



Fractional order PID controller for power control in perturbed pressurized heavy water reactor



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ABSTRACT

This paper presents an interval fractional-order proportional integral derivative (INFOPID) controller design for the power control of a highly nonlinear Pressurized Heavy Water Reactor (PHWR) under step-back condition. A single robust INFOPID controller is designed utilizing stability boundary locus method for eight nuclear reactor models considering eight interval conditions for each reactor model of the PHWR. The interval models have been obtained using Edge theorem. Simulation results show that the proposed INFOPID controller applied for active step-back in the reactor gives an efficient set point tracking performance, defined for variation in initial power level or control rod drop. The performance of the proposed INFOPID controller is evaluated using different integral error criterion by comparing its performance with existing methods in the literature. The proposed controller is found to give better results than the existing techniques.

1. Introduction

The pressurized heavy water reactors (PHWR) are an extremely vital part of the present day power generation industry. The PHWR is a highly nonlinear system whose parameters fluctuate with time as a function of initial reactor power and control rod level (Stacey, 2007). Rapid drop of the bulk power in a nuclear reactor is usually required to be done under load following operations or under some unusual operating conditions. For the diminution of global power in the Indian PHWRs the control rods are pushed into a pre-specified level inside the reactor and simultaneously the set point of the stipulated power is gradually decreased. This operation is known as step-back (Saha et al., 2010) which is governed by the reactor regulating system (RRS). In the RRS with passive step-back, proportional controllers are very commonly used to control the reactor power. However, this technique results in a power undershoot and also produces a slow response which is not desirable. Also, at very low power undershoot the PHWR may get poisoned out due to thermal neutron flux reduction (Das and Gupta, 2011). Therefore, it is very important to have an effective and robust control algorithm to regulate the step back mechanism in a PHWR.

A number of PID controllers designs have been reported for different linearized models of the PHWR at different operating points (Saha et al., 2010; Das and Gupta, 2011; Liu et al., 2009). Liu et al. (2009) proposed a fuzzy PID controller designed differently for each operating point to cope with the reactor non-linearities. However, it may not prove to be an efficient solution if there is a wide variation in operating

point and also the stability constraints are not guaranteed. Talange et al. and Shimjith et al. (2010) developed mathematical models of large PHWRs and linearized the nonlinear equations around a definite steady-state operating point to design the controllers. Saha et al. (2010) proposed an active step back mechanism with robust controller which is a combination of FO phase shaper and a LQR tuned PID. However, improvements in robustness and high frequency noise rejection are obtained at the cost of minor increase in sensitivity function at low frequency. Das and Gupta (2011) proposed a robust FOPID controller using frequency domain tuning technique based on solving of simultaneous non-linear equations. The reduced order models have been obtained in fractional form giving minimum modeling error. However, an undershoot is obtained at all operating points. Das et al. (2013) also proposed a continuous order PID like controller using optimized pole assignment like approach. Bhase and Patre (2014) proposed a robust FOPI controller for stabilizing the nonlinear PHWR using the stability domain boundaries in parameter plane for the fractional order plant. Although, the proposed controller ensures the iso-damped time response without any undershoot for all the reactor models of type Non Integer Order plus Time Delay-II, but it increases the settling time of the system.

Although, the recent research literature illustrates various controller design techniques for the step back condition of PHWR. However, most of the controllers face performance precincts while working in an uncertain or varying environment. In nearly all real time complex systems, the controller needs to cope with two most important issues i.e.

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parameter uncertainty and external disturbances. Although, the control algorithms formulated using fixed values of the system parameters, reveal a certain level of robustness, however, if the parameter values of the system go beyond a certain limit due to some external disturbance or some abnormal system behaviour, the nominal controllers (i.e., controllers designed using fixed parameter values) may at times fail to stabilize the system or to maintain the system output at the required level. Therefore, it is necessary to have a controller design technique which can stabilize the system and at the same time exhibit good disturbance rejection and good set point tracking for a bigger range of parameter values.

According to the recent control system literature, many techniques like LMI, QFT, H_∞ , pole placement, etc. (Purohit and Nataraj, 2015; Bhattacharya et al., 1993; Bondia et al., 2004; Tu and Ho, 2012) exist for designing the controller for interval systems. However, most of the techniques are either mathematically intricate or do not give very efficient performance under the varying operating conditions for large and complex systems. Edge theorem is a widely used method for testing the stability of fractional order interval systems (Tan et al., 2009). This technique requires 2^n polynomials for n parameters for testing the stability of the fractional order interval plants.

In recent years, the fractional order control has come up as a very competent control algorithm for the systems experiencing parametric improbability and outside disturbances (Vinagre et al., 2007; Monje et al., 2008; Hamamci and Koksul, 2010; Padula and Visioli, 2016; Li et al., 2016; Liu et al., 2016; Talange et al., 2006; Bhase and Patre, 2014; Saha et al., 2010; Sagar et al., 2016). The different advantages of fractional order control are discussed in Sondhi and Hote (2012). The thriving performance of fractional controllers to a wide range of applications has motivated the authors to think of implementing the fractional order control algorithm to the interval model of the PHWR as well Saxena et al. (2015), Sondhi and Hote (2014a,b,c), Sondhi and Hote (2015), Ostalczyk and Stolarski (2009), Calderón et al. (2006)). Hence, in this paper, a technique has been proposed in which the FOPID controller is designed for an interval fractional order system model using edge theorem. Using this technique, a range of parameter values have been considered for designing a controller rather than any specific value. Such controllers are able to stabilize the system for all the values of the system parameters within the chosen range. At the same time, these controllers are capable of maintaining the system output close to the required level. Thus, this technique helps us in incorporating a higher level of robustness for a larger range of variations in system parameters. Upto the best of author's knowledge, there is no technique available in the literature for the design of fractional order controller for the interval model of PHWR based on edge theorem.

