Performance Evaluation of a Fractional Order PID Controller Applied to Separately Excited Direct Current Motor Speed Control

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ABSTRACT - At the present time, Direct Current (DC) motors have been widely used in many industrial applications. The main reason for their popularity is the ability to control their torque and flux easily and independently. The most commonly used controller for the speed control of DC motor is conventional Proportional-Integral-Derivative (PID) controller. However, the conventional PID controller has some disadvantages. To overcome these disadvantages, various types of modified conventional PID controllers such as Fractional Order PID (FOPID) controllers were developed. This paper presents a comparison of time response specifications between FOPID and conventional PID controllers for a speed control of DC motor. Performance of two controllers has been verified through simulation results using MATLAB/SIMULINK software. Simulation results show that the FOPID controller performs better performance and more robustness than a conventional PID controller.

Keywords: *Direct Current Motor, Speed Control, PID Controller, FOPID Controller.*

المستخلص – فى الوقت الحالى, فإن محركات التيار المباشر تستخدم فى العديد من التطبيقات الصناعية. والسبب الرئيسى لشعبيتها هو القدرة على التحكم فى عزم الدوران والفيض بسهولة و بشكل مستقل. المتحكم الأكثر إستخداماً للتحكم فى سرعة محرك التيار المباشر هو الحاكمة التناسبية–التكاملية–التفاضلية التقليدية. و مع ذلك، فإن الحاكمة التناسبية–التكاملية–التفاضلية التقليدية لها بعض المساوئ. للتغلب على هذه المساوئ، تم تطوير أنواع مختلفة من الحاكمة التناسبية–التكاملية–التفاضلية التقليدية مثل الحواكم التناسبية–التكاملية–التفاضلية كسرية الرتبة. هذه الورقة تقدم مقارنة لمواصفات الإستجابة الزمنية بين الحاكمة التناسبية–التكاملية–التفاضلية كسرية الرتبة و الحاكمة التناسبية–التكاملية–التفاضلية التقليدية للتحكم فى سرعة محرك التيار المباشر. تم التحقق من أداء الحاكمتين من خلال نتائج المحاكاة بإستخدام برنامج MATLAB/SIMULINK. نتائج المحاكاة توضح أن الحاكمة التناسبية–التكاملية–التفاضلية كسرية الرتبة أظهرت أداء أفضل و أكثر متانة من الحاكمة التناسبية–التكاملية–التفاضلية التقليدية.

INTRODUCTION

Direct current motor drives, because of their simplicity, ease of implementation; high reliabilities, flexibilities and favorable cost have long been a backbone of industrial applications. They cover wide range of applications including computer peripherals, robotic manipulators, actuators, steel rolling mills, electrical vehicles, paper machine and home appliances [1]. Therefore, the control of the speed of a DC motor is an important issue and has been studied since the early decades in the last century. Numerous controllers have been developed in literature for DC motor speed control. Some of these methods were based on classical and also intelligent approaches [2-5]. Out of various closed loop controller designs available till date, the most commonly used controller for the speed control of DC motors is classical PID controller [5-7].

This is mainly because the classical PID controller is easy to implement either by hardware or by software. No deep mathematical theory is necessary to understand how the classical PID controller works, so everybody is able to imagine what is happening inside the controller during the control process. Furthermore, it has the ability to eliminate steady state offset trough integral action and it can anticipate the changes through

derivative action. In addition to this, traditional PID controllers have very simple control structure and inexpensive cost. However, major problems in applying a standard PID controller in a speed control are the effects of nonlinearity in a DC motor. The nonlinear characteristics of a DC motor such as saturation and friction could degrade the performance of standard PID controller [3-8]. Generally, an accurate nonlinear model of an actual DC motor is difficult to find and parameter obtained from systems identification may be only approximated values. In order to tackle these problems and improve the dynamic response of DC motor, a FOPID controller has been used [9].
The main objective of this paper is to control the speed of DC motor using a FOPID controller. The proposed controller is analyzed for its performance using MATLAB/SIMULINK software package. A comparative study has also been made to highlight the advantage of using a FOPID controller over standard (integer order) PID controller for speed control of direct current motor.

DYNAMIC MODEL OF DC MOTOR

Direct current motors are widely used for various industrial and domestic applications. There are various types of direct current motors. In this paper, the Separately Excited DC (SEDC) motor model is chosen according to its good electrical and mechanical performances more than other direct current motor models. Figure 1 shows a separately excited direct current motor equivalent model [2-4].

