tag{5}$$

2.2. Simulation model of a pH Control Process

The model used to implement the fuzzy controller was developed as part of the activities of a project named REDICONT (Design and Implementation of Regulatory Controllers in Nonlinear Processes Used in the Petroleum Industry) Fontes *et al.* (2008).

The complete system showed in Figure 3 consists of the following blocks: Reference Generator, Fuzzy-PI Controller, Valve Actuator, relationship of openness and manipulated variable (OP_MV), Simplified Plant, Sensor, Normalization and Disturbance Model. At the bottom of the simulation files there are three blocks that display the results of performance evaluation metrics.

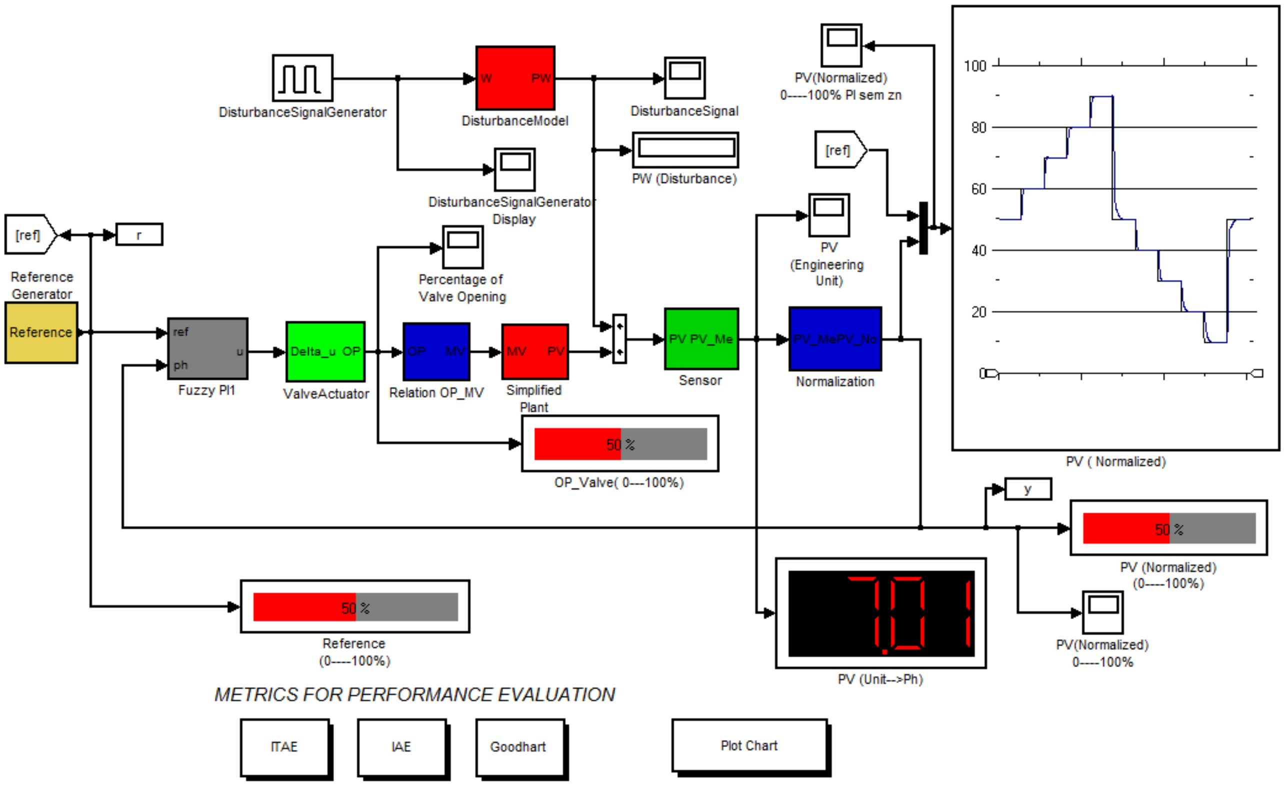

Figure 3. Simulink diagram for regulation system of **pH**

3. THE PROPOSED FUZZY CONTROLLER

With the aim of compensating system nonlinearities, the use of fuzzy controllers might be a proper solution to control nonlinear industrial plants. This work proposes a fuzzy-PI system to control the **pH** process, described earlier.

The controller structure has a feedback loop and three inputs: error, error variation and the measured **pH**. The fuzzy-PI output is the control signal to operate the actuator/valve of acid flow. The block diagram of the controller is showed in Figure 4.

