Vol. 06, No. 2 (2024) 753-760, doi: 10.24874/PES06.02A.002

Proceedings on Engineering Sciences

www.pesjournal.net

# SOFT COMPUTING APPROACH FOR OPTIMAL POWER CONTROL IN LARGE-SCALE NUCLEAR POWER REACTORS UNDER ADVERSE OPERATING CONDITIONS

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Received 08.09.2023.
Received in revised form11.01.2024.
Accepted 21.02.2024.
UDC – 681.5.015.23

Keywords:

*Fractional Order Controller, Grey Wolf Optimization, Model Order Reduction, Nuclear Reactor, Optimization*

A B S T R A C T

*Nuclear reactors, as a class, exhibit nonlinear and higher-order system characteristics, posing a consistent challenge for researchers in the design of effective controllers. The specific focus of this study is on the Pressurized Heavy Water Reactor (PHWR), a representative example of such intricate systems. Given the inherent complexity of higher-order system dynamics, this work tackles the challenge by employing a reduced-order modeling approach, capturing the essence of the original system's behavior. In the context of this research, a novel approach is taken in the design of a controller for the PHWR system. The method involves the use of an optimization-based Fractional Order Proportional Integral Derivative (FOPID) controller tailored for the lower-order model of the PHWR. The reduced-order model is derived through the application of the Balanced Truncation method, which enables the creation of a simplified yet representative model that faithfully emulates the behavior of the original higher-order system. The optimization of the FOPID controller parameters is achieved through the adoption of the Grey Wolf Optimization (GWO) algorithm. To substantiate the efficacy of the proposed controller, a comprehensive performance analysis is conducted. Various performance indices are employed to evaluate the controller's robustness and overall effectiveness in regulating the PHWR system.*



## 1. INTRODUCTION

Power generation through Nuclear Reactors has garnered significant attention in numerous developed nations. The impetus behind this keen interest lies in the inherent advantage that electricity produced by Nuclear Reactors does not contribute to environmental pollution. A noteworthy illustration of this commitment to clean energy is found in the Canada Deuterium Uranium (CANDU) reactor. This specific reactor model falls under the category of Pressurized Heavy Water Reactors (PHWR) and plays a crucial role in electricity generation within Canada.

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The operational dynamics of the PHWR are intricately designed to ensure efficient and sustainable power production. In its functioning, the PHWR relies on uranium as its primary input material. This uranium undergoes controlled nuclear reactions, releasing a substantial amount of energy. Notably, the heavy water serves a dual purpose within the reactor system. Primarily, it functions as a coolant, absorbing and dissipating the heat generated during the nuclear fission process. Simultaneously, it acts as a moderator, regulating the speed of neutrons to sustain a controlled chain reaction. The synergy between uranium and heavy water in the CANDU reactor exemplifies a sophisticated engineering solution for electricity generation. The absence of greenhouse gas emissions during the energy production phase aligns with the global pursuit of sustainable and environmentally friendly power sources. As nations strive to meet their energy demands while mitigating the impact on the environment, Nuclear Reactors like the CANDU PHWR stand as a testament to technological innovation and a commitment to cleaner energy alternatives.

Although, Nuclear reactor-based power generation has above-mentioned benefits but with these benefits comes a need for reliable control strategy to achieve effective power control. While in operation, sometimes a need arises to reduce the output power of the reactor in a very short period. This phenomenon is known as step-back condition (S. Saha et al, 2010). This required power reduction can be easily achieved conventionally by inserting the control rods deep inside the reactor (S. Saha et al, 2010). But these traditional methods depend on many physical parameters such as gravity, the level of control rods insertion, human operator, to name a few. Therefore, the focus in this work is to design a robust control strategy which can provide effective power control under the step-back condition and, in this process, improve the overall system's performance.

