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A Comprehensive Comparison of Classical and Modern Controllers in the Steam Level of a Power Plant

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Abstract

One of the most important factors leading to have a weak control effect in a power plant is the uncontrolled state level. This phenomenon causes to the shutdown of electricity grid and for this reason, preventing this problem could be vital in each power plant. The steam levels are considered on two levels, the narrow and the wide steam level. In this paper an optimal controller based on linear quadratic regulator is used to control the narrow steam level. Therefore, a linear model is employed while the steam generator parameters are introduced by lookup tables from outdoor experiments. Also In this work, fractional-order PID controller as a classical controller and type 2-fuzzy as a modern controller are compared with LQR and classical PID to show the capability of the each one.

***Keywords**: power plant, steam level, LQR, Fractional order PID Controller, Fuzzy type2*

1. Introduction

The monitoring of Power plants is essential as infrastructure issues. The power plant industry is working to reduce generation costs by adopting condition-based maintenance policies and automating testing activities. These developments have stimulated great interest in online monitoring (OLM) technologies and new diagnostic and prognostic approaches to expect, identify, and resolve equipment and process difficulties and ensure plant safety, efficiency, and immunity to accidents. Unexpected shutdowns or reactor trips initiated due to traditional safety considerations, which in turn are necessitated by poor control, are particularly expensive and must be minimized. Various approaches which address one or more of the above issues in the design of the level controller have been reported in the literature. In [1], the authors presented a linear parameter varying model to describe the SG(system generator) dynamics over the entire operating power range and proposed a model reference adaptive proportional integral derivative (PID) level controller. This model was used to design a PI-like locally stabilizing controller[2]. A robust level controller design was studied in [3]. The Optimization of a fuzzy PID controller is studied in [4]. This paper introduces a fuzzy proportional-integral-derivative (fuzzy-PID) control strategy, and applies it to the power control system. At the fuzzy-PID control strategy, the fuzzy logic controller (FLC) is exploited to extend the finite sets of PID gains to the possible combinations of PID gains in stable region and the genetic algorithm to improve the ‘extending’ precision through quadratic optimization for the

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membership function (MF) of the FLC. Although in many Power plants the industrial PID controller could be well known for this performance. Recently the approach of fractional PID could be more effective. Development and analysis of some versions of the fractional-order point reactor kinetics model for a reactor is studied in [5]. The paper reports e report the development and analysis of some novel versions and approximations of the fractional-order (FO) point reactor kinetics model. Level control systems based on fuzzy logic have been reported in numerous references [6, 7]. According to these definitions can be used to obtain the vapor level linear model. An adaptive fuzzy controller based on harmony search is organized in [8]. Recently the approach of fuzzy type 2 was employed to consider the uncertainties of systems. In this case the control effort of the controllers also can be decreased. A comprehensive study of fuzzy type 2 is studied in [9-11]. The rest of the paper is organized as follows. In the steam level modeling section, a linear model is introduced. The inputs and the outputs are organized. Also the constant parameters are presented by a lookup table in a simulink model. In the control section, the relations of different control theory are considered and applied in the proposed model. PID, Fractional PID, LQR and fuzzy type2 methods are employed to show the performance of each controller on steam level control.

2. Steam Level Modeling

The steam generator is shown in Figure 1.

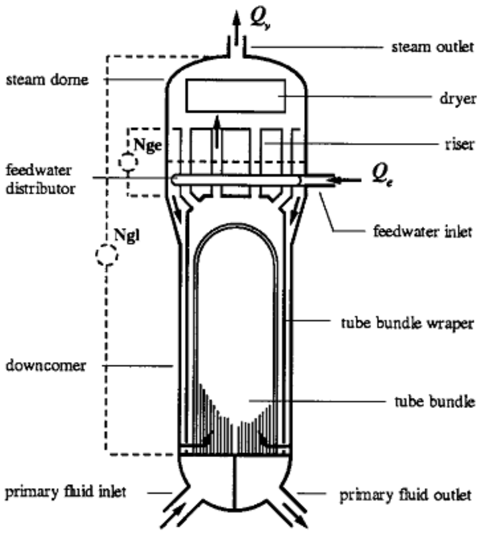

Figure 1. Steam Generator[1]

