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ORIGINAL RESEARCH ARTICLE

TUNING RULES FOR FRACTIONAL ORDER PID CONTROLLERS FOR INDUSTRIAL PROCESSES: A CONCEPTUAL FRAMEWORK

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ABSTRACT

This paper presents a brief review of Fractional Order Proportional, Integral and Derivative (FOPID) controllers. The prominent tuning procedures are presented and a conceptual framework for a new design of efficient FOPID controller is presented. The presented framework is based on the concept of output feedback, where a threshold is applied on the output response before feeding its feedback to the comparator. The threshold output was compared with the reference to make a proper decision on when a new controller gain should be selected. This way, control effort will be minimized and the system can settle as fast as possible. This paper presents a brief study of Fractional Order Proportional, Integral and Derivative (FOPID) controllers with their prominent tuning procedures and an introduction to a conceptualize idea for a new tuning technique that can be adopted for efficient tuning this type of controllers... The presented framework is based on the concept of output feedback, where a threshold is applied on the output response before feeding its feedback to the comparator. The idea was to compare the applied threshold output with the reference so as to make a proper decision on when a new controller gain should be selected. The result would be a minimized control effort and thus making the system to settle as fast as possible.

1.0 Introduction

Fractional Order Proportional Integral Derivative (FOPID) Controller is expressed by fractional order differential equation where the fractional part of the integral and derivative can be a positive integer or zero (Lee and Chang, 2010). Control system response can be improved when the integral and derivative of a PID controller are expanded into fractional order form (Ismayil et al., 2014). Over the years, fractional order systems were approximated as integer order systems for easy analysis (Dingyu et al., 2006). Presently, there are many fractional order controllers available for solving fractional order problems such as the voltage-current relation of lossy transmission line (Zamani et al., 2009, Zhang et al., 2016, Chunna et al., 2005) The PID controllers are the most commonly used control techniques in industrial feedback application (Mishra et al., 2015). This is due to its simplicity of implementation and maintenance (Padula and Visioli, 2011). Fractional order PID controller is an extension of the Integer Order PID controller with two additional tuning knobs (Chunna et al., 2005, Padula and Visioli, 2011). These knobs include the three gains of the PID controllers along with the fractional part of the integral and derivative gain. This flexibility allows the design of a more robust control system than the integer order PID controller.

Also, the advancement in the knowledge of fractional calculus has led to a better mathematical description of the environment which makes it useful in many fields of science and engineering. Fractional calculus is concern with the study of integrals and derivatives of non-integer orders and nowadays becoming popular due to large number of researches that exploit its application especially in fractional order modelling and fractional order control theories (Zamani et al., 2009, Efe 2011). Fractional order modelling is a way of describing the physical behavior of a system through the use of partial differential equations. Fractional order system can be regarded as a direct extension of classical integer order system that can be modelled by a fractional order differential equation containing derivative of non-integer order (Monje, et al., 2010). There is wide range of operations that a fractional order system may offer especially in robust control application, which is one of the advantages of using fractional calculus. These characteristics will enable the design of controllers that can control a system in achieving robustness and for comparative fractional order controllers (Salawudeen et al., 2017, Jibril et al., 2016). As a result, fractional order controllers can provide many benefits in the control area especially for compensation of disturbances due to undesired nonlinearities and static distortion in the system which consequently improved the overall performance of the system (Monje, et al., 2010).

Among the various fractional order controllers, the FOPID have attracted the attention of many researchers because of its consequential flexibility to the designers more than that of the conventional PID controller structure as it has five parameters instead of the three for the PID (Kumar and Kumar, 2018, Muhammadikia and Aliasghary, 2019).

Parts of the paper are organized as follows: literature review is presented in section two. Section three present the overview of FOPID controller and section four presents the conceptual framework for the proposed tuning method.