In order to design a controller for any process, a reliable mathematical model is required. As Nuclear systems are quite complex in nature, the mathematical models for these systems are of high order (S. Saha et al, 2010; S. Das and A. Gupta, 2011; C. Liu et al., 2009; Vineet Vajpayee et al., 2021). The control and analysis for these types of systems is not easy as the order of these models is very high, which, in turn, requires rigorous mathematics for design and analysis. In such a situation, Model Order Reduction (MOR) are used to simplify and approximate high order and complex dynamical system (L. Fortuna, 1992). After obtaining the reduced order approximation of the high order model, the design of the controller can be performed with a relative ease. MOR techniques are generally categorized into frequency and time domain-based methods. In the literature, there are numerous MOR methods. Every method has its benefits and drawbacks. Based on the problem at hand, a particular MOR method is selected and applied to get the approximated model of a high order system. Balanced Truncation is used in this work to approximate the order of the PHWR system. Balanced truncation is very important method of model order reduction and talking about it having two parts, first one is balancing the dynamical system and the other is truncation some state variables for finding a reduced system has the same properties like the original one, such as, stability and conserve most of the original system energy. As a result, the mathematical complexity associated with the controller's design is drastically decreased. After obtaining the simplified model for the system the next task is to design a controller. The selection of the controller is done based on many factors such as, disturbance rejection capability, handling of parametric uncertainty, the robustness it provides, etc. A variety of control strategies are available in the literature. Out of all these controllers' Proportional Integral derivative (PID) controller is the most popular. Despite its wide acceptability, PID controllers have some shortcomings such as poor disturbance rejection, ineffective handling of parametric uncertainty, etc. Therefore, in this work a better controller strategy is adopted which is known as Fractional Order PID (FOPID). FOPID controllers provide additional flexibility in design as they have five degrees of freedom to be tuned whereas PID had only three (I Podlubny, 1999; S. Das, 2011; S. E. Hamamci, 2007). Many researchers have created FOPID controllers for use in a variety of industrial applications which shows the versatility and wide acceptance of this type of control strategy (R. Lamba et al. 2020; P. Shah and S. Agashe, 2016; S. Sondhi, and Y.V. Hote 2014, O. Safarzadeh and O. Noori-kalkhoran, 2021). The advantages of the FOPID controller over other available control strategies are addressed in (Sondhi, and Y.V. Hote, 2012). A variety of control strategies has been designed, tested, and implemented for power control of PHWR system. In (S. Das and A. Gupta, 2011) a FOPID controller using frequency domain tuning methods was designed for a fractional However, undershoots were observed in this design under operating conditions. Patre et al. created a FOPI controller for the PHWR system's nonlinear model in (S. S. Phase and B. M. Patre). The stability boundary locus method was used to find the unknown controller parameters. However, the overall design suffers from a long settling time in this approach. To meet the design specifications, D. K. Arif (2012) used a Non-Integer Order Plus Time Delay (NIOPTD) model of nuclear plant to design a FOPID controller. The controller performed admirably across a wide frequency range, with no undershoots. The objectives of the current study can be summarized as follows:

1) Determine reduced order system using Balanced Truncation Method:
    - Employ the Balanced Truncation method to derive a reduced-order model for the Pressurized Heavy Water Reactor (PHWR).

- Ensure that the reduced-order model accurately replicates the dynamic response of the original higher-order system.
- Validate the fidelity of the reduced-order model through comparative analysis with the original system's responses under various conditions.

2) Design FOPID Controller for the Reduced Order System:
    - Develop a Fractional Order Proportional Integral Derivative (FOPID) controller specifically tailored for the reduced-order model of the PHWR.
    - Ensure the controller design addresses the unique dynamics and characteristics of the reduced-order system.
3) Tuning Controller's Parameters with GWO Optimization Algorithm:
    - Apply the Grey Wolf Optimization (GWO) algorithm to fine-tune the parameters of the FOPID controller.
    - Optimize the controller parameters to enhance the performance of the reduced-order system, considering factors such as stability, response time, and robustness.
4) Performance Analysis based on Performance Indices:
    - Conduct a thorough analysis of the FOPID controller's performance using various performance indices.
    - Evaluate performance based on metrics such as Integral Square Error (ISE), Integral Absolute Error (IAE), and Integral Time Absolute Error (ITAE).
    - Compare the performance of the FOPID controller with the original system's response and potentially with other control strategies or benchmarks.

The rest of the paper is organized as follows:
Section 2: This section provides an exhaustive exploration of the Model Order Reduction (MOR) of the Pressurized Heavy Water Reactor (PHWR) system. The Balanced Truncation method is intricately detailed, shedding light on its application and relevance to the PHWR system.

Section 3: Here, the focus shifts to the design and implementation of the optimization-based proposed Fractional Order Proportional Integral Derivative (FOPID) controller. This section not only outlines the conceptual framework of the FOPID controller but also delves into the specific steps involved in the application of the Grey-Wolf optimization algorithm. This algorithmic approach is crucial for optimizing the parameters of the FOPID controller, and its procedural intricacies are expounded upon.

Section 4: The fourth section is dedicated to the presentation of simulation studies and a comprehensive analysis of the performance of the system. Through detailed simulations, the effectiveness and efficiency of the proposed FOPID controller are evaluated, providing valuable insights into its practical application within the context of the PHWR system.
Conclusions: The concluding section encapsulates the key findings and takeaways from the study. It serves as a summary of the research, highlighting the significance of the MOR, the design and implementation of the FOPID controller, and the outcomes of the simulation studies.