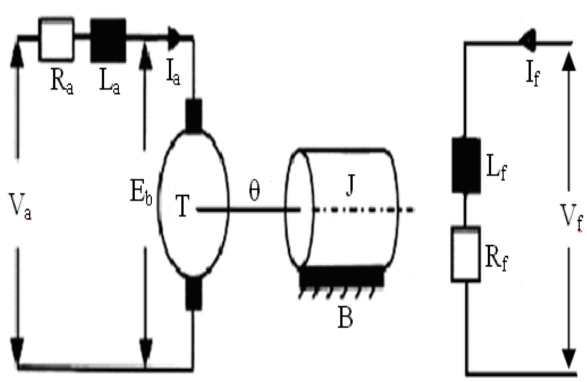

Figure 1: A separately excited DC motor model

The state space model of a separately excited DC motor may be expressed as follows [2-4]:

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-R_a}{L_a} & \frac{-K_b}{L_a} \\ \frac{K_T}{J} & \frac{-B}{J} \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix} v_a \qquad (1)$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix}$$

Where v_a is the input terminal voltage (armature voltage) in volt, R_a is the armature resistance in ohm, L_a is the armature inductance in H, J is the moment of inertia of the motor in kgm^2/s^2, B is the viscous friction coefficient in Nms, K_b is the back emf constant in Vs/rad, K_T is the torque factor constant in Nm/A, ω is represents angular speed in rad/s, and i_a is the armature current in A. The physical and functional parameters of the separately excited DC motor used for simulation testing are given in Table1 [2-4].

Table 1: Parameters of the SEDC motor

Parameters	Values
Armature Resistance, R_a	1Ω
Armature Inductance, L_a	0.05H
Moment of Inertia, J	$0.01kgm^2/s^2$
Viscous Friction Coefficient, B	0.0000 3Nms
The Back EMF Constant, K_b	0.023Vs/rad
The Torque Factor Constant, K_T	0.023Nm/A

ORDINARY PID CONTROLLER

In the past decades, modern control theories have made great advances. Control techniques including optimal control, fuzzy control, neural network control, predictive control, and so on, have been developed significantly. Nevertheless, the conventional PID controller has still been widely utilized in many industrial applications such as process control, motor drives, flight control. This is mainly because classical PID controllers have simple structure to be easily understood by engineers, and easiness to design and implement. However, it has been known that ordinary PID controllers generally do not work well for nonlinear systems, and particularly complex and vague systems that have no precise mathematical models. The differential equation of a conventional proportional-integral-derivative controller is given by [6-8]:

$$u(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \qquad (2)$$

Where e(t) is the error signal and u(t) is controller's output. The parameters K_P, K_I, and K_D are the proportional, integral and derivative gains of the conventional PID controller, respectively. K_P, K_I, and K_D parameters usually take positive values. The transfer function of a classical PID controller is expressed as follows [6-8]:

$$G_{PID}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s \qquad (3)$$

REVIEW OF FRACTIONAL CALCULUS

The history of the Fractional Calculus (FC) covers over three hundard years, similar to that of classical differenrial calculus. In last two decades, the FC has become much pouplar among the researchers of different streams. Fractional calculus was not much pouplar earlier because of its highly complex mathematical expressions. But with the development of computational technologies it has become possible to deal with fractional calculus. Fractional calculus is an extension of integer order calculus in which ordinary differential equations have been replaced by fractional order differential equations. In fractional order differential equations, derivatives and integrals are not necessarily of integer order and they span a wider range of differential equations. Fractional calculus deals with fractional integration and differentiation. Therefore, a generalized differential and integral operator has been introduced as a single fundamental operator represented by ${}_aD_t^{\delta}$ where a and t denote the two integration limits related to the opearion of the fractional differentiation, and δ is the order of fractional differentiation or integration. Positive δ indicates differentiation and negative δ indicates integration. The continuous integro-differential operator (D) is defined as follows [10]:

$$ {}_aD_t^{\delta} = \begin{cases} \dfrac{d^{\delta}}{dt^{\delta}}; & \delta>0 \\ 1; & \delta=0 \\ \int_a^t (d\tau)^{-\delta}; & \delta<0 \end{cases} \qquad (4)$$

There are several definitions of fractional order integration and differentiation. Some of the definitions extend directly from integer order calculus. The most often used are Riemann Liouville (RL) definition and Grunwald-Letnikov (GL) definition. Recently the concept of FC is widely introduced in many areas in science and engineering [10].