2. Literature Review

Several researches like in (Sondhi and Hote, 2014, Liu, et al., 2017 and Padula and Visioli, 2011) had been conducted on different aspect of tuning the parameters of FOPID controllers. For example, (Sondhi and Hote, 2014) proposed an empirical tuning method for a new type of fractional controller known as Fractional Order Filter Proportional Integral Derivative (FOF-PID) controller. A procedure which was based on set point overshoot was employed to tune the controller. Simulation on various first order with time delay processes were carried out and correlations were derived to obtain the parameters of the controller. In Liu et al. (2017), a universal fractional order linear phase lead compensation multi-rate repetitive controller for pulse width modulated inverters was proposed. The idea is to provide a flexible selection of sampling frequency, fundamental frequency of the reference signal and down-sampling ratio in order to enhance effectiveness in applications. Multi-rate Repetitive Control (MRC) and Fractional Order Multi-rate Repetitive Control (FOMRC) schemes were used to achieve the design objectives. The effectiveness of the design was tested on a series of application examples of programmable AC power supplies with high tracking accuracy, low total harmonic distortion and good transient response. In a study by Padula and Visioli, (2011), a new practical tuning method for fractional order PID controller was proposed. The propose method uses the rule of thumb that engages loop shaping principles to achieve robustness against gain variation based on the flatness of the phase plot of the controller around the cross over frequency. The effectiveness of this method was validated experimentally using a precision planar positioning stage. Trivedi and Padhy (2020) introduced a new optimal tuning rule for a fractional order PID controller using an indirect design approach – 1(IDA-1). In this approach, the plant to be controlled was shifted in the frequency domain using a variable shifting parameter which helped in the setting of the robustness and tuning of the transient response of the frequency shifted process. The tuning rules were then designed for the new process and for accuracy, a valid range of the shifting parameter is proposed. The propose work is validated with some examples of stable and unstable processes. Some examples of stable and unstable processes were used to validate the proposed work. A practical experimental set up is also considered to test the effectiveness of the method. In a study, Nayak, et al. (2015) presented a FOPID controller to minimize the deviation in frequency of a single-area power system. Three types of turbines (non-reheat, hydro and reheat) were considered in the designed power system Three types of turbines namely; non-reheat, hydro and reheat turbines were considered in the design of the power system. The robustness of the designed method was verified via parameter variation. The optimum values of the FOPID controller gain were obtained on the integral error criterion where the value of either one of kp, ki or kd is arbitrary chosen and the other two were calculated. Results obtained reveal that the designed FOPID controller minimizes frequency deviation even in the presence of parameter variation. However, the design method minimized frequency deviation even for parameter uncertainties on a single area non-reheat turbine. For the reheat and hydro turbine, the transfer function has some unstable poles, as such; the designed method is only effective for non-reheat thermal system. The proposed method will be extended to multi-area network considering reheat turbine and physical constraints. Delassi et al. (2018), proposed a FOPID controller for load frequency control of two-area non-reheat thermal power systems. Particle swarm optimization was used to implement a tuning procedure for the FOPID controller. A comparative analysis of the controller showed the superiority of these approaches over other numerical based methods.