## 2. ORDER DIMINUTION OF PHWR SYSTEM

In this work, a PHWR system is considered from [S. Saha et. al 2010]. Four different high order transfer functions of PHWR system for corresponding operating conditions are tabulated below. These operating conditions depicts the different levels of control rods insertion into the reactor of PHWR system. For example, shows the transfer function for the operating condition in which the level of control rod insertion is up to $P_{100}^{30}$ , and the corresponding output power of the reactor is 100%. As for $P_{100}^{30}$ operating condition, the insertion level of rods is the least among all the other operating conditions, the power control is hard to achieve on this case. Therefore, the controller design is performed for this operating condition only.

$$P_{100}^{30} = G_1 = \frac{44.79s^5 + 8408s^4 + 7.687\times10^4 s^3 + 8.42\times10^6 s^2 - 2.561\times10^7 s + 1.336\times10^7}{s^6 + 12.31s^5 + 1088s^4 + 6624s^3 + 5.75\times10^4 s^2 + 7.683\times10^5 s + 6.946\times10^4}$$

$$P_{90}^{30} = G_2 = \frac{-81.59s^5 + 8625s^4 - 2.028\times10^4 s^3 + 9.119\times10^6 s^2 - 2.544\times10^7 s + 1.682\times10^7}{s^6 + 17.41s^5 + 1129s^4 + 9406s^3 + 5.397\times10^4 s^2 + 9.21\times10^5 s + 9.474\times10^4}$$

$$P_{80}^{30} = G_3 = \frac{22.75s^5 + 9232s^4 + 6.87\times10^4 s^3 + 7.943\times10^6 s^2 - 2.047\times10^7 s + 1.4\times10^7}{s^6 + 14.49s^5 + 1101s^4 + 7680s^3 + 5.278\times10^4 s^2 + 8.547\times10^5 s + 8.839\times10^4}$$

$$P_{70}^{30} = G_4 = \frac{-61.92s^5 + 9106s^4 - 1.907\times10^4 s^3 + 7.272\times10^6 s^2 - 2.017\times10^7 s + 1.215\times10^7}{s^6 + 15.31s^5 + 1105s^4 + 8861s^3 + 5.144\times10^4 s^2 + 9.169\times10^5 s + 8.911\times10^4}$$

This section gives a detailed description for the order reduction method for the system under consideration. The higher order transfer function of the PHWR system is known to be unstable. Thus, it is first separated into the stable and unstable parts. Then, Balanced realisation method is used to obtain the lower order model for the stable transfer function, and the unstable part is retained.

The general idea of balanced truncation method is to neglect the original states that are difficult to control, i.e., require a large amount of control energy, and states that are difficult to observe, i.e., produce a small observation energy. Hopefully, this would lead to a system that is of lower order and retains the important dynamic behaviour of the original system. Finally, both these parts are combined to get the overall reduced order model. PHWR system to be of the form,

$\bar{G}(s) = \bar{C}(sI - \bar{A})^{-1}\bar{B} + \bar{D}$ and its representation in the state-space to be as:

$$\left.\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned}\right\} \qquad (1)$$

here, $x \in \mathbb{R}^n, u \in \mathbb{R}^m, y \in \mathbb{R}^r$ represents the states, inputs and outputs of the system under consideration. In addition, the conditions of controllability and observability are satisfied. To obtain the system's lower order model, Hankel Singular Values (HSVs) analysis is performed. HSV analysis provides an idea about the energy contained by the states of a system (D. Kumar and S. K. Nagar, 2014; J. C. Lagarias et. al, 1998). Using this analysis, the states containing the less energy can be identified and then truncated. consequentially, reducing the order of the system under consideration. It is clear from the figure 1.

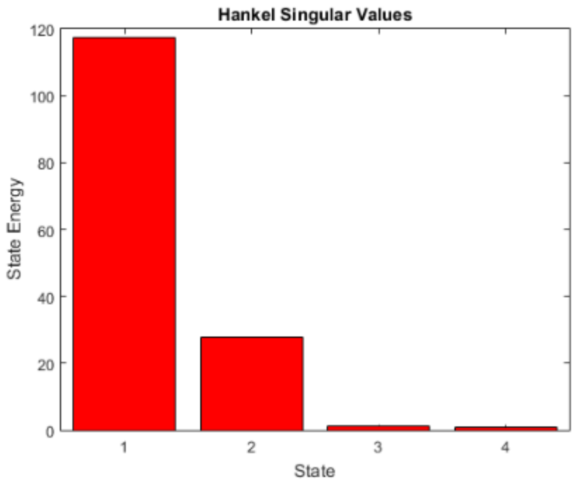


**Figure 1**. Hankel singular values.

**Step 1**: Separate the transfer function in stable and unstable part.

**Step 2**: Find the simplified model of the stable part Gs(s). Then, by solving the following Lyapunov equations, determine the controllability and observability gramians, $C_G$ and $O_G$ as:

$$A_s C_G + C_G A_s^T = -B_S B_S^T \qquad (2)$$

$$A_s O_G + O_G A_s^T = -C_S C_S^T \qquad (3)$$

Calculate the Cholesky factors $L_C$ and $L_o$ of $C_G$ and $O_G$

$$C_G = L_C L_C^T \ , \ \ O_G = L_O L_O^T$$

Determine the singular value decomposition of the matrix $L_O^T L_C$, such that,

$$L_O^T L_C = U \sum V_T \qquad (4)$$

Then compute, where, $\sum = diag\left(\sigma_1, \sigma_2 .....\sigma_n\right)$, the decreasing positive numbers $\sigma_1 \geq \sigma_2 .... \geq \sigma_n$ are Hankel Singular Values.

$$\sqrt{\sum} = diag\left(\frac{1}{\sigma_1}, \frac{1}{\sigma_2} ...... \frac{1}{\sqrt{\sigma_n}}\right) \qquad (5)$$

Then, $T = L_C V \dfrac{1}{\sqrt{\sum}}$, Here, transformation matrix $T$ ensures that the controllability gramians are diagonalized and equal.

Then the matrices representing the balanced realization can be written as,

$$\tilde{A} = T^{-1} A_S T \qquad \tilde{B} = T^{-1} B_S \qquad \tilde{C} = C_S T$$

$$\tilde{A} = \begin{pmatrix} A_R & A_{12} \\ A_{21} & A_{22} \end{pmatrix}, \tilde{B} = \begin{pmatrix} B_R \\ B_2 \end{pmatrix}, C = \begin{pmatrix} C_R & C_2 \end{pmatrix}$$

States with smaller numerical values of HSVs are truncated and the following is obtained,

$$G_R(s) = C_R (SI - A_R)^{-1} B_R$$

*G(s)* represents the high order model and, $G_s(s)$ and $G_{US}(s)$ are its stable and unstable parts, respectively.

$$G(s) = G_{Stable}(s) + G_{Unstable}(s). \qquad (6)$$

Balanced Realization method is used to obtain the lower order model of the stable part of the PHWR system. On the other hand, the unstable part is simply retained. Finally, to obtain the overall low order model of the system under consideration, retained and lower order model of the stable part are combined.

$$G_R(s) = G_{reduced}(s) + G_{unstable}(s). \qquad (7)$$

(Here, $G_{reduced}(s)$ represents the reduced part of the stable part, $G_{unstable}(s)$ shows the retained unstable part and overall reduced order model is given by $G_R(s)$.

$$G(s) = \frac{1.336\times10^7 - 2.561\times10^7 s + 8.42\times10^6 s^2 + 7.687\times10^4 s^3 + 8408 s^4 + 44.79 s^5}{6.946\times10^4 + 7.683\times10^5 s + 5.75\times10^4 s^2 + 6624 s^3 + 1088 s^4 + 12.31 s^5 + s^6}$$

Transfer function is decomposed into the stable and unstable parts using (8) as:

$$G_{Stable}(s) = \frac{-493.5s^3 - 3741s^2 - 4.946\times10^5 s + 1.4706\times10^5}{s^4 + 15.93s^3 + 1061s^2 + 9122s + 821.5},$$

$$G_{US}(s) = \frac{1785 + 538.3s}{84.56 - 3.623s + s^2}.$$

The lower order model obtained after using balanced truncation method is the following:

$$G_{Reduced}(s) = \frac{551.4s^2 + 1768s + 1209}{s^3 - 3.567s^2 + 84.36s + 4.73}.$$

Figure 2 shows the fair comparison of the open-loop step responses for the original and reduced model to show the good approximation of the high and lower order model of PHWR. It is clear from the Fig. 2 that both the responses are very close which validates that the lower order model, in fact, retains almost all the characteristics of the system.