REVIEW OF FOPID CONTROLLER

Fractional Order Control (FOC) means controlled systems and/or controllers described by fractional order differential equations [11]. Recently, there are increasing interests to enhance the performance of ordinary PID controller by using the concept of fractional calculus, where the orders of derivatives and integrals are non-integer. The idea of fractional order controller was first proposed by A. Oustaloup through Commande Robuste d'Ordre Non Entier (CRONE) controller in 1991 [12]. Later on, Igor Podlubny had initiated the most common form of fractional order PID in the form of $PI^{\lambda}D^{\mu}$ in 1999 involving an integrator of order λ and differentiator of order μ, where the values of λ and μ lie between 0 and 1 [13]. Clearly, depending on the values of the orders λ and μ, the numerous choices for the controller's type can be made. He also demonstrated that the response of this type of controller is better as compared to the classical PID controller. One of the most important advantages of the FOPID controller is the better control of dynamical systems, which are described by fractional order mathematical models. Another advantage lies in the fact that the FOPID controllers are less sensitive to changes of parameters of a controlled system. This is due to the two extra degrees of freedom to better adjust the dynamical properties of a fractional order control system. However, up till now there is no systematic way to set the value for λ and μ [14-19]. The fractional integro-differential equation of the FOPID controller is given by [13-19]:

$$u(t) = K_P e(t) + K_I D_t^{-\lambda} e(t) + K_D D_t^{\mu} e(t) \quad (5)$$

The transfer function of the FOPID controller is obtained through Laplace transform as follows:

$$G_{FOPID}(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s^{\lambda}} + K_D s^{\mu} \quad (6)$$

Or:

$$G_{FOPID}(s) = \frac{U(s)}{E(s)} = K_P + K_I s^{-\lambda} + K_D s^{\mu} \quad (7)$$

where E(s) is an error and U(s) is controller's output. It is obvious that the fractional order PID controller not only needs design three parameters K_P, K_I, and K_D, but also design two orders λ and μ of integral and derivative controllers. Figure 2 shows the block diagram configuration of the FOPID controller [13].

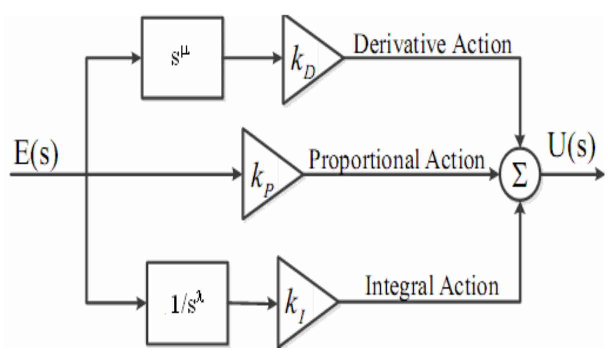

Figure 2: Block diagram of the FOPID controller

In Equation (6), s^{λ} and s^{μ} have fractional orders which are not directly compatible with MATLAB software and it becomes difficult to realize hardware of the FOPID controller. Therefore, there are several integer order approximation methods available for fractional order elements. In MATLAB fractional order PID controller is implemented using FOMCOM toolbox where Oustaloup's approximation is realized [20]. Figure 3 depicts the FOPID controller and explains how the order of the integrator and the order of the differentiator can vary versus the horizontal and vertical axis. As shown in Figure 3, the fractional order PID controller generalizes the ordinary integer order PID controller and expands it from point to plane. This expansion could provide much more flexibility in ordinary PID controller design. Point (0, 0) corresponds to P controller, point (0, 1) corresponds to ordinary PD controller, point (1, 0) corresponds to ordinary PI controller and point (1, 1) corresponds to ordinary PID controller, where as the shaded portion between four corners represent the FOPID controllers. Evidently, all these classical types of PID controllers are special cases of the FOPID controller, when the values of λ and μ are integer values of 0 or 1 [13-19].

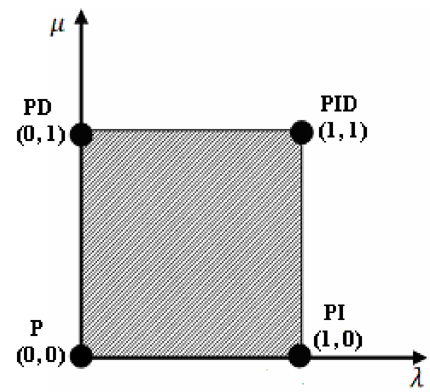

Figure 3: Pictorial representation of the fractional order PID controller

RESULTS AND DISCUSSION

This section shows the simulation results of speed control of the separately excited direct current motor using FOPID controller and traditional PID controller. Simulation results are performed by MATLAB/SIMULINK software to compare the performances of both controllers under several operating scenarios. Simulation tests are based on the facts that whether the FOPID controller is better performance and more robust than the traditional PID controller or not. Figure 4 shows the MATLAB/SIMULINK overall model of speed control of the separately excited DC motor using fractional order PID controller and classical PID controller.