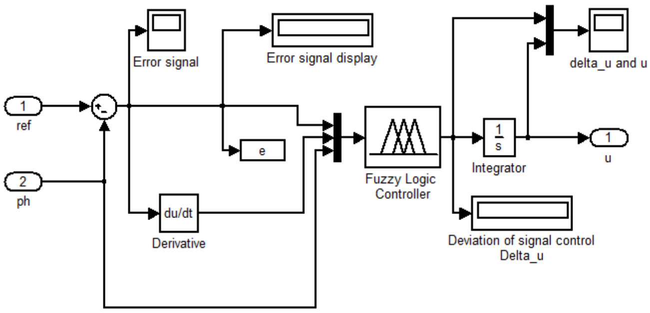

Figure 4. Simulink diagram of the fuzzy-PI controller

3.1 Fuzzy variables and inference system

The input fuzzy variables *error (Err)* and *error variation (VarErr)* have trapezoid membership functions named *ErrZero* and *VarErrZero*. The input *pH* has nine triangular membership functions named *ph10, ph20, ph30, ph40, ph50, ph60, ph70, ph80 and ph90*. The parameters of these inputs variables are showed in Table 1.

Table 1. Inputs Fuzzy Variables

Variable	Type	Parameters
Err	Trapezoid	[-102 -100 100 102]
VarErr	Trapezoid	[-1.8 -0.3 0.3 1.8]
ph10	Triangular	[-90 10 20]
ph20	Triangular	[10 20 30]
ph30	Triangular	[20 30 40]
ph40	Triangular	[30 40 50]
ph50	Triangular	[40 50 60]
ph60	Triangular	[50 60 70]
ph70	Triangular	[60 70 80]
ph80	Triangular	[70 80 90]
ph90	Triangular	[80 90 150]

The initial gains of the plant in closed loop for each membership function output (parameters) were designed based on Fontes *et al*. (2008). The output *(output1)* has 09 linear membership functions named *pi10* to *pi90* as showed in Table 2. The used inference model was Takagi-Sugeno to facilitate computational implementation.

The linear Sugeno functions were:

$$Delta\_u_i = p_i \cdot Err + q_i \cdot VarErr + r_i \cdot pH + s_i \quad (6)$$

Where:

$Delta\_u_i$ → Fuzzy-PI output variable inferred by the ith Sugeno linear function;

p_i , q_i , r_i and s_i → Parameters of ith Sugeno linear function of the Fuzzy-PI;

Err , $VarErr$, and pH → Fuzzy-PI input variables.

Table 2. Parameters of Output Membership functions

Membership Function	Parameters
pi10	[0.0155 2.5 0 0]
pi20	[0.0075 1.286 0 0]
pi30	[0.0056 0.898 0 0]
pi40	[0.0052 0.745 0 0]
pi50	[0.0038 0.7 0 0]
pi60	[0.0041 0.748 0 0]
pi70	[0.005 0.902 0 0]
pi80	[0.0073 1.333 0 0]
pi90	[0.0152 2.759 0 0]

The rule base of Fuzzy Inference System-FIS is composed of 09 rules to describe 09 **pH** set points. These rules are showed in Table 3.

Table 3. Rules of FIS

If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph50*) then (*output1* is *pi50*) (1)
If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph10*) then (*output1* is *pi10*) (1)
If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph20*) then (*output1* is *pi20*) (1)
If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph30*) then (*output1* is *pi30*) (1)
If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph40*) then (*output1* is *pi40*) (1)
If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph60*) then (*output1* is *pi60*) (1)
If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph70*) then (*output1* is *pi70*) (1)
If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph80*) then (*output1* is *pi80*) (1)
If (*Err* is *ErrZero*) and (*VarErr* is *VarErrZero*) and (*pH* is *ph90*) then (*output1* is *pi90*) (1)

4. RESULTS

Presented results in this article have the following characteristics:

- Simulation time: 22000 seconds;
- Sequence of references: 50, 60, 70, 80, 90, 50, 40, 30, 20, 10 and 50%;
- For each reference, it was used 2000 seconds;
- Overshoots and undershoots smaller than 5%.

Some simulation tests were accomplished with different approaches to verify controller behavior when faced to variations of its operating point according to the waveform function.

The three controllers designed for the simplified model of the process control of **pH** were simulated in the Simulink/Matlab®.

Figures 5, 6 and 7 shows the system response with references ranging from 10 to 90%. Following each figure, the respective control signals are showed.

Figure 5 shows the reference signal output from the plant and efforts to control the system when was used the algorithm of the PI. It is observed that for operating point values greater than 70%, the system response becomes slower. This is caused mainly by the decrement of the static gain of the process.