A tuning technique for FOPID controller using differential evolution algorithm has been proposed. The Integral of Squared Error (ISE) criterion was minimized as an objective function to obtained the all the gains of the FOPID controller that gives the minimum ISE. Results obtained when applied to load frequency control showed that the designed controller has an improvement when compared to simulation results for PI fractional D controller (PID^{μ}) and PID in terms of peak overshoots and settling time. In a research conducted by Mishra et al. (2017), a tuning method for FOPID controller using Social Spider Optimization algorithm (SSO) was utilized. The SSO based FOPID controller was applied to load frequency control using Integral Time Absolute Error (ITAE) as performance criterion. The results demonstrate that the FOPID controller based on SSO have a high ability in damping the frequency deviation and the deviation in tie-line power exchange for each power generation area. An optimal tuning of PID controller using a novel optimization algorithm named Smell Agent Optimization (SAO) was presented by Abba et al. (2022). The SAO which was developed to mimic the intelligent behaviors of an agent trailing a smell source was used to optimally select the Kp, Ki and Kd parameters of PID controller. The optimized PID was in turn used for speed control of direct current moto used for industrial applications. Jain and Hote (2018) studied an optimized FOPID and a Tilted Integral Derivative with Filter (TIDF) controller for a two-area multi-source power system. The parameters of PID, TIDF and FOPID controller were obtained using Differential Evolution algorithm and the Integral Time Absolute Error (ITAE) was minimized as the objective function. Finally, the model was investigated under various load conditions of parameter variation and time delay. Results obtained show that TIDF gave better transient response when compared against FOPID and PID controllers. Dastjerdi et al. (2019) developed a technique for load frequency control of power system using FOPID controller. The optimal values of the FOPID parameters were obtained using Big Bang Big Crunch (BB-BC) optimization algorithm and internal model control scheme. An IMC based PID controller was first designed for the power system. Then the gains of the FOPID controller were obtained using BBBC optimization algorithm while the gains of the PID controller first obtained was use to specify the bound on the solution space. Results obtained show a better performance than other recent designed methods from literature. Munoz et al. (2020) presented a simplified tuning for fractional order controllers using frequency domain characteristics. The tuning rules are based on the method of symmetrical optimum principles of Kessler. The paper has two parts, with first part presented the generalized tuning rules and the second part introduced the fractional order that offers solution for any desired closed loop performance measures. The proposed method was verified using numerical simulation and experimental results. For simulation, it includes relevant process that has integer order and fractional order transfer functions while for the experimental case, a simple mechatronics application, and basic loop control in production systems and DC motors were considered. The simulation results show that the desired performances were met. Liu et al. (2018) presented a simplified and direct tuning method for fractional order controllers using a graphical solution that tends to avoids solutions by nonlinear equations and avails the designer ways to solve control problem in a very intuitive way. The proposed fractional controllers were the FOPD and FOPI. The method was tested using servomotor position control of the soft robotic neck prototype mechanism. The tuning method would allow the designer to observe the parameter variation graphically and allow easy and fast re-tuning of the controller from the observed curves without the need to repeat the algorithm all over again. The result shows that the controllers exhibit a robust performance on the selected process. A novel tuning strategy for fractional order PID controller based on Bode's optimal loop shaping that is commonly used for LTI feedback systems was presented (Angel and Viola, 2018). Here, the controller parameters are tuned using a flat phase property and Bode's optimal reference model which will make the controlled system to be robust to gain variation with an achievable desirable transient performance under various control requirements. They presented three different examples of controlled plants to verify the effectiveness of the proposal and also carried out a robustness analysis of the controlled system to support the result. Ambreesh and Rajneesh (2018) who design a control system capable of tracking a parallel robotic manipulator type delta using both FOPID and IOPID controllers was presented. The MATLAB model of the Delta robot was built and used for the stages of identification, design and validation of the control strategies. Least squares algorithm is used to identify the dynamic model of the robot while a linearized model of the robot was obtained by using computed torque control strategy. From the linearized models, the two controllers were design to analyze the dynamical behaviors for many evaluation trajectories. From this, controllers' robustness is evaluated against external disturbances which are detriment to the performance index for the joint and spatial error, applied torque in the joint and the trajectory tracking. Result shows that the FOPID controller with the computed torque control strategy gives a better robust performance against the external disturbances that affects the tracking ability of the delta robot. Meneses et al. (2018), an easy tuning method for fractional order proportional integral controller (FOPI) to control a first order plus dead time process was presented. The design is subject to minimizing the integrated absolute error (IAE) for load disturbance rejection with a constraint on the maximum sensitivity. The parameters of the FOPI controller were optimized using genetic algorithm. The authors use wide range of processes with non-oscilatory and oscillatory characteristics to verify the effectiveness of the proposed method. The simulation results show that the level of robustness can be evaluated when considering the range of values of the order of the integral part and that of maximum sensitivity.

3. Fractional Order PID Controller

The fractional order PID controller popularly called FOPID is an extension of the traditional PID controller with some additional fractional integral and derivative parameters. For example, the traditional PID controller which is expressed as

$$C(s) = K_p + \frac{1}{s}K_i + K_d s \tag{1}$$

can be transformed into its fractional equivalent as:

$$F_C(s) = K_p + \left(\frac{K_i}{s^{\lambda}}\right) + K_d s^{\mu} \tag{2}$$

where K_p, K_i and K_d are the proportional, integral and derivative control gains of the controller. The parameters μ and λ are the fractional part of the derivative and integral gains respectively.

From eqn. (2), it can be observed that the FOPID controller has the traditional three tuning parameters of PID in the form of K_p, K_i and K_d and λ, μ which are the fractional part of the integral and derivative gain respectively.

When $\lambda = \mu = 1$, an Integer Order PID controller is obtained. When $\lambda = \mu = 0$, an integer order promotional controller is obtained, when $\lambda = 0$ and $\mu = 1$, an Integer Order promotional derivative controller is obtained, and for $\lambda = 1$ and $\mu = 0$, an Integer Order proportional integral controller is obtained. As a demonstration, these configurations of the FOPID controller are showed in Figure 1.