The state space model of the steam level is as follows:

$$\dot{x}(t)=\begin{bmatrix}0 & 0 & 0 & \frac{1}{T_n}\\ 0 & -\frac{1}{T_n} & 0 & -\frac{1}{T_n}\\ 0 & 0 & -\frac{1}{T_g} & 0\\ 0 & 0 & 0 & -\frac{1}{\tau}\end{bmatrix}x(t)+\begin{bmatrix}0\\0\\0\\\frac{1}{\tau}\end{bmatrix}u(t)+\begin{bmatrix}-\frac{1}{T_n}\\0\\\frac{1+F_g}{T_n}\\0\end{bmatrix}d(t)$$

$$y(t)=\begin{bmatrix}y_1(t)\\y_2(t)\end{bmatrix}=\begin{bmatrix}1 & 1 & 1 & 0\\ \frac{T_n}{T_{\text{int}}} & 0 & 0 & \frac{\tau}{T_{\text{int}}}\end{bmatrix}x(t)$$

Where $u(t)$ and $d(t)$ are the input and disturbance of model respectively. In this notation, also Q_e and Q_v are the flow rate of fresh feed water and dry steam respectively entering the steam generator. The outputs of model are two values. N_{ge} and N_{gl} are the narrow and wide range steam generator level. In the model, some parameters are based on the amount of power generators. These values are given in the Table 1.

Table 1. Parameters in Steam Generators of Different Capacities

Parame	3.2	4.1	9.5	24.2	30	50	100
T_n	5.14	8	9	6.29	5.71	5.71	5.71
F_g	13	18	10	4	4	4	4
T_h	24.29	8	4.29	1.43	1.14	0.71	0.71
τ	1.43	1.43	1.43	4.29	4.29	4.29	4.29

These parameters can be identified by SIMULINK search tables based on a linear regression model to be injected. The use of this technique in SIMULINK is shown in Figure 2.

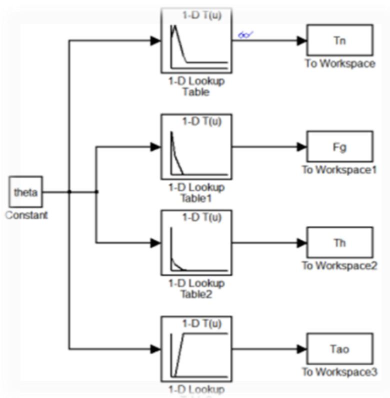

Figure 2. Lookup Table Used in Steam Generators

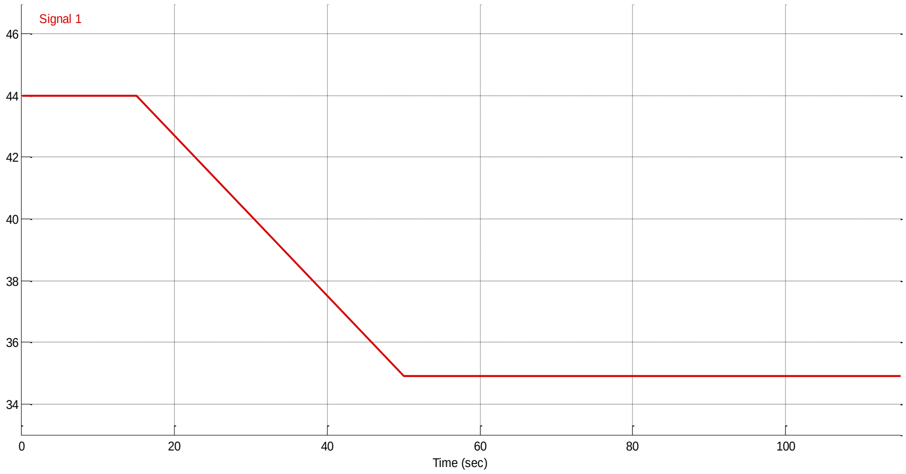

Figure 3. System Input in the Signal Builder

3. Control Designing

3.1. Optimal Control

Equation 1, shows the system state space. Where U the controller is input and X is the system state parameter.