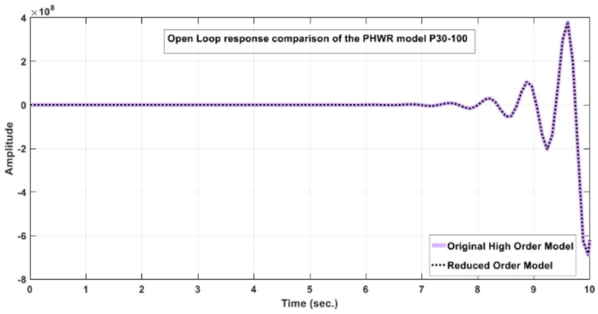


**Figure 2**. Open-loop response for the reduced and original system.

## 3. PROPOSED FRACTIONAL ORDER CONTROLLER

The FOPID controller is the expansion of the conventional PID controller based on fractional calculus. For many decades, PID controllers have been very popular in industries for process control applications. Their merit consists in simplicity of design and good performance, such as low percentage overshoot and small settling time (which is essential for slow industrial processes). Owing to the paramount importance of PID controllers, continuous efforts are being made to improve their quality and robustness. In the field of automatic control, the fractional order controllers which are the generalization of classical integer order controllers would lead to more precise and robust control performances. Though it is reasonably true, that the fractional order models require the fractional order controllers to achieve the best performance, in most cases the fractional order controllers are applied to regular linear or nonlinear dynamics to enhance the system control performances. The mathematical representation of the FOPID controller is given below in (8).

$$u(t) = k_P e(t) + k_I D_t^{-\lambda} e(t) + k_D D_t^{\mu} e(t) \qquad (8)$$

In Laplace domain the above equation becomes as given below,

$$G_{Controller}(s) = k_P + k_I s^{-\lambda} + k_D s^{\mu} \qquad (9)$$

here $k_P, k_I, k_D, \lambda$ and $\mu$ are the controller parameters.

As it can be seen from the above equation, five parameters of controller are required to be tuned in order to get the complete controller design ISE is used to formulate the objective function. Fig. 3 depicts a pictorial representation of the structure of unity feedback closed loop system with the designed FOPID controller. The GWO algorithm is used to find the best values. The obtained optimization based FOPID controller is given in (10) below:

$$G_C(s) = \frac{0.0082s^{0.9098} + 0.0492s^{1.6155} + 0.1499}{s^{0.9098}} \qquad (10)$$

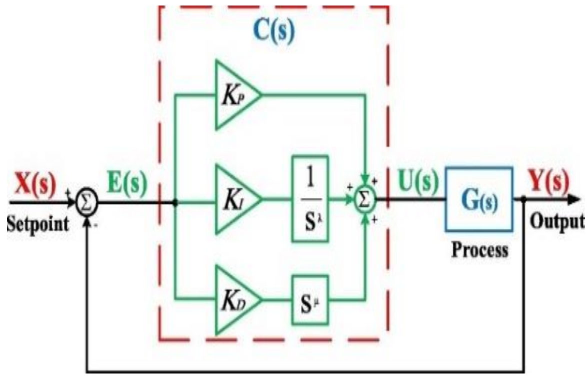


**Figure 3**. Structure of control scheme

### 3.1 Grey wolf optimization (GWO) algorithm

Recently, Faris et al. (2018) reviewed the scientific applications of GWO. They reported that GWO had shown promising results in a wide variety of optimization problems. The high degree of GWO success in dealing with optimization problems in the literature could be due to the impressive characteristics of this method over other swarm intelligence methods. This review highlights that GWO requires no derivation information of the search space, and the algorithm also has only a few parameters. Besides, GWO is scalable, flexible, easy to use, and straightforward. The algorithm benefits from a balance between exploration and exploitation through the search process, which results in an excellent convergence. Thus, the GWO has attracted the attention of researchers in various scientific and engineering fields.

GWO algorithm is a meta-heuristic optimisation algorithm which is based on the hunting and leadership behaviour of grey wolves. It is one of the latest and advanced optimisation algorithms which has been extensively used in many areas and applications, including control systems. In this algorithm, grey wolves are taken to be at the peak of the food chain. Wolves are graded into four categories which are Alpha, Beta, Delta and Omega. This is shown in Figure 4.