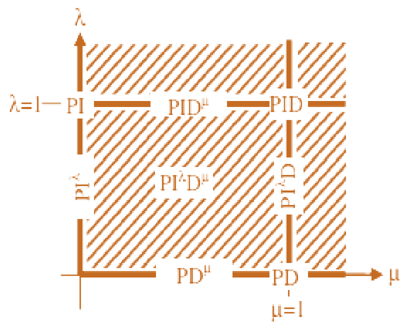

Figure. 1: FOPID Controllers Illustration

Since the integer order PID controller has two less tuning parameters than the FOPID, the FOPID controller gives a better chance to design a more robust controller than the IOPID controller particularly when a fractional system is to be controlled. The general block diagram representation of the FOPID controller is given in Figure 2

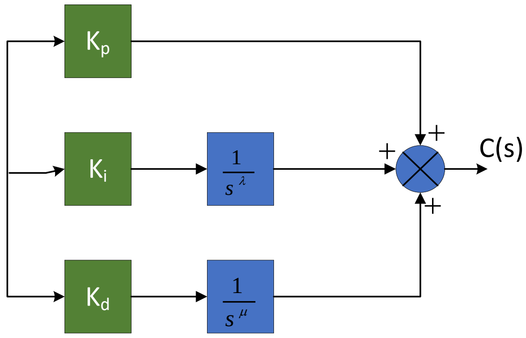

Figure 2. Block Diagram FOPID Controller

From Figure 2, the controller force obtained from the output the fractional order controller is denoted as C(s). Though, there is no definite empirical values defined for the fractional parameters of the FOPID controller, some literatures have showed that values between the range of 1 and 2, appears suitable and optimal (Meneses et al., 2018).

4. Conceptual Framework

This section describes a new ideology which could be effective for tuning the parameters of FOPID controller as other prominent tuning methods. The generalized tuning procedures for tuning controllers are conceptualized in Figure3.

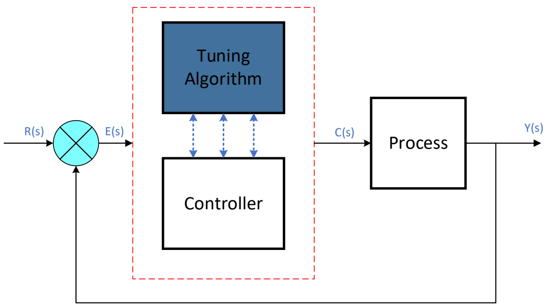

Figure 3. Conceptualized Conventional Controller Tuning

Usually, the tunning algorithm shown in Figure 3 is the codified procedure for intelligent selection of the controller parameters. If the boundary conditions of the parameters are known, the selection is done as in optimization where the objective is to minimize an error expressed as cost function. This cost function is solved using the analytical or computation optimization procedures. The computational optimization tuning procedures are heuristics or metaheuristic based, where the algorithm seeks to obtain the minimum of the objective function. In addition to the analytical methods been computational costly and requiring a lot of control effort, the computational optimization approach only considers the margin between the output and the input. The characteristic and performance requirements of the systems are not considered explicitly. To address these challenges, this paper presents a new idea for tuning the parameters of controllers using output feedback thresholding technique. The best knowledge of the researcher, this idea is novel and has not been reported in literature. The proposed controller can be applied to industrial processes and practical problems requiring PID or FOPID controller. This idea is demonstrated in Figure 4.

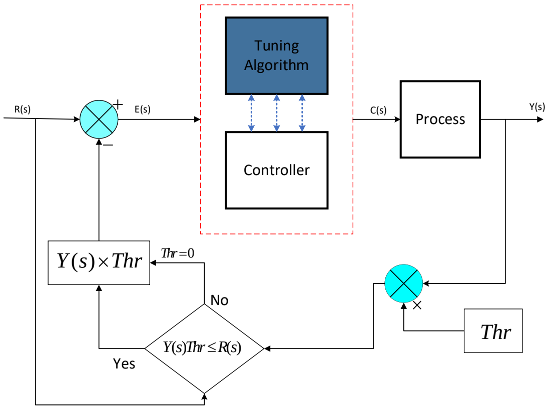

Figure 4. Proposed Tuning Technique

From Figure 4, the *Thr* is an output threshold defined by the controller designer. The threshold output is used to check the performance of the controller in comparison with the reference input. This information is used to check the closeness of the output to the reference input before the cost function is computed. This way, the output whose reference is outside the threshold values is not computed. Among other advantages, this new idea is expected to provide a good reference tracking with high precision using the output information

Conclusion

This paper presents a brief review of fractional order proportional integral derivative controller popularly called the FOPID controller. The tuning methods adopted by previous studies were discoursed and a conceptual idea for tuning the FOPID controller is presented. The presented idea employs the threshold of the output response as feedback to select the right values of the controller gains. This idea is novel because the output feedback thresholding technique has not been reported in the past and will be implemented in the next research. Various first and second order plus dead time system will be used to evaluate the performance of the tuning rules using performance criteria like maximum overshoot and settling time. When implemented, the controller will also be applied to various real life control systems like the DC motor. This study has extended the capacity that tuning of fractional order controllers has great potential in which it can accommodate new ideas that can provide additional quality to enhance control system performance

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