$$\dot{X} = AX + BU$$

Having a system for optimizing the objective function is discussed in Equation 2. In this equation, H is positive definite matrix, Q is a positive semi-definite matrix and R is the weight matrix.

$$J = \frac{1}{2} X^T HX + \frac{1}{2} \int_{t_0}^{t_f} \left(X^T QX + U^T RU \right) dt \tag{2}$$

Given that this form of the equation is expressed as an optimization problem with state space constraints. Hamiltonian equation is defined in Equation 3. In this regard, the vector of Lagrange multipliers.

$$\mathrm{H} = \frac{1}{2} X^T QX + \frac{1}{2} U^T RU + P^T AX + P^T BU \tag{3}$$

Conditions necessary to solve this equation are listed in 4.

$$\begin{aligned} \dot{X}^* &= AX^* + BU^* \\ \dot{P}^* &= -\frac{\partial H}{\partial X} = -QX^* - A^T P^* \\ 0 &= \frac{\partial H}{\partial U} = RU^* + B^T P^* \end{aligned} \tag{4}$$

Therefore, the control input for the system to be introduced in equation 5.

$$U^* = -R^{-1} B^T P^* \tag{5}$$

$$\dot{X} = AX^* - BR^{-1} B^T P^* \tag{6}$$

Using this approach, we can derive the vector P^* is introduced into Equation 8. The force applied to the solution of the resulting equation 9 into equation 10, which is known as Riccati equation. Numerical techniques to solve the differential equation can be used. The software MATLAB, can be found by state space matrix and weight matrix to determine these values.

$$P^{*} = KX^{*} \tag{7}$$

$$\dot{P}^{*} = \dot{K}X^{*} + K\dot{X}^{*} \tag{8}$$

$$-QX^{*} - A^{T}KX^{*} = \dot{K}X^{*} + K\left(AX^{*} - BR^{-1}B^{T}\left(KX^{*}\right)\right) \tag{9}$$

$$\dot{K} = -KA - A^{T}K - Q + KBR^{-1}B^{T}K \tag{10}$$

$$\dot{K}X^{*} + KAX^{*} - KBR^{-1}B^{T}KX^{*}$$

In determining this matrix, the control law can be introduced into equation 11:

$$U^{*} = -R^{-1}B^{T}KX^{*} \tag{11}$$

To compare the optimal controller with another one, a PID controller with a tuned gains is employed. Although the optimal controller shows a proper response, the PID could track the desired values dramatically.

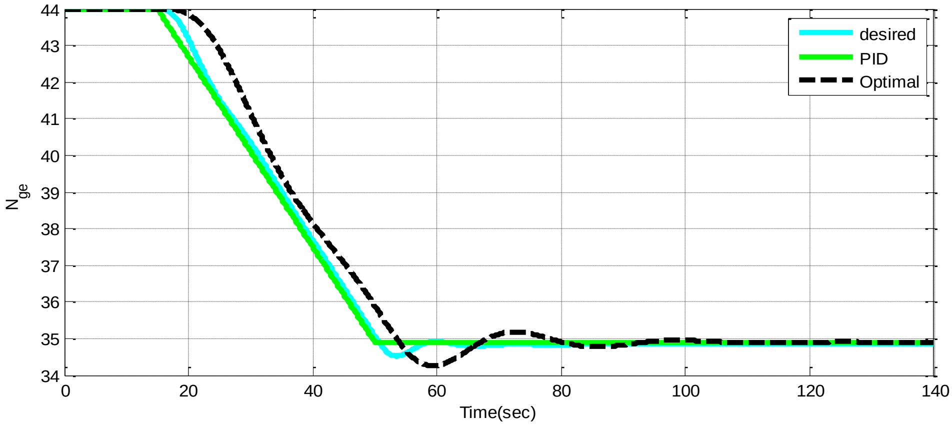

Figure 4. Output Controlled by Lqr

Nevertheless, this result can't show the eligibility of PID controller. Figure 5, shows the control effort of each controller. The control signal means the fresh water has entered into the steam generator. As this figure shows, PID appears as a frequent chattering controller whereas the optimal controller doesn't have this behavior.