This paper comprises of 6 sections. The objectives and preliminaries of fractional order control, Edge theorem and a concise introduction of interval model of PHWR are discussed in Section 2. The Section 3 elaborates the proposed FOPID controller design technique for the interval systems, Section 4 gives the simulation results while the performance analysis of the proposed technique in comparison to the existing techniques is shown in Section 5, and the conclusion of the paper is discussed in Section 6.

2. Objectives and preliminaries

The purpose of this work is to suggest a fractional order PID controller design method for the fractional order interval system using the Edge theorem. The main objectives can be stated as:

- Design of FOPID controller using Edge theorem, for the interval model of pressurized heavy water reactor.
- Optimization of the controller parameters using the integral error criterion.
- Finally, the evaluation of the performance of the proposed controller using the integral error criterion under different interval conditions

as well as different step back conditions

In the field of control system the use of fractional calculus started gaining popularity when the fractional order PID controller was proposed in 1999 (Sondhi and Hote, 2012). It can be expressed mathematically as

$$C(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu \quad (1)$$

where, μ and λ can take any values within the range (0,2).

This range of values for μ and λ is selected to keep the controller structure comparable to the conventional PID controller. If the values exceed this range, although the controller would be valid, but not structurally comparable to conventional PID controller. Since, the conventional PIDs are very widely used and easily comprehensible to the engineering community, in this paper, the structure of the proposed controller has been kept in close alignment with the conventional PID controllers.

2.1. Edge theorem

For designing an effective control system the two most important components are stability testing and controller design. For both these tasks it is important to have a mathematical model that closely describes the real time dynamic behavior of the system. However, in most of the cases, either the precise values of the system parameters are not known or the values of system parameters are not fixed rather they keep varying within a certain range. Therefore, often it is not possible to obtain a fixed mathematical model of the physical system. In such cases the systems are modeled in interval form. In Tan et al. (2009), the author has proposed the edge theorem for testing the stability of fractional order interval systems. In this theorem, 2^n polynomials are required for testing the stability of polynomial having n uncertain parameters. Consider a fractional order interval polynomial family represented by

$$P(s,q) = p_0 s^{\alpha_0} + p_1 s^{\alpha_1} + p_2 s^{\alpha_2} + \dots + p_n s^{\alpha_n} \quad (2)$$

where $\alpha_0 < \alpha_1 < \dots < \alpha_n$ are generally real numbers, $q = [p_0, p_1, \dots, p_n]$ is the uncertain parameter vector and uncertainty box is $Q = \{q: p_i \in [\underline{p}_i, \overline{p}_i], i = 0, 1, 2, \dots, n\}$

Here $\underline{p}_i$ and $\overline{p}_i$ are specific lower and upper bounds of i^{th} perturbation p_i respectively. The 2^{n+1} edge polynomials for $P(s,q)$ can be written as

$$\begin{aligned} v_1(s) &= \underline{p}_0 s^{\alpha_0} + \underline{p}_1 s^{\alpha_1} + \underline{p}_2 s^{\alpha_2} + \dots + \underline{p}_n s^{\alpha_n} \\ v_2(s) &= \overline{p}_0 s^{\alpha_0} + \underline{p}_1 s^{\alpha_1} + \underline{p}_2 s^{\alpha_2} + \dots + \underline{p}_n s^{\alpha_n} \\ v_3(s) &= \underline{p}_0 s^{\alpha_0} + \overline{p}_1 s^{\alpha_1} + \underline{p}_2 s^{\alpha_2} + \dots + \underline{p}_n s^{\alpha_n} \\ &\vdots \\ v_{2^{n+1}}(s) &= \overline{p}_0 s^{\alpha_0} + \overline{p}_1 s^{\alpha_1} + \overline{p}_2 s^{\alpha_2} + \dots + \overline{p}_n s^{\alpha_n} \end{aligned}$$

According to edge theorem if all these polynomials are stable, then the original family of polynomials $P(s,q)$ is stable under all possible given perturbed conditions. This idea can further be extended to design of fractional order controllers. In this paper, an effort has been done to use Edge theorem for designing FOPID controller for the problem of power control in PHWR.

2.2. Interval model of PHWR

The reactor power in Indian PHWR is controlled by the three components in reactor regulating system (RRS) viz. control rods (CR), adjust rods (AR), and zone control compartments (ZCC). The fast startup of reactor is dealt by ARs. Coarse control is provided by CRs and fine control of power load is provided by ZCCs. When the PHWR is required to work under varying load conditions or under some abnormal conditions, the bulk power of the nuclear reactor is required to

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