New Smith Predictor Controller Design for Time Delay System

Youcef Zennir, Mohand Said Larabi and Hassen Benzaroual
Automatic Laboratory of Skikda, Université 20 Août 1955, 26 route El-hadaiek, Skikda, Algeria

Keywords: Identification, Modelling, Time Delay System, IMC Controller, PID Controller, FOPID Controller, Didactic Industrial System.

Abstract: This paper presents a robust control design based on Smith predictor and Fractional order PID (PIλDμ) controller. This control technique has been used with other type of controllers (PID and IMC internal model Controller) in order to ensure all performances required by several complex industrial process. Detailed descriptions of the process with different mathematical models (with time delay) are exposed. One model is validated around different operating points, by using different identification methods. We have used the singularity function method to approximate fractional order in the FOPID structure. We have described control principle's and compare it with a different types of mentioned controllers in this study. Finally several simulations have proved the efficiency of the new control design in term of stability, robustness and precision.

1 INTRODUCTION

To be competitive, an industrial process must be well controlled. Indeed, competitiveness requires keeping process values as close as possible to its required optimum performance and process conditions: such as the products quality, production flexibility, energy saving and safety of personnel, facilities and the environment. The main role of industrial controller is to keep the process under control with the guarantee of a good dynamic and static behaviour performance. Which can be achieved by adjusting and adapting the transfer function parameters in order to as close as possible to the real process. In general, an industrial process is modelled by a non-linear, linear (after linearization) or linear mathematical model with a time delay (Boyd, 1991). Regardless if these models are stable or not are required a controller (control action) to ensure the desired performance. The objective of automatic regulation or servo-control of a process is to keep the process values as close as possible to its optimum of operating points, predefined by the process specification (imposed conditions or performance). Safety aspects of staff and facilities should be taken into accounts, such as those relating to energy and respect for the environment. The specifications define qualitative criteria to be imposed, which are usually translated by quantitative criteria, such as stability, precision, speed or evolution laws. Before going ahead and develop the controller architecture and structure and in case of unknown process parameters, an identification phase is mandatory. Different identification methods are existed in the literature (Boyd, 1991; Ljung, 1999; Barraud, 2006). In our study we are interested in the analogue flow control system (Figure 1) by computing its mathematical model via applying a different identification methods (Broida, Strejc, etc.) and synthesis of its control laws using several types: IMC, PID, FOPID and Smith predictor controller and then at the end we checked the simulation results with the process experiments.

Figure 1: Experiment setup of a flow control (Abraham and Denker, 2015).

Zennir, Y., Larabi, M. and Benzaroual, H.
New Smith Predictor Controller Design for Time Delay System.
DOI: 10.5220/0006426105980605
In *Proceedings of the 14th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2017) - Volume 1*, pages 598-605
ISBN: 978-989-758-263-9

2 DIDACTIC INDUSTRIAL PROCESS

The process illustrated in FIG. 1 consists of numerous components and accessories (Abraham and Denker 2015). The accessory components are pre-installed on plates. The basic module offers a large chassis for fast and safe mounting of the respective required components of a test. The basic module contains one storage tank: 75L (1), Centrifugal pump (2), Compressed air controller with pressure gage (0-2,5bar) with quick coupling for supplying experiments (3), orifice with Differential Pressure Sensor (Electro-pneumatic control valve) (4), flow Rate Sensor (Electromagnetic) (5), rotameter (6), valve (7) and Switch cabinet (8). The Controlled System Flow is operated with water as the working medium and consists of a variable area flow meter. The flow resistance can be configured using a valve (7), which changes the flow properties in the controlled systems.

One particular benefit of these controlled systems is that, thanks to the float, all changes in the flow rate caused by interference or behaviour of a controller can be observed directly. The training system has an electronic sensor with display for measuring flow rates. It is suitable for measuring flow rates of liquids in closed tubes. The measurement variable is the flow rate. The ideal flow velocity is 1-3m/s. The measurement principle is electromagnetic induction according to Faraday's law. Electromagnets or coils generate a magnetic field, in which a conductor moves. This induces a voltage. Here, the medium flowing in the flow rate sensor corresponds to the moving conductor. Therefore, for this type of measurement, a minimum conductivity of the flowing medium is a prerequisite.