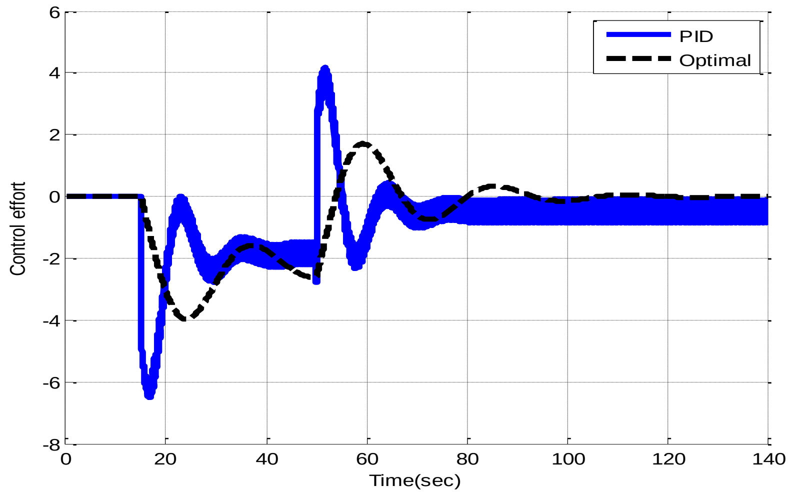

Figure 5. Control Effort of PID and Optimal Controllers

3.2. Fractional-Order PID Controller

To study the fractional order controllers, the starting point is of course the fractional order differential equations using fractional calculus. A commonly used definition of the fractional differointegral is the Riemann-Liouville definition[12].

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(m-\alpha)} \left(\frac{d}{dt} \right)^m \int_0^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \tag{12} $$

For m − 1 <α<m where Γ(0) is the well-known Euler's gamma function. An alternative definition, based on the concept of fractional differentiation, is the Grunwald-Letnikov definition given by:

$$ {}_aD_t^{\alpha} f(t) = \lim_{h \to 0} \frac{1}{\Gamma(\alpha) h^{\alpha}} \sum_{k=0}^{(t-\alpha)/h} \frac{\Gamma(\alpha+k)}{\Gamma(k+1)} f(t-kh) \tag{13} $$

One can observe that by introducing notion of the fractional order operator ${}_aD_t^{\alpha} f(t)$ the differentiator and integrator can be unified. Another useful tool is the Laplace transform. It is show in [13] that the $L\left\{D^n x(t)\right\} = s^n X(s)$ Laplace transform of an nth (n ∈ R+) derivative of a signal x(t) relaxed at t =0 is given by. So, a fractional order differentia equation, provided both the signals u(t) and y(t) are relaxed at t =0, can be expressed in a transfer function form

$$ G(s) = \frac{a_1 s^{\alpha_1} + a_2 s^{\alpha_2} + \ldots + a_m s^{\alpha_m}}{b_1 s^{\beta_1} + b_2 s^{\beta_2} + \ldots + b_m s^{\beta_m}} \tag{14} $$

Where $(a_m, b_m) \in R^2, (\alpha_m, \beta_m) \in R^2, \forall (m \in N)$

The most common form of a fractional order PID controller is the PID controller [14], involving an integrator of order λ and a differentiator of order μ where λ and μ can be any real numbers. The transfer function of such a controller has the form

$$ G_c(s) = K_p + \frac{K_I}{s^{\lambda}} + k_D s^{\mu} \tag{15} $$

The integrator term is s^{λ} that is to say, on a semi-logarithmic plane, there is a line having slope −20λdB . /dec. The control signal u(t) can then be expressed in the time domain a