Scenario one: Constant speed

To test the performance of the speed control of SEDC motor drive at a constant speed without any load torque. The SEDC motor drive is started up from stand still to trace the speed command of 10rad/sec.

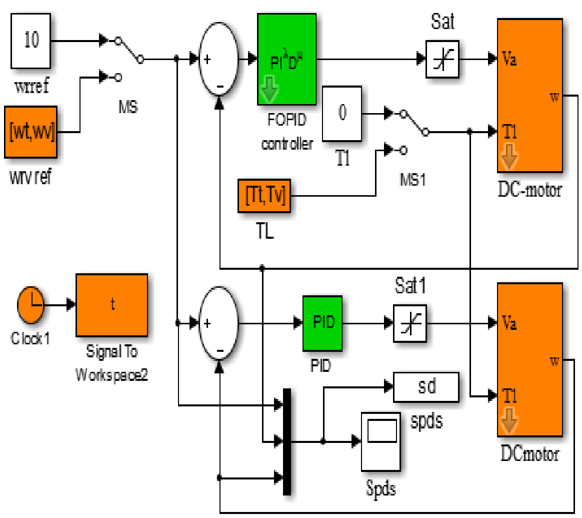

Figure 4: MATLAB/SIMULINK overall model of speed control of DC motor using FOPID and PID

Figure 5 gives the speed responses of the separately excited DC motor drive with FOPID controller and ordinary PID controller. In terms of the speed control trajectories shown in Figure 5, two controllers have a similar performance in term of fast tracking of the desired speed. Also, steady state error with both controllers is almost zero. However, in Figure 5 it can be easily observed that the speed response of the separately excited direct current motor drive with FOPID controller shows no sign of overshoot as observed with classical PID controller thus reducing the settling time. Furthermore, the rise time for FOPID controller is smallest value than for traditional PID controller.

Scenario two: Variable speed

For the checking of robustness, the separately excited direct current motor drive was tested by applying step changes in command speed at regular interval without load torque. The separately excited direct current motor drive is initially started from standstill to trace the speed of 5rad/sec, 15rad/sec and 10rad/sec respectively at a regular interval of 5sec. Figure 6 shows the speed response for a stepped speed reference for FOPID and standard PID controllers.

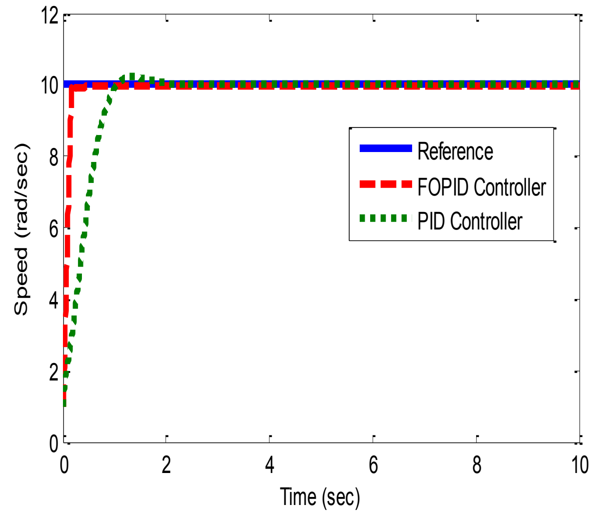

Figure 5: Step response of SEDC using ordinary PID and FOPID controllers

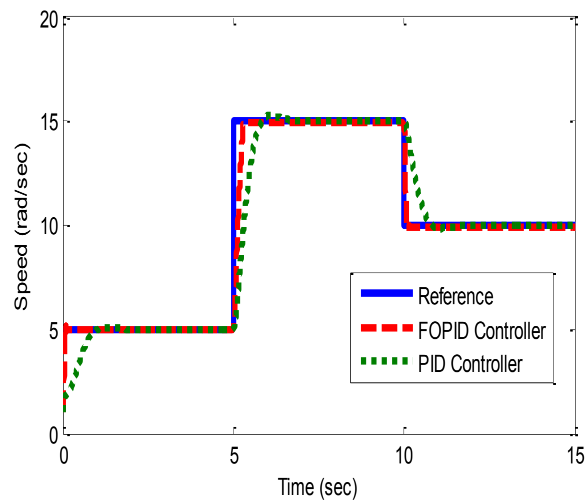

Figure 6: Simulation result at variable speed

It can be evident from the reponse graph shown in Figure 6 that FOPID controller gives better performance in comaparison to ordinary PID controller. Furthermore, when carefully study Figure 6 according to time domain specifications such as settling time, rise time and overshoot, the best performance belongs to FOPID controller.