The magnetic field is generated by pulsed direct current of alternating polarity. The induced voltage is proportional to the flow velocity and is tapped by two measuring electrodes. The flow volume is calculated from the flow velocity using the known pipe cross-section. After a transformation there is a standardized 4-20mA current signal proportional to the flow rate available at the output. This sensor has the advantage that flow resistances do not cause any pressure drop, since it does not involve any moving mechanical elements and the system's pipe cross-section remains unchanged. The valves are connected to the pipe system with PP-H plastic pipes and clamp fittings or hoses. The closed loop flow control diagram block, control with different elements, which is represented by P&I diagram with the follows figure (Abraham and Denker 2015). The P&ID of flow control is presented as follows:

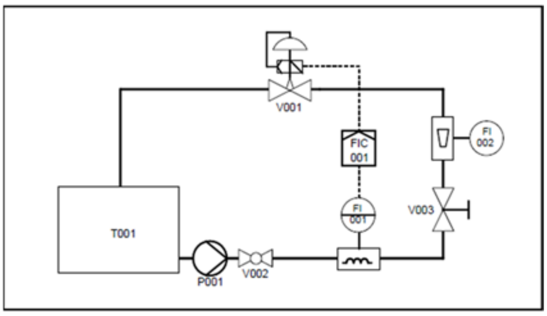

Figure 2: Flow control diagram (Abraham and Denker, 2015).

The identification methods used to identify our process are described in the following section.

3 PROCESS IDENTIFICATION

The research of an industrial process model is necessary in a model correctly representing the process behaviour of the process. However, the model must not be too sophisticated, at the risk of being incompatible with the available corrector, or be too simplistic not to mask certain aspects that are detrimental to proper functioning. The choice of a model, like its determination, must therefore be judicious. The identification operation is carried out in an open loop and this loop is no longer controlled automatically. The controller is switched to manual mode in order to act on the control signal. The system can then be excited by a step signal with different values. In principle, the output and input must be of the same type with linear system (figure 3). If not, the system is nonlinear ((Ljung, 1999; Barraud, 2006).

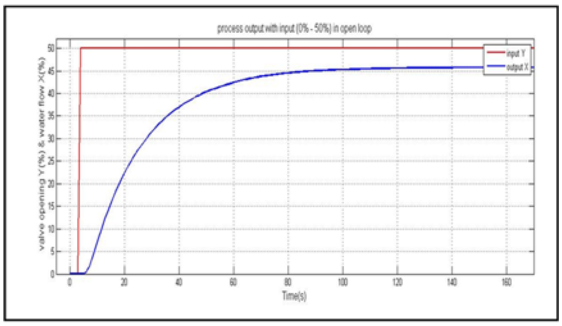

Figure 3: Process step response with input 0 %→ 50%.

The figure 3 represents the system response to a step input from 0% to 50%. We can see that the output (flow measurement) converges towards the input and that the system behaves us a first order system with a certain time delay. In order to check the linearity of the system, the used method is to excite the system by two different steps inputs (0% -30%) and (0% -50%), thus Y1 = 30% and Y2 = 50% Y1 + Y2 = 80%, then the system was excited with one input (0% -80%), shown in the follows figure:

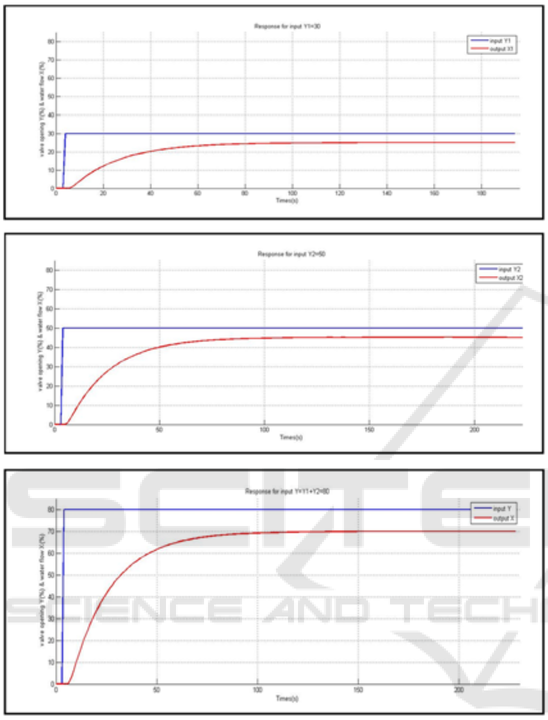

Figure 4: Linearity proof of Process.