$$ u(t) = k_p e(t) + k_I D^{-\lambda} e(t) + k_D D^{\mu} e(t) \tag{16} $$

Clearly, selecting λ =1 and μ =1, a classical PID controller can be recovered. The selections of λ =1, μ =0, and λ =0, μ =1 respectively corresponds conventional PI & PD controllers. All these classical types of PID controllers are the special cases of the fractional $PI^{\lambda}D^{\mu}$ controller given by (15). It can be expected that the $PI^{\lambda}D^{\mu}$ controller may enhance the systems control performance. One of the most important advantages of the $PI^{\lambda}D^{\mu}$ controller is the better control of dynamical systems, which are described by fractional order mathematical models. Another advantage lies in the fact that the $PI^{\lambda}D^{\mu}$ controllers are less sensitive to changes of parameters of a controlled system [13]. This is due to the two extra degrees of freedom to better adjust the dynamical properties of a fractional order control system. However, all these claimed benefits were not systematically demonstrated in the literature. In this paper, from practical application point of view, we attempt to illustrate the benefits in a reproducible manner. It was pointed out in [14]that a band-limit implementation of fractional order controller is important in practice, and the finite dimensional approximation of the fractional order controller should be done in a proper range of frequencies of practical interest. This is true since the fractional order controller in theory has an infinite memory and some sort of approximation using finite memory must be done. In the next section, we will present a modified approximation scheme whose performance is better than Oustaloup's method[15].

3.3. Fuzzy Type 2

In traditional fuzzy sets, the membership functions put on figures individually by crisp points. But in fuzzy type-2, a distance for the functions is considered. As Figure 6 shows, P1 to P9 can build the as single membership function.

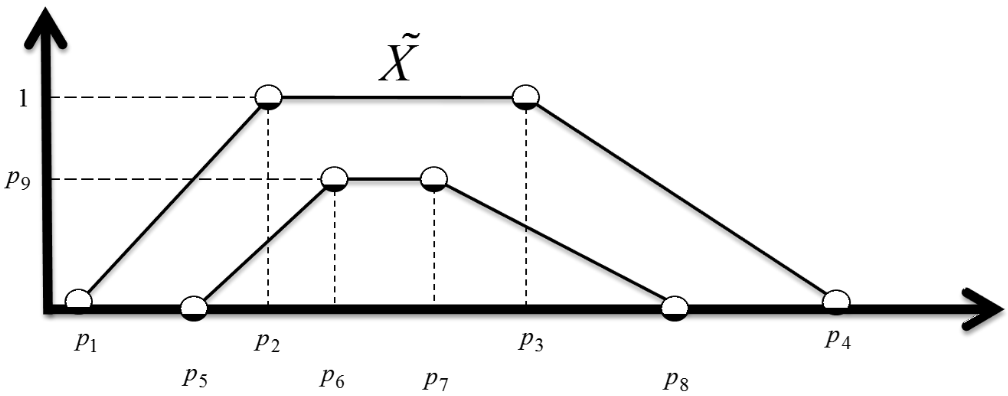

Figure 6. The Position of a Simple Fuzzy Type 2 Sets

The rules of these systems could be made as 17 and 18:

$$\text{IF } x_1 \text{ is } \tilde{X}_1^n \text{ and } \dots \text{ and } x_2 \text{ is } \tilde{X}_2^n \text{ THEN } y \text{ is } Y^n \tag{17}$$

$$\begin{aligned} R^1 &: \text{If } x_1 \text{ is } \tilde{X}_{11} \text{ and } x_2 \text{ is } \tilde{X}_{21}, \text{ THEN y is } Y^1 \\ R^2 &: \text{If } x_1 \text{ is } \tilde{X}_{11} \text{ and } x_2 \text{ is } \tilde{X}_{22}, \text{ THEN y is } Y^2 \\ R^3 &: \text{If } x_1 \text{ is } \tilde{X}_{12} \text{ and } x_2 \text{ is } \tilde{X}_{21}, \text{ THEN y is } Y^3 \\ R^4 &: \text{If } x_1 \text{ is } \tilde{X}_{12} \text{ and } x_2 \text{ is } \tilde{X}_{22}, \text{ THEN y is } Y^4 \end{aligned} \tag{18}$$

Table 2, shows the rules tabular. In the next relations, the magnitude and number intervals are considered.