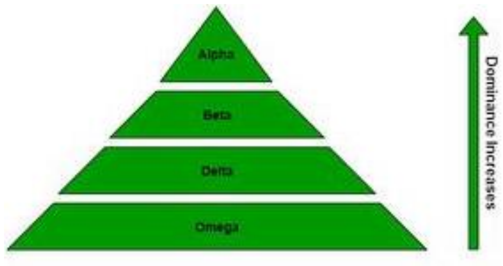


**Figure 4.** Dominance of grey wolves

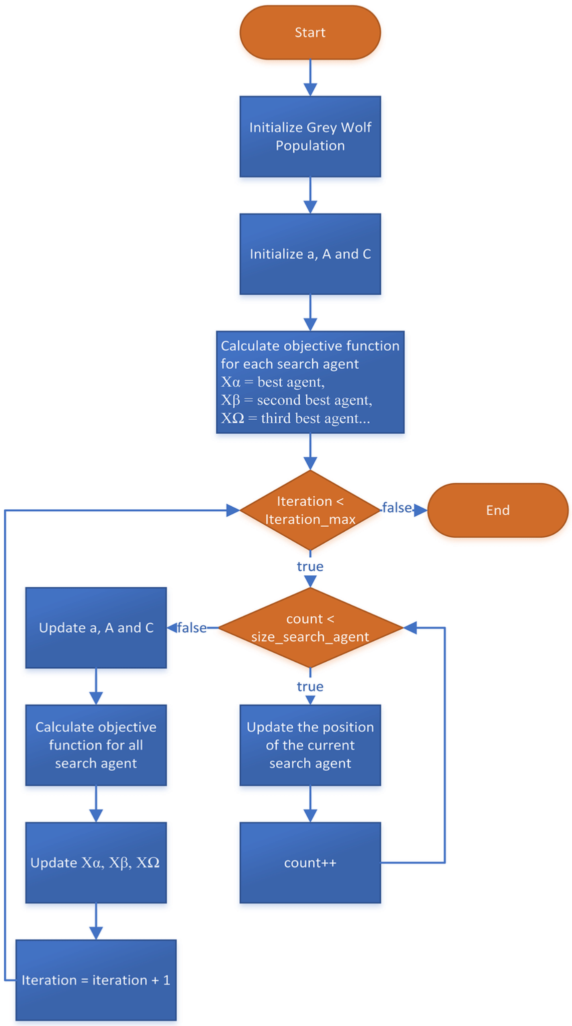


**Figure 5**. Flowchart of GWO.

In figure 4, Alpha wolf is the most dominant one. There are primarily three main steps in grey wolf algorithm which are:

1) Approaching and tracking the prey.
2) Encircling and harassing the prey until the movement stops.
3) Attacking the prey.

A more detailed analysis of the steps involved in the GWO is given in the flowchart in figure 5. The Pseudo code of GWO is given as below:

```
START
Initialization of algorithm parameters
Position generation wolves (Pw), agent (PA)
Fitness of agent is determined
Estimate Xα, Xβ and XΩ
        While (t<Nmax)
        {
        For
                {
                update Pcurr
                }
        End for
                Search agents are updated
                Fitness value is calculated
                Update Xα, Xβ and XΩ
                Count++
                }
                End while
Return best value (Xα)
END
```

Where Pw is position of wolves, PA is position of agent, Nmax is maximum number of iteration and Pcurr is current position of search agent.

## 4. RESULTS AND DISCUSSION

All simulations are carried out at MATLAB/SIMULINK platform with the machine Intel(R) Core (TM) i3-1005G1 CPU @ 1.20GHz 1.19 GHz. The designed controller has been tested for step responses with and without disturbances and positive and negative parametric uncertainty. The designed controller has been integrated into the PHWR system. The obtained simulation results for step response are shown for all cases have been discussed below.