Scenario three: Inversion of the speed

Figure 7 presents the simulation result obtained for speed inverting from 15rad/s to -15rad/s under no torque load. When the speed is inverted, the response of the SEDC motor shows overshoot and undershoot in case of ordinary PID controller whereas in FOPID controller speed settles smoothly without any remarkable overshoot and undershoot. In addtion, the settling time and rise time for FOPID controller is shorter than for conventional PID controller.

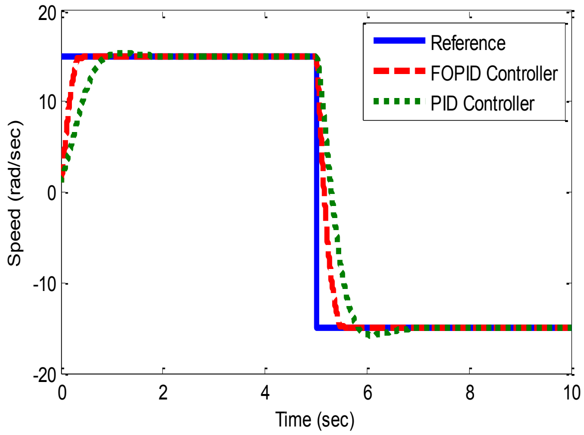

Figure 7: Speed responses of FOPID and ordinary PID controllers with reversing speed

Scenario four: Load torque

Load disturbance rejection is also important to evaluate the controller's robustness. Figure 8 gives the speed responses when the SEDC motor is commanded to follow the speed reference with sudden change in load torque. Similary, Figure 9 shows their corresponding motor torque responses versus load torque disturbances.

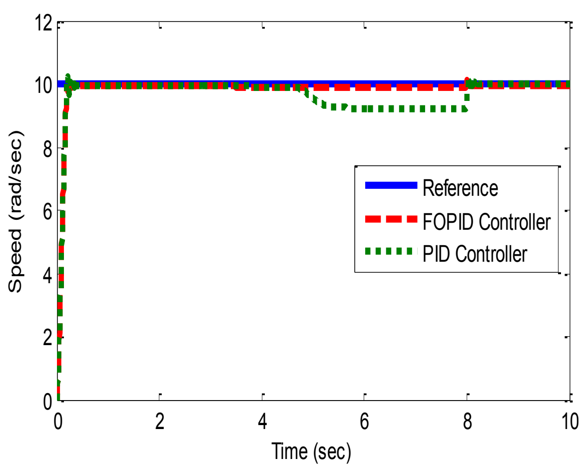

Figure 8: Speed responses of two controllers against sudden change in torque load

Initially the external torque load is zero and then suddenly a load torque of 1Nm is applied at t=5sec and then withdrawn at time 8sec. Here the ordinary PID controller was affected by change in load, but FOPID controller has no affect by the change in load. Furthermore, there is no overshoot when FOPID controller is applied whilst using ordinary PID controller, the speed significantly decreases during 5 and 8 period of time.

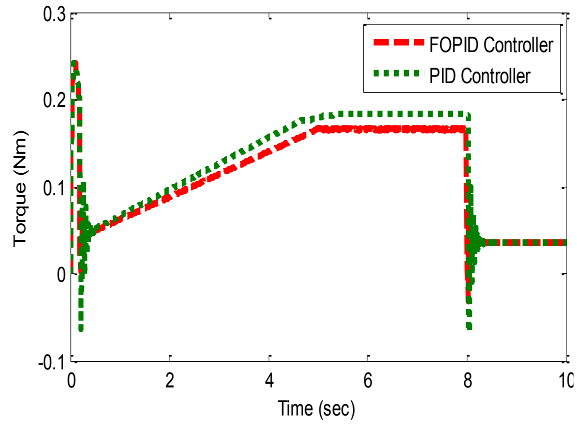

Figure 9: DC motor troque responses under load torque disturbance

CONCLUSIONS

Fractional order PID and ordinary PID controllers have been considered in this paper for controlling the speed of a separately excited DC motor. Performance of FOPID controller and classical PID controller has been verified through simulation using MATLAB/SIMULINK software package. From the simulation results, it can be concluded that the proposed FOPID controller improves the overshoot, rise time, settling time, good tracking of reference speed and maintaining the speed even while applying the load torque.