From Figure 4, we can see that the process has a linear behaviour under certain operating conditions. Using some several open-loop tests, the characteristic curve, outputs = f (input) is determined in steady state (figure 5).

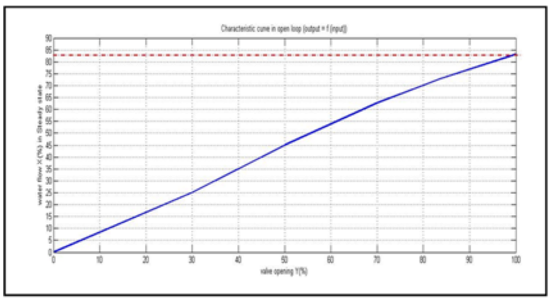

Figure 5: Curve output=f(input).

The resulting curve (figure 5) is of the substantially linear form, a straight line passes through the origin Y=K * X, note that K represents the system gain. The relation between flow rate and opening of the valve is described by the following equation: X (Y) ≈0.87 * Y. The mathematical model of a stable process with a first-order model behaviour and a time delay is described by the following transfer function:

$$tf(s) = \frac{X(s)}{Y(s)} = \frac{K_p}{T_p \cdot s + 1} \cdot e^{-T_d \cdot s} \quad (1)$$

Using Broida identification method and applying these inputs (20% -84%), (0% -50%), (30% -50%) (50%-70%) to the open loop. We have obtained the following models:

$$Br_1(s) = \frac{e^{-1.8\,s}}{22 \cdot s + 1} \quad (2)$$

$$Br_2(s) = \frac{0.9}{16.5 \cdot s + 1} \quad (3)$$

$$Br_3(s) = \frac{0.9}{19.25 \cdot s + 1} \cdot e^{-1.8 \cdot s} \quad (4)$$

$$Br_4(s) = \frac{0.85}{16.5 \cdot s + 1} \cdot e^{-3.6 \cdot s} \quad (5)$$

The step responses of the models are illustrated in the following figure:

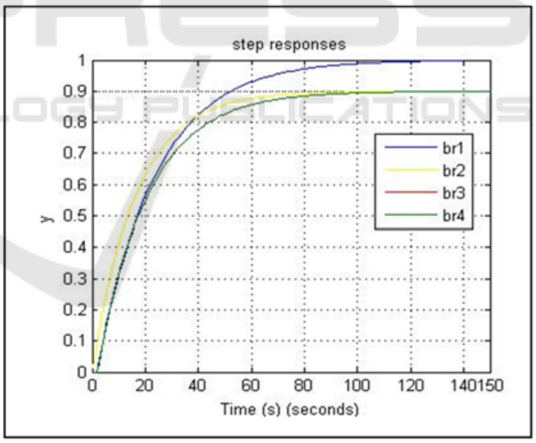

Figure 6: Linearity proof of Process.

In the second time we have used Strejc-Davost identification method (Ljung, 1999), and we applied the same inputs and the obtained the transfer functions models: St_1, St_2, St_3 and St_4 respectively are as follows:

$$St_1(s) = \frac{e^{-0.79\,s}}{(9.07 \cdot s + 1)^2} \quad (6)$$

$$St_2(s) = \frac{0.9\, e^{-1.02\,s}}{(9.64 \cdot s + 1)^2} \quad (7)$$

$$\mathrm{St}_3(s) = \frac{0.9\ e^{-0.74\,s}}{(9.6\ \cdot s\ + 1)^2} \qquad (8)$$

$$\mathrm{St}_4(s) = \frac{0.85\ e^{-0.6\,s}}{(8.83\ \cdot s\ + 1)^2} \qquad (9)$$

4 IDENTIFICATION METHODS

We could identify our processes easily and, using matlab function: ident command from the toolbox identification. And we have obtained the dynamic of the systems using input-output data from the identified system. By following the follwing steps are: Import of the data system, estimation and validation of the model parameters. The Matlab toolbox allows to identify a transfer functions, a process models and the state space models, and also provides an algorithms to evaluate the accuracy of the identified models. We have used for each operating point the data system of two tests carried out under the same conditions (with the same inputs) in order to estimate the model with the first test and validate it with the second test. We have used as well "Process model" method for model estimation. The structure of this parametric estimation method is a simple transfer function in continuous time which describes a linear dynamic system. This model is characterized by a static gain, time constant and time delay. If some parameters are known, we need just to enter their value and tick the box "Known". The estimation algorithm will use these values for the model. The behaviour of the system is close to the first-order systems with a small time delay, so we start from this point and we have made the identification with the four datasets (same measurement data used in the Broida or Strejc-Davost identification methods). The general form of the transfer function is given by (1).