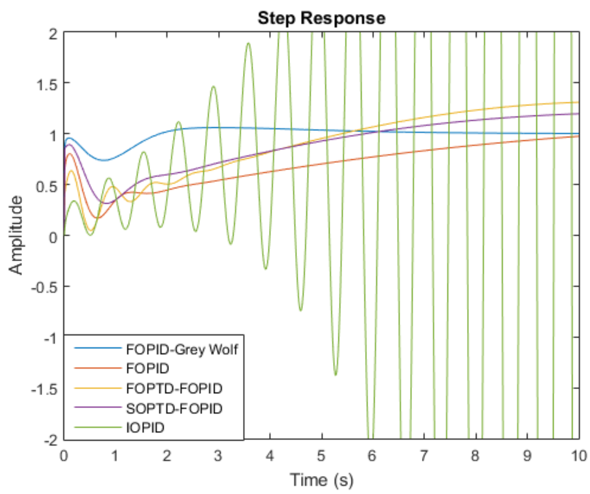


**Figure 6**. Step response without disturbance

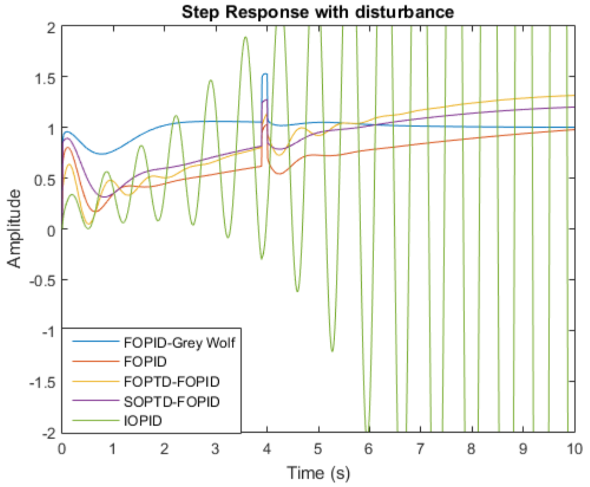


**Figure 7**. Step response with the disturbance

Figure 6 and 7 show the step response with and without the effects of disturbance. In Figure 7, a disturbance signal is added at 3.9 seconds. It is clearly observed from the simulation result that the designed controller can handle and reject the disturbance within the few seconds which validates the disturbance rejection proficiency of the FOPID controller. To check the robustness of the controller, it has also been tested under parameter uncertainty of 25 percent. Figure 8 and 9 show the step response for +25% and -25% uncertainty respectively. It is cleared from the simulated response that the controller can easily handle the parameter uncertainty, thus, proving the robustness of the design.

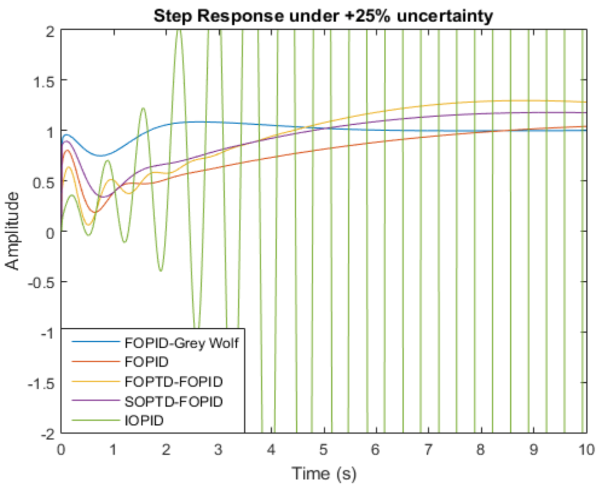


**Figure 8**. Step response under +25% uncertainty.

A tabulated comparison among various performance indices has also been performed and obtained results are shown in Table 1. The values of ISE, IAE and ITAE are least for the FOPID controller which proves the efficacy of the adopted control strategy.

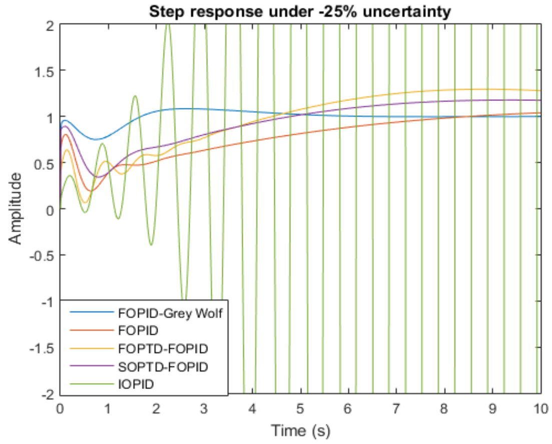


**Figure 9**. Step response under -25% uncertainty.

**Table 1.** Performance analysis based on various control strategies

| **Controllers** | **Performance indices** | | |
|---|---|---|---|
| | **ISE** | **IAE** | **ITAE** |
| Designed Controller | 0.0529 | 0.3251 | 0.9561 |
| FOPID | 1.485 | 3.2574 | 20.412 |
| FOPTD-FOPID | 1.2664 | 4.2374 | 38.556 |
| SOPTD-FOPID | 0.8335 | 2.5247 | 21.8463 |

## 4. CONCLUSION

The simulation and control of large order engineering and physical systems makes mathematical operations complex, therefore the storage space is large and the design of the system and its implementation is costly. Therefore, the model order reduction appears. In this work the balanced truncation as the main method of model order reduction has been considered after the system was represented as state space representation. The main concentration is having reduced system simulates the original system and inherit its properties by MATLAB. The PHWR is nonlinear and higher order system in nature. Firstly, the model of higher order system is reduced into model of lower order system by MOR technique. Then FOPID controller has been proposed for reduced order PHWR whose parameters are tuned by GWO algorithm. To demonstrate the effectiveness of the designed controller, a performance analysis based on ISE, IAE, and ITAE is performed. The proposed scheme may be useful to engineering professionals interested in the operation of high order systems such as nuclear reactors.