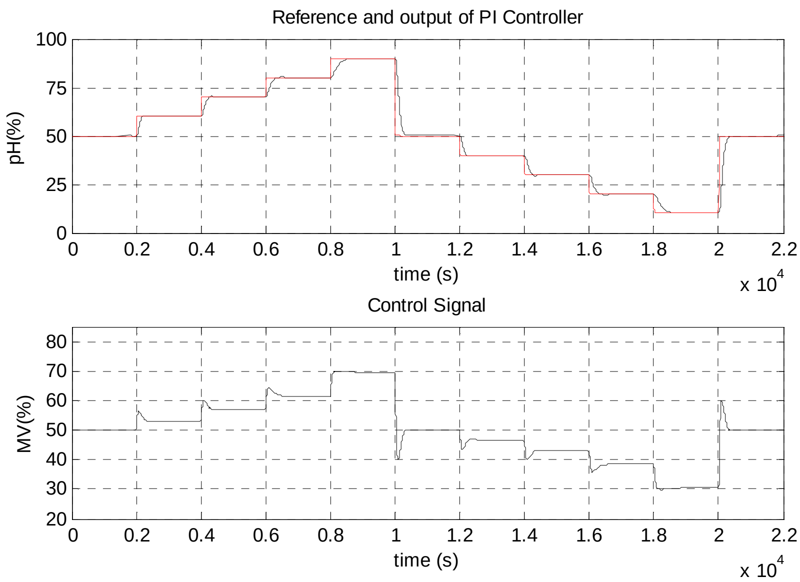

Figure 5. Response of PI controller

With the algorithm of the scheduling of PI controller gains the output of the plant was able to track the reference in a shorter time in the operating point greater than 70%. The reference signal output from the plant and efforts to control the system of this controller can be seen in Figure 6.

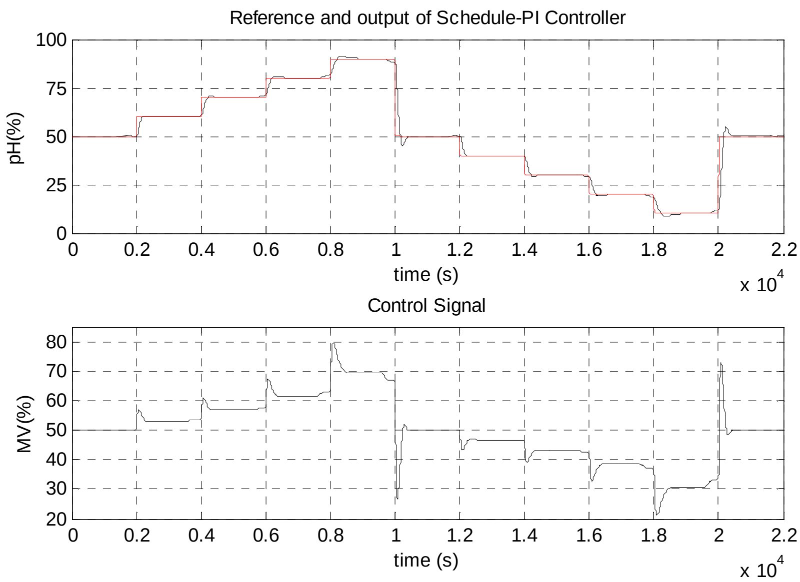

Figure 6. Response of Schedule-PI controller

Figure 7 shows the response and control effort of a system when used the Fuzzy-PI controller. When overshoots and undershoots occurred in the plant responses they were smaller than 5% and in most operation points are more satisfactory than those shown in the two previous controllers. The effort of this controller is higher in some references, but as it is an oil plant where power is available for this control and the cost/benefit ratio becomes very low.

Additional Membership Functions can be used in input variables *error (Err)* and *error variation (VarErr*) to generate new results that reduce the control effort, minimize the overshoots, undershoots and to other parameters like response time.