Table 2. Table of Rules

X_{11}	X_{21}	Y_1
X_{11}	X_{22}	Y_2
X_{12}	X_{21}	Y_3
X_{12}	X_{22}	Y_4

To compute the output value, it's needed to calculate the main fuzzy type-2 values as:

$$y_l = \min_{k \in [1, N-1]} \frac{\sum_{n=1}^{k} \bar{f}^n \underline{y}^n + \sum_{n=k+1}^{N} \underline{f}^n \underline{y}^n}{\sum_{n=1}^{k} \bar{f}^n + \sum_{n=k+1}^{N} \underline{f}^n} \equiv \frac{\sum_{n=1}^{L} \bar{f}^n \underline{y}^n + \sum_{n=L+1}^{N} \underline{f}^n \underline{y}^n}{\sum_{n=1}^{L} \bar{f}^n + \sum_{n=L+1}^{N} \underline{f}^n} \tag{19}$$

$$y_r = \max_{k \in [1, N-1]} \frac{\sum_{n=1}^{k} \underline{f}^n \bar{y}^n + \sum_{n=k+1}^{N} \bar{f}^n \bar{y}^n}{\sum_{n=1}^{k} \underline{f}^n + \sum_{n=k+1}^{N} \bar{f}^n} \equiv \frac{\sum_{n=1}^{R} \underline{f}^n \bar{y}^n + \sum_{n=R+1}^{N} \bar{f}^n \bar{y}^n}{\sum_{n=1}^{R} \underline{f}^n + \sum_{n=R+1}^{N} \bar{f}^n} \tag{20}$$

$$y = \frac{y_l + y_r}{2} \tag{21}$$

The membership functions of input and output are shown in Figures 7 and 8 respectively.

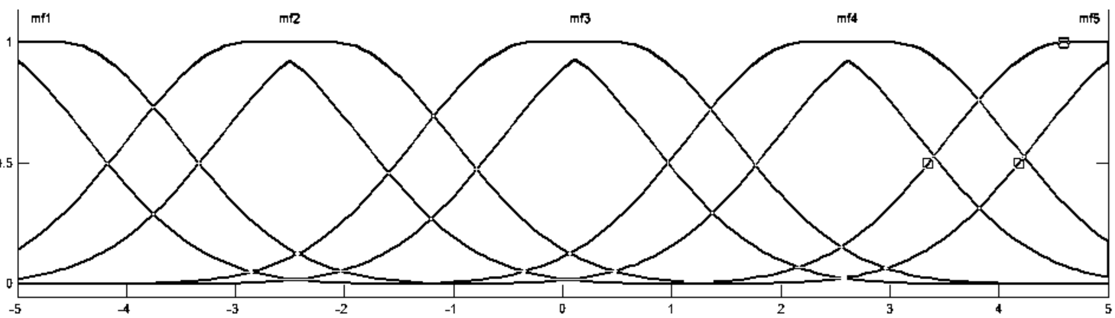

Figure 7. Input Membership Function

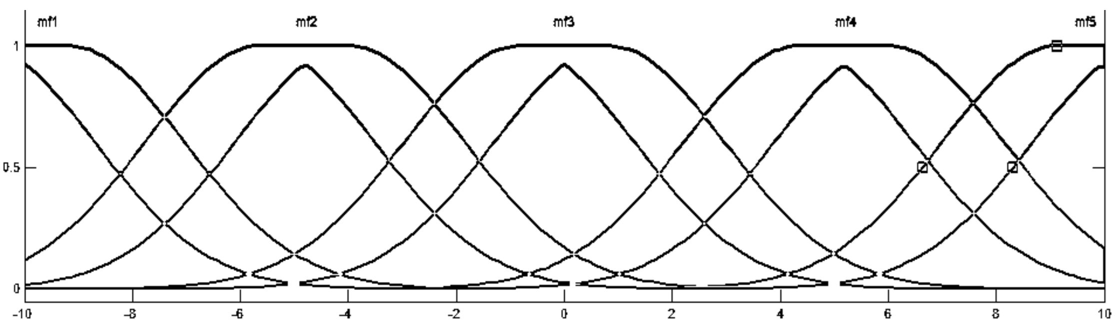

Figure 8. Output Membership Function

The determined controller by these rules is shown in Figure 9 as a policy.