**Acknowledgement:** The author expresses sincere gratitude to the MIT, Moradabad, Uttar Pradesh, India, for their generous provision of essential facilities and support throughout the duration of the research work. The invaluable resources and conducive environment offered by MIT have significantly contributed to the successful completion of this study. The author acknowledges the institution's commitment to fostering a conducive research atmosphere, which has played a pivotal role in the advancement of knowledge and the successful execution of the research study.

## References:

Arif, D. K. (2012). Implementation of the algorithm Kalman filter on reduction model. In *International Conference on Mathematics, Statistics and its Applications*, Bali, Indonesia, 23-28.

Das, S. (2011). *Functional fractional calculus*. Berlin: Springer. doi:10.1007/978-3-642-20545-3

Das, S., & Gupta, A. (2011). Fractional-order modeling of a PHWR under step-back condition and control of its global power with a robust PI λD μ controller. *IEEE Trans. Nuclear. Science*, *58*(5–2), 2431-2441. doi:10.1109/TNS.2011.2164422

Faris, H., Aljarah, I., Al-Betar, M. A., & Mirjalili, S. (2018). Grey wolf optimizer: a review of recent variants and applications. *Neural Comput. Appl.*, *30*(2), 413-435. doi:10.1016/j.csite.2021.101250

Fortuna, L. (1992). *Model order reduction techniques with applications in Electrical Engineering* (1st ed.). Springer-Verlag London Limited. doi:10.1007/978-1-4471-3198-4

Hamamci, S. E. (2007). Stabilization using fractional-order PI and PID controllers. *Nonlinear Dynamics*, *51*(1), 329-343. doi:10.1007/s11071-007-9214-5

Kumar, D., & Nagar, S. K. (2014). Model reduction by extended minimal degree optimal Hankel norm approximation. *Applied Mathematical Modelling*, *38*(11-12), 2922-2933. doi:10.1016/j.apm.2013.11.012

Lagarias, J. C., Reeds, J. A., Wright, M. H., & Wright, P. E. (1998). Convergence Properties of the Nelder-Mead simplex method in low dimensions. *SIAM J. on Optimization*, *9*, 112-147. doi:10.1137/S1052623496303470

Lamba, R., Sondhi, S., & Singla, S. K. (2020). Reduced-order model based FOPID controller design for power control in Pressurized Heavy Water Reactor with specific gain–phase margin. *Progress in Nuclear Energy*, *125*, 103363. doi:10.1016/j.pnucene.2020.103363

Liu, C., Peng, J. F., Zhao, F. Y., & Li, C. (2009). Design and optimization of fuzzy-PID controller for the nuclear reactor power control. *Nuclear Engineering and Design*, *239*(11), 2311-2316. doi:10.1016/j.nucengdes.2009.07.001

Podlubny, I. (1999). *Fractional differential equations, ser. Mathematics in Science and Engineering*. Academic Press.

Safarzadeh, O., & Noori-kalkhoran, O. (2021). A fractional PID controller based on fractional point kinetic model and particle swarm optimization for power regulation of SMART reactor. *Nuclear Engineering and Design*, *377*. doi:10.1016/j.nucengdes.2021.111137

Saha, S., Das, S., Ghosh, R., Goswami, B., Balasubramanian, R., Chandra, A. K., Das, S., & Gupta, A. (2012). Design of a fractional-order phase shaper for iso-damped control of a PHWR under step-back condition. *IEEE Transactions on Nuclear Science*, *57*(3), 1602-1612. doi:10.1109/TNS.2010.2047405

Shah, P., & Agashe, S. (2016). Review of fractional PID controller. *Mechatronics*, *38*, 29-41. doi:10.1016/j.mechatronics.2016.06.005

Sondhi, S., & Hote, Y. V. (2012). Fractional-order controller and its applications: A review. In *Proc. of AsiaMIC*. doi:10.2316/P.2012.769-089

Sondhi, S., & Hote, Y. V. (2014). Stability testing and IMC based fractional order PID controller design for heating furnace system. *Annual IEEE India Conference (INDICON)*, 1-5. doi:10.1109/INDICON.2014.7030379

Vajpayee, V., Becerra, V., Bausch, N., Deng, J., Shimjith, S. R., & Arul, A. J. (2021). LQGI/LTR based robust control technique for a pressurized water nuclear power plant. *Annals of Nuclear Energy*, *154*. doi:10.1016/j.anucene.2020.108105

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