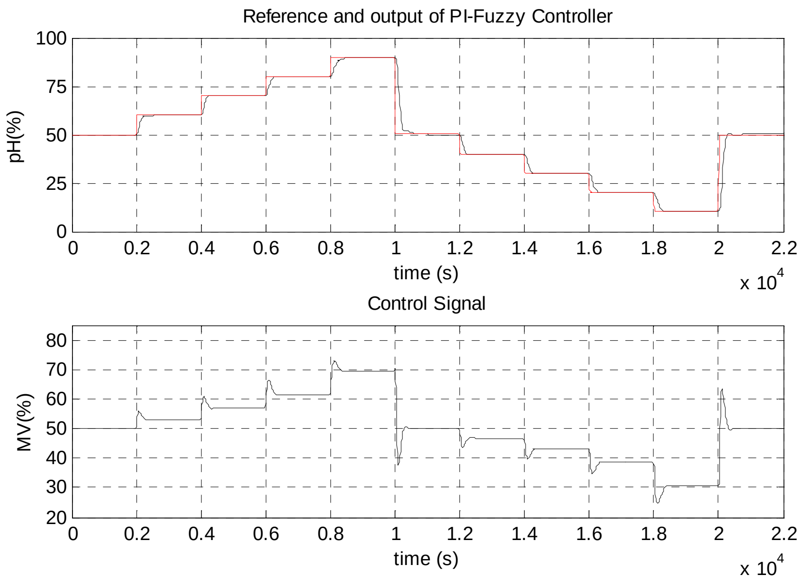

Figure 7. Response of Fuzzy-PI controller

4.1 Evaluation of controller performance

Evaluation of control algorithms was performed using three metrics: integral of absolute error (IAE), integral of the absolute value of the error-weighted time (ITAE) and using three metrics that were used in Goodhart *et al.* (1991). The values obtained in these metrics can be found in tables 4, 5 and 6 in order to compare the performance of the controllers.

The values in Table 4 are relative to the metric IAE. In this metric values of Fuzzy-PI controller are better in all references (set points) than the PI and Schedule-PI controllers.

Table 4. Performance metrics for the IAE

Set Point	PI	Schedule-PI	Fuzzy-PI
50 - 60%	524.37	521.48	172.60
60 - 70%	333.54	343.73	124.32
70 - 80%	343.48	325.94	124.14
80 - 90%	342.08	293.32	163.82
90 - 50%	1881.85	1589.40	857.95
50 - 40%	277.91	272.35	111.44
40 - 30%	293.88	282.49	118.08
30 - 20%	313.16	287.92	124.43
20 - 10%	355.36	276.83	137.14
10 - 50%	1755.76	1545.20	749.34

Table 5 shows the results obtained with the metric ITAE. Fuzzy-PI controller also generated better results than the PI and Schedule-PI in all references (set points).

Table 5. Performance metrics for the ITAE

Set Point	PI	Schedule-PI	Fuzzy-PI
50 - 60%	19627.06	21039.49	10922.24
60 - 70%	19001.66	30525.81	9622.48
70 - 80%	20021.90	69589.32	10162.72
80 - 90%	24959.45	63881.14	18886.27
90 - 50%	95529.10	79127.99	59545.59
50 - 40%	12770.29	13949.23	12271.11
40 - 30%	14849.38	32954.73	13640.24
30 - 20%	17674.65	58307.90	12579.83
20 - 10%	25622.83	43093.58	12073.15
10 - 50%	100773.71	75604.41	43639.44

Table 6 shows the results of Goodharts metric that takes into account information about the error and control signal. PI and Schedule-PI controllers have better performances than the Fuzzy-PI in some references. This occurred because effort for the control signal was greater in some cases in Fuzzy-PI. However as the test system is a plant used in the petroleum industry the relationship between expended energy control compensates for the outcome of the final product.

Table 6. Performance Metrics by Goodhart (Goodhart et al. 1991).

Set Point	PI	Schedule-PI	Fuzzy-PI
50 - 60%	55.05	58.25	52.43
60 - 70%	41.89	48.71	57.41
70 - 80%	44.20	61.00	67.35
80 - 90%	50.24	79.34	84.76
90 - 50%	47.10	42.94	49.49
50 - 40%	42.06	39.59	49.22
40 - 30%	20.69	23.84	32.94
30 - 20%	16.17	20.46	26.07
20 - 10%	12.46	13.04	16.42
10 - 50%	38.05	49.78	44.15

5. CONCLUSIONS

This paper details the implementation of a Fuzzy-PI controller in Simulink/Matlab® for a petroleum plant. The results were compared to PI controllers and Schedule-PI through graphs and three metrics for evaluating performance. For all references Fuzzy-PI controller showed better results than the PI and schedule-PI in metrics IAE and ITAE. In Goodharts metric, the PI and schedule-PI controllers shown smaller values than the Fuzzy-PI, probably because the Fuzzy-PI uses bigger amplitude control signal in some references.

For further research, it is intended to apply a disturbance in the plant and compare the responses obtained with these three controllers. Another suggestion is to use more linear variables for the error and the error variation.

The exchange of the classic controller for more complex control algorithms is a tendency for better performance in industrial control plants, especially in systems with nonlinear pronounced. The fuzzy-PI used has demonstrated that nonlinearity compensation of the simulated system is achievable.

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8. RESPONSIBILITY NOTICE

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