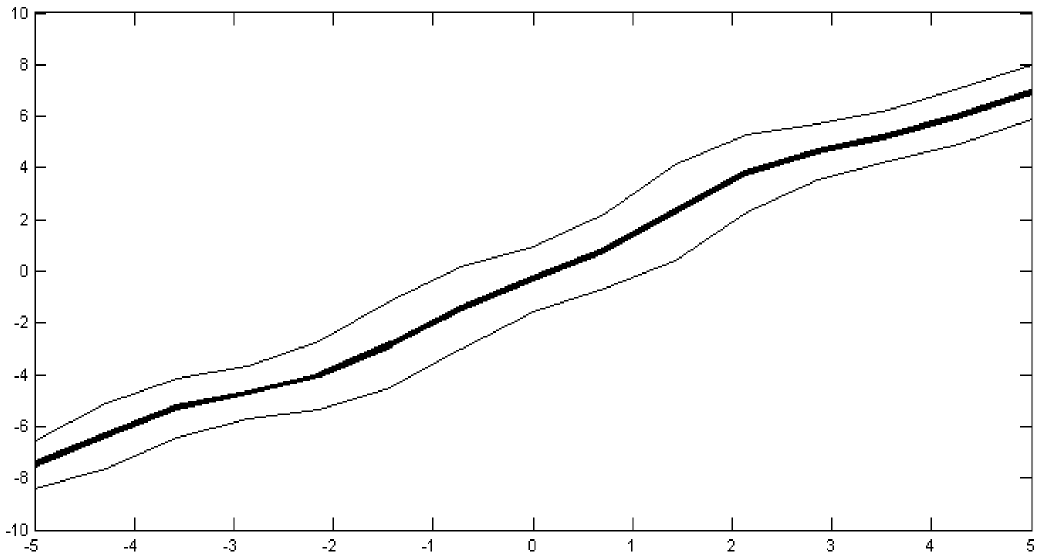

Figure 9. Fuzzy Type 2 Policy

4. Simulation and Results

The linear model described in the previous section is demonstrated in the Figure 10. The steam generator is modeled in Simulink. The ode45 which is a suitable solver is used with variable step time.

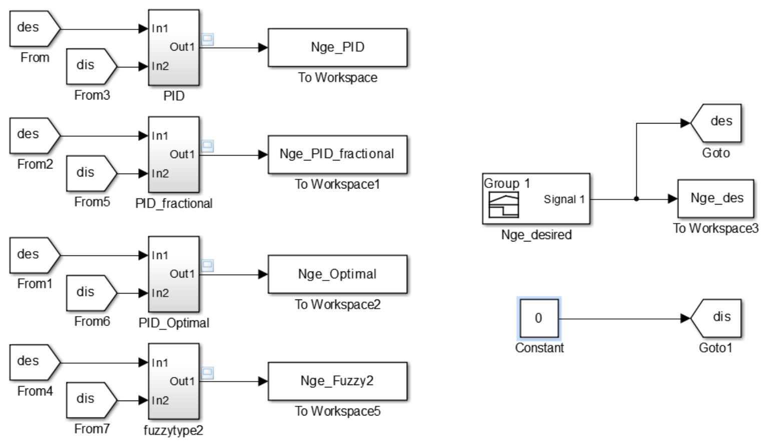

Figure 10. SIMULINK Model

The comparison of all Controller described above is shown in Figure 11. The PID and Fractional-order PID could track the desired value. Fuzzy type 2 in comparison with optimal controller could be more effective.