The obtained models (transfer functions tf1, tf2, tf3, tf4) with this method are illustrated in the following table:

Table 1: Transfer functions with Ident (matlab).

Model	Kp	Tp	Td
tf1	0.92514	20.571	1.342
tf2	0.86879	19.891	2.541
tf3	0.91525	20.332	2.548
tf4	0.89686	20.539	0.5

We have visualized the behaviour of the obtained models with the different inputs and we have compared the adjustment with the actual Best Fits system. The obtained results are illustrated in the following figures (response of the model described by transfer function tf4):

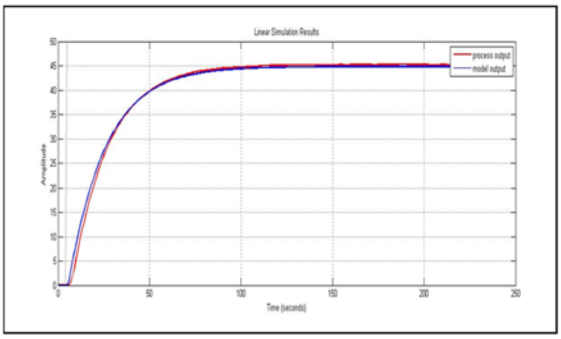

Figure 7: Process step response with input 0 %→ 50%.

In the (figure 7) we could observe, that the output process and model are very close to each other after transitory regime. The following table illustrates the best adjustments given by the models with the different applied inputs. It is found that the percentage of adjustment is always greater than 84.95%, with the model described by the tf4 transfer function compared to the other models which give a lower adjustment percentage.

Hence, we can say that tf4 is the model that represents better the real system. The index response of the open-loop model (tf4) is illustrated in the following figure:

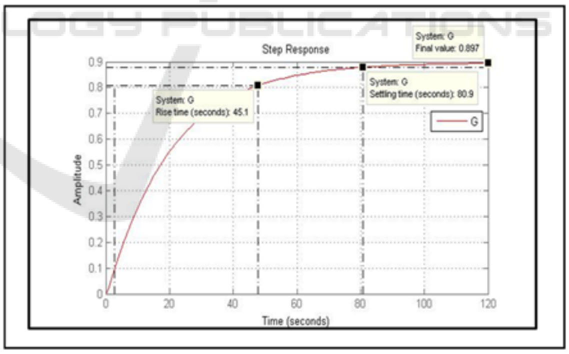

Figure 8: Step response of model tf4 in open loop.

The characteristics on open loop are not satisfactory (the system is very slow, final value different of 1) (figure 8). Hence we need to used a controller to ensure the optimal characteristics and improved the stability of process.

In the following section we use different controllers in this study have been described and on particularly the Smith's predictor controller with new structure.

5 NEW DESIGN OF SMITH PREDICTOR

In the literature, there are a large number of linear or discrete linear controllers adequate for industrial process control, which has linear system behaviour (Kumar and Singh 2014). Among the most common and most used controllers are PI, PD and PID with different structures (Ali and Majhi, 2009). Also, there is another type of controller that is more robust than the conventional PID such as the internal model controller (IMC) (Li et al., 2009; Wang et al., 2016; Shamsuzzoha et al., 2012; Santosh kumar et al., 2016; Xiao-Feng et al., 2016) and the Fractional order PID controller (FOPID) (Bettou, 2011; Bettou and Charef, 2008; Bouras et al., 2013).

Other types of controllers are developed specifically to control systems with time delay such as Smith's predictor (Shahri et al., 2014). This controller was proposed for the first time by OJ Smith in 1957 (Aidan and John, 1996; Resceanu, 2009).The main idea behind Smith's predictor is that, since it is well known to correct systems without time delay with a corrector (PID for example) (Resceanu, 2009).