REFERENCES

[1] Dubey (2011), "Fundamental of Electrical Drives Fundamental of Electrical Drives", Narosa Publication, Second Edition.

[2] Aamir Hashim Obeid Ahmed (2013), "Optimal Speed Control for Direct Current Motors Using Linear Quadratic Regulator", SUST Journal of Engineering and Computer Science (JECS), Vol. 14, No. 3, pp. 32-38.

[3] Aamir Hashim Obeid Ahmed (2012), "High Performance Speed Control of Direct Current Motors Using Adaptive Inverse Control", WSEAS TRANSACTIONS on SYSTEMS and CONTROL, Issue 2, Volume 7, pp. 54-63.

[4] Akhilesh K. Mishra, Anirudha Narain (2012), "Speed Control of DC Motor Using Particle Swarm Optimization", International Journal of Engineering Research and Technology, Vol. 1.

[5] Aamir H. Obeid Ahmed (2012), "Performance Comparison of Sliding Mode Control and Conventional PI Controller for Speed Control of Separately Excited Direct Current Motors", SUST Journal of Engineering and Computer Science (JECS), Vol. 13, No. 2, pp. 74-80.

[6] Meshram and Rohit (2012), "Tuning of PID Controller using Ziegler-Nichols Method for Speed Control of DC Motor", IEEE-ICAESM, pp. 117-122.

[7] T. Chamsai, P. Jirawattana and T. Radpukdee (2010), "Sliding Mode Control with PID Tuning Technique: An Application to a DC Servo Motor Position Tracking Control", Energy Research Journal, Vol. 1 (2), pp. 55-61.

[8] H. Kim, I. Maruta, T. Sugie (2008), "Robust PID Controller Tuning Based on the Constrained Particle Swarm Optimization", Automatica, Vol. 44, Issue 4, pp.1104 -1110.

[9] Singhal, Padhee, Kaur (2012)," Design of Fractional order PID Controller for speed control of DC Motor", IJSRP, Vol.2, Issue 6.

[10] D. Cafagna (2007), "Fractional Calculus: A Mathematical Tool from the Past for Present Engineers", IEEE Industrial Electronics Magazine, Vol. 1, No. 2, pp. 117-122.

[11] Monje, Chen, Vinagre, Dingyü Xue, Vicente Feliu (2010), "Fractional-order Systems and Controls-Fundamentals and Applications", Springer-Verlag, London Limited.

[12] Oustaloup, Melchoir, Lanusse, Cois, and Dancla (2000), "The CRONE Toolbox for MATLAB", In Proceeding of the 11th IEEE International Symposium on Computer Aided Control System Design-CACSD, Anchorage, USA, pp 190-195.

[13] I. Podlubny (1999), "Fractional Order systems and $PI^{\alpha}D^{\lambda}$ controllers", IEEE Transactions on Automatic Control, Vol.44, No.1, pp208-214.

[14] C. Y. Wang (2013), "Study on Fractional Order PID Controller Parameter Tuning Method and Design", Jilin University.

[15] Shekher, Rai, Prakash (2012), "Tuning and Analysis of Fractional Order PID Controller", International Journal of Electronic and Electrical Engineering, Vol. 5, No. 1, pp 11-21.

[16] Karanjkar D. S., Chatterji s., Venkateswaran P. R (2012), "Trends in Fractional Order Controllers", IJETAE, Vol.2, Issue 3.

[17] S. Karad, S. Chatterji, Prasheel (2012), "Performance Analysis of Fractional-Order PID Controller with the Conventional PID Controller for Bioreactor Control", International Journal of Scientific and Engineering Research, Vol. 3, Issue 6.

[18] Padula, Visioli (2011), "Tuning Rules for Optimal PID and Fractional-Order PID Controllers", JPC, Vol. 21, pp. 69–81.

[19] F. Padula and A. Visioli (2010), "Set-point Weighting for Fractional PID Controllers", Proceedings of Fractional Differentiation and its Applications, Badajoz, Spain.

[20] A. Teplijakov, E. Petlekov, J. Pelikov (2011), "FOMCON Fractional Order, Modeling and Control Toolbox for MATLAB".