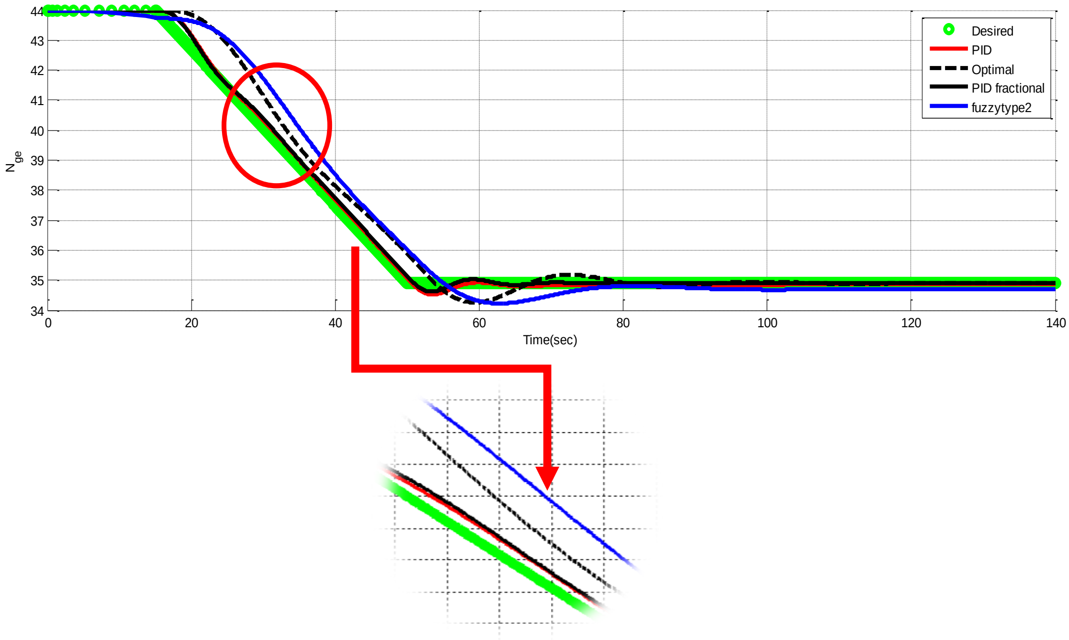

Figure 11. Output of PID Fractional and Fuzzy Type2 Control

With the different view to the controller performance, as the Figure 12 shows, the PID controller is not applicable at all. A high frequency made for its chattering disturb the performance of controlling. But as it emphasizes, the fractional PID could decrease the chattering and produce a proper controller. Although the fuzzy PID is not as effective as fractional PID, the control effort of this logical method is so appropriate.

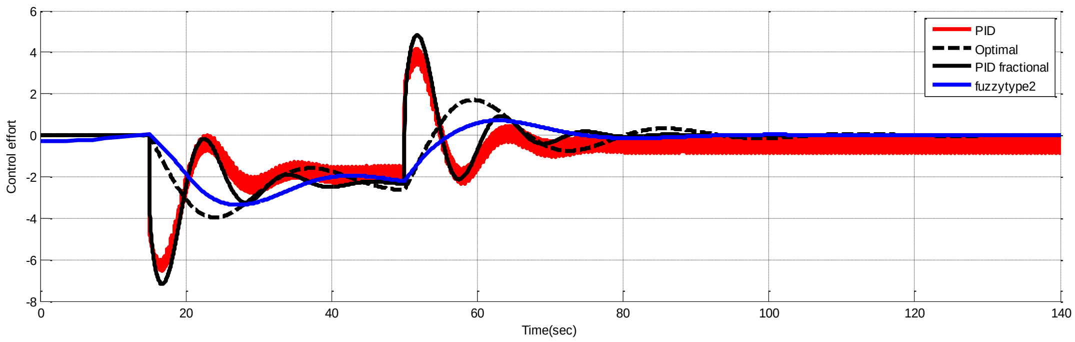

Figure 12. Effort of PID, Optimal, Fractional-Order PID and Fuzzy Type2 Controller

5. Conclusion

In this paper four types of conventional PID, fractional-order PID, optimal and fuzzy controllers are compared with each other for steam level controlling in a power plant. The linear model of the steam generator is employed. The result shows the Fractional-order PID can be the most appropriate controller among the others. Also in the sense of minimizing the controller effect, the fuzzy type 2 could role as an efficient regulator.

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