It does not correct the system without delay but the output will then be estimated by delaying it by the value of the system time delay. This very simple approach leads to the following structure:

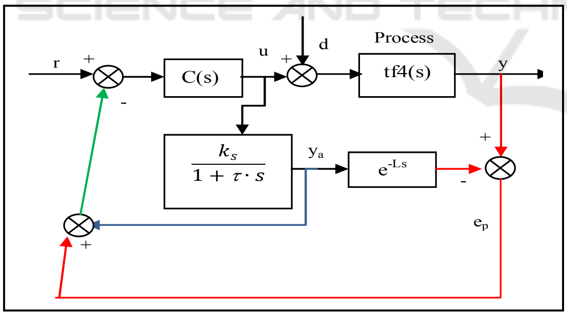

Figure 9: Smith predictor (L=Td; Ks=Kp; τ=Td).

Different structures of Smith predictor has been proposed in literature with different controllers. Note that, the implementation of a Smith predictor controller needs a very good model of the process. In our study we have used only Fractional order PID (FOPID) controller and with Smith predictor. The structure type of the FOPID controllers is Fractional order controller: $PI^{\lambda}D^{\mu}$. In control theory, the conclusion about fractional control system is that it can increase the stability region and robustness (Esmaeilzade, 2014) moreover it gives performances at least as good as its integer counterpart (Grimble, 2006). The transfer function of a FOPID controller, which was initially proposed by Podlubny in 1999 (Esmaeilzade, 2014), is given by :

$$G_c(s) = K_p + K_I\frac{1}{s^{\lambda}} + K_D s^{\mu}, (\lambda,\mu > 0) \tag{10}$$

Where Kp, KI, KD∈ R and λ,μ∈ R+: are the controller tuning parameters and the controller design problem is to determine the suitable values of these unknown parameters in such way it responds to all control objectives (Grimble, 2006). Many methods in literature have been proposed for FOPID approximation (Bouras, 2013).

In this work we have used singularity function approximation method of Charef (Bettou, 2011), applied in FOPID controller. The fractional-order integrator $s^{-\lambda}$, μ∈R+ is approximated as:

$$H(s) = \frac{1}{s^{\lambda}} \cong \frac{K_I}{\left(1+\frac{s}{\omega_c}\right)^m}, with\ 0 < m < 1\,, \lambda \in R^+ \tag{11}$$

To have a good tuning parameters of the $PI^{\lambda}D$ (Kc, Ti , λ) we have used the following algorithm (Bouras, 2013) described in the steps below:

Step1: calculate the parameters θ_i for 0≪i≪2

$$\theta_0 = \frac{1}{2},\ \theta_1 = \frac{-m}{4\cdot\omega_u},\ \theta_2 = \frac{m}{4\cdot{\omega_u}^2} \tag{12}$$

ω_u: the unit magnitude frequency of reference model;

m: the derivation fractional order of the reference model;

θ_i: calculated with the reference model parameters.

Step 2: calculate the parameters y_i for 0≪i≪2

Using the following formulas:

$$y_0 = \sum_{k=0}^{N} G_P(kT)\cdot e^{-KT\omega_u} \tag{13}$$

$$y_1 = -\sum_{k=0}^{N}(kT)\cdot G_P(kT)\cdot e^{-KT\omega_u} \tag{14}$$

$$y_2 = \sum_{k=0}^{N} G_P(kT)\cdot(kT)^2\cdot e^{-KT\omega_u} \tag{15}$$

With y_i: calculated from the transfer function Gp(s) compared to the variable s at the point ωu; N: samples number.

Step 3: calculate the parameters X_i for 0 ≪ i ≪ 2

As per the following formulas:

$$X_0 = \frac{\theta_0}{y_0(1-\theta_0)} X_1 = \frac{\theta_1}{y_0(1-\theta_0)^2} - \frac{x_0.y_1}{y_0} \tag{16}$$

$$X_2 = \frac{\theta_2}{y_0(1-\theta_0)^2} + \frac{2\theta_1{}^2}{y_0(1-\theta_0)^3} - \frac{2.x_1.y_1+x_0.y_2}{y_0} \quad (17)$$

With X_i: derived from the controller transfer function C(p).

Step 4: calculate the parameters K_c, T_i, λ with the following formulas:

$$\lambda = -\frac{\omega_u.x_2}{x_1} - 1, T_i = -\frac{\omega_u{}^{(1+\lambda)}.x_1}{\lambda} \quad (18)$$

$$K_c = x_0 - T_i.\omega_u{}^{-\lambda} \quad (19)$$

A comparative study is presented in the simulation section between the various controllers cited before in order to improve the performances of the process and choose the best control suited for this type of system.

6 SIMULATION

The simulation was done with closed loop and step signal as input. Different diagram blocks has been used with different controllers types. The simulation time period equal 50s. We have used controller Smith's predictor with IMC, PID, $PI^{\lambda}D^{\mu}$ controllers. We have applied an external and internal perturbation (different time delay). The controller's parameters values are shown in the following tables:

Table 2: Parameters of Controllers.

Controller	Kp	K_I	K_D	
PID	10.5	0.808	1.87	
$PI^{\lambda}D^{\mu}$	10.5	147.3459	1.87	m=λ=0.7 μ=1

The transfer function of the IMC controller is as follows:

$$C(s) = \frac{1.219.10^{15}\cdot s^2+5.861\cdot 10^{15}\cdot s+2.764\cdot 10^{14}}{1.98\cdot 10^{14}\cdot s^2+1.1\cdot 10^{15}\cdot s-1} \quad (20)$$

The simulation is organized as below:

1. First study: Smith predictor controller with IMC and PID controllers. Time delay equal 0.5 and 0.7. Perturbation applied after 25 s.
2. Second study: Smith predictor controller with IMC or PID controllers, and FOPID controller. Time delay equal 0.5s and 0.7s. Perturbation applied after 25 s.

The block diagram of the control is as follows:

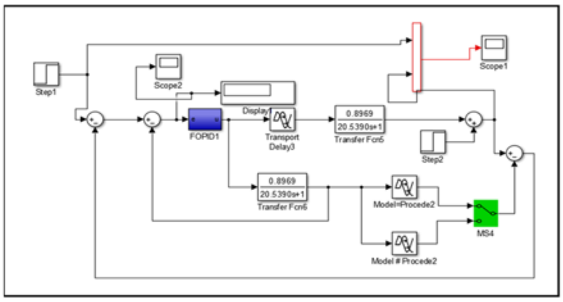

Figure 10: Block diagram of closed loop control with Smith predictor and FOPID controller.

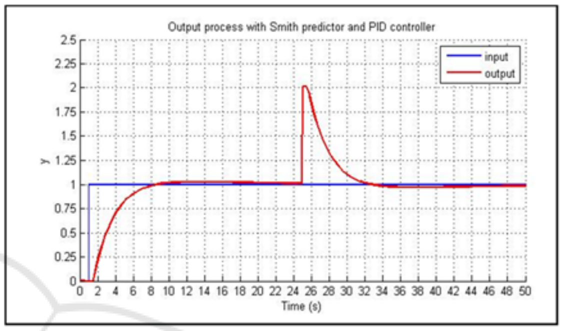

Figure 11: Input and Output curve (Process= model), with Smith predictor and PID controller.

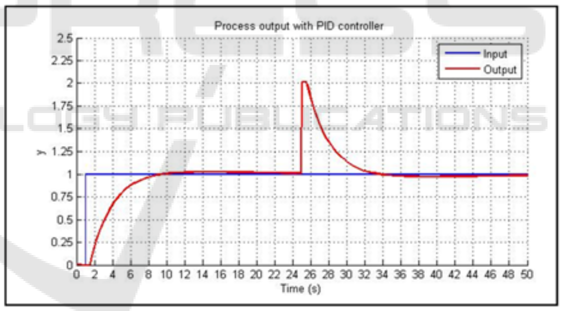

Figure 12: Input and Output curve (Process ≠ model, time delay=0.7s), with Smith predictor and PID.

The obtained results illustrated by Fig.10, Fig11, Fig.12 and Fig.13 show the PID controller is more efficient (short response time) but IMC controller give more precision. The obtained results illustrated by Fig.14, Fig15, Fig.16, Fig.17, Fig.18 and Table III shows the FOPID controller more efficient then the PID and IMC (short response time and good precision and stability).

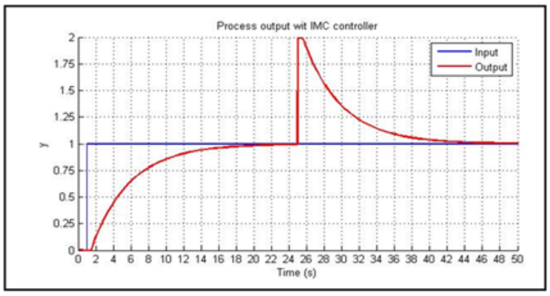

Figure 13: Input and Output curve (Process= model), with Smith predictor and IMC controller.

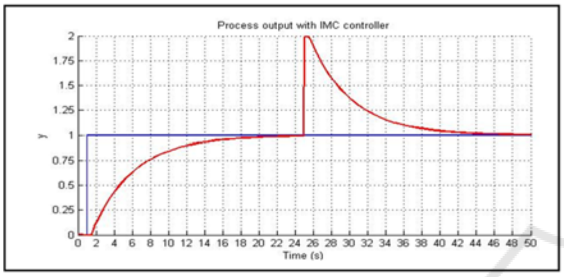

Figure 14: Input and Output curve (Process ≠ model, time delay=0.7s), with Smith predictor and IMC.

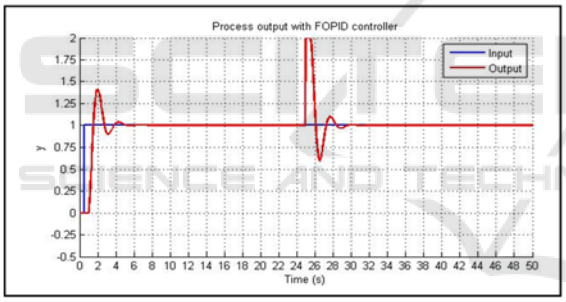

Figure 15: Input and Output curve (Process= model), with Smith predictor and FOPID controller.

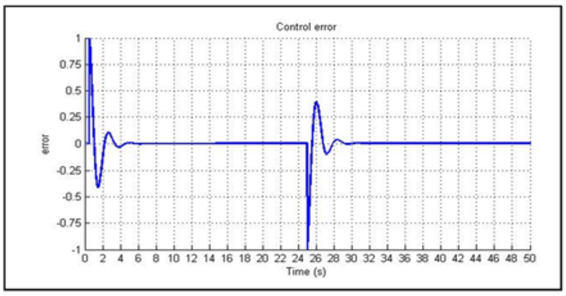

Figure 16: Error control (Process = model), with Smith predictor and FOPID controller.

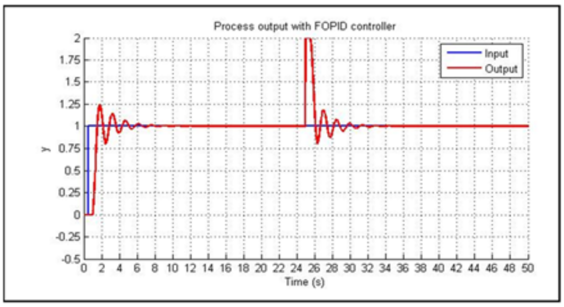

Figure 17: Input and Output curve (Process ≠ model, time delay=0.7s), with Smith predictor and FOPID controller.

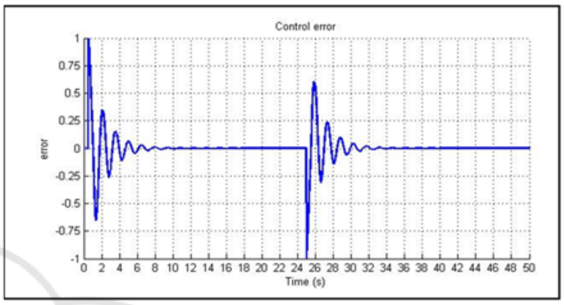

Figure 18: Error control (Process ≠ model, time delay=0.7s), with Smith predictor and FOPID controller.

Table 3: Control error.

Control error	PID	IMC	FOPID
Process=model (time delay = 0.5s)	$1.06.e^{-2}$	$-3.9.e^{-3}$	$2.42.e^{-5}$
Process ≠ model (time delay = 0.7s)	$1.14.e^{-2}$	$-4.3.e^{-3}$	$2.48.e^{-5}$
Process ≠ model (time delay =5s)	$5.2.e^{-4}$	$-3.1.e^{-4}$	

7 CONCLUSION

In this work we have presented the Smith Predictor with IMC, PID and Fractional order PID controllers applied to one of the industrial didactic process, modelled by a linear model with time delay. A detailed description of the system was presented with different identification methods (Broida, Strejc) used to obtain the best model. The chosen model has been validated. And the obtained results show that the new smith predictor structure with a Fractional order PID control provides better performances to the process compared with PID or IMC controllers. And keep the study open for further optimization of the FOPID parameters in case of a big time delay. Different optimization algorithms can be applied such as PSO or Genetic algorithms.

REFERENCES

Abraham, D. and Denker, T. 2015. “Instruction Manual RT 450 Modular Process Automation Training System”. G.U.N.T. Gerätebau, Barsbüttel, Germany,V. 0.1, p. 215.

Aidan, O. and John, R. 1996. “The control of a process with time delay by using a modified Smith predictor compensator”. *Proceedings of the Irish Conference on DSP and Control, Trinity College Dublin*, pp. 37-44.

Ali, A. Majhi, S. 2009. "PI/PID controller design based on IMC and percentage overshoot specification to controller set point change". *ISA Transactions*, vol.48, pp.10-15.

Barraud, J. 2006. “Control of processes with variable parameters”. *Mathematics. Ecole Nationale Supérieure des Mines de Paris*, p.161.

Bettou, K. 2011. "Analyse et réalisation de correcteurs analogiques d'ordre fractionnaire", Mémoire de thèse, Université de Constantine, p.111.

Bettou, K. Charef, K.A. 2008. "A New design method for fractional $PI^{\lambda}D^{\mu}$ controller", IJSTA, vol.2(1), pp 414-429.

Bouras, L. Zennir, Y. and Bourourou, F. 2013. "Direct torque control with SVM based a fractional controller: Applied to the induction motor". *Proceeding of the 3rd IEEE international conference on system and control* 29-31 October. Algeria, pp.702-707.

Boyd, S. and Barratt C. 1991. “Linear Controller Design: Limits of Performance”, Originally published by *Prentice-Hall*, p.426.

Esmaeilzade, S.M., Balochian, S., Balochian, H., and Zhang, Y., 2014. Design of Fractional–order PID Controllers for Time Delay Systems using Differential Evolution Algorithm. *Indian Journal of Science and Technology*, vol. 7(9), pp.1307–1315.

Grimble, M. J., 2006. Robust Industrial Control Systems: Optimal approach for polynomial systems. *Book*, pp.554.

Kumar, S. Singh, V.K. 2014. “PID controller design for unstable Processes With time delay”. *International journal of innovative research in electrical, electronics, instrumentation and control engineering*, vol. 2, Issue 1, pp.837-845.

Ljung, L. 1999. “System Identification: Theory for the User”. 2nd ed. Englewood Cliff, NJ: *Prentice Hall*.

Li, D. Zeng, F. Jin, Q. Pan, L. 2009. "Applications of an IMC based PID Controller tuning strategy in atmospheric and vacuum distillation units". *Nonlinear Analysis: Real World Applications*, vol. 10, pp.2729-2739

Reşceanu, F. 2009. “New Smith Predictor Structure Used for the Control of the Quanser SRV-02 Plant”, *Annals of the university of Craiova*, vol.2. p.7.

Shamsuzzoha, M. Skliar, M. and Lee, M. 2012. “Design of IMC filter for PID control strategy of open-loop unstable processes with time delay”. *Asia-pacific journal of chemical engineering*, vol.7, pp.93–110.

Santosh Kumar, D.B. Padma Sreen, R. 2016. “Tuning of IMC based PID controllers for integrating systems with time delay”. *ISA Transactions*, 2016, vol.63, pp.242-255

Shahri, M.E., Balochian, S. Balochian, H. and Zhang, Y. 2014. ”Design of Fractional–order PID Controllers for Time Delay Systems using Differential Evolution Algorithm”. *Indian Journal of Science and Technology*, vol 7(9), pp.1307–1315.

Wang, Q. Lu, C. and Pan, W. 2016. “IMC PID controller tuning for stable and unstable processes with time delay”. *Chemical engineering research and design*, vol.105, pp.120-129.

Xiao-Feng, L., Chen, G. Wang, Y. 2016. “IMC-PID controller Design for power control loop Based on closed-loop identification in the frequency domain”. *IFAC Papers online*, vol.49, n° 4, pp